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Legitimation Code Theory as an Analytical Framework for Integrated STEM Curriculum and Its Enactment

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Abstract

Recent reform initiatives in STEM disciplines inspired the development and implementation of integrated STEM approaches to science teaching and learning. Integrated STEM as an approach to science teaching and learning leverages engineering principles and practices to situate learning in an authentic and meaningful science learning environment. However, integrated STEM curricular activities can be cognitively challenging for learners, so it is essential that teachers employ scaffolding techniques to facilitate student understanding of the connections between concepts and practices of the integrated disciplines. In this paper, we describe Legitimation Code Theory as an analytical framework and provide an analysis of semantic patterns of an integrated STEM unit (written discourse) and a middle school teacher's enactment of that unit (oral discourse). Specifically, this analysis focused on the semantic gravity (SG), or level of context dependency, of the activities and dialogue present throughout the unit. Creating a semantic profile offers a snapshot of how abstract (weaker SG) or how specific (stronger SG) a concept is presented in relation to other concepts. Curriculum that presents ideas through the formation of semantic waves, or oscillations between areas of stronger and weaker semantic gravity, is linked to enhanced learning of complex ideas. The results of this study identify the areas in the curriculum unit and instruction that enable or constrain knowledge-building within the science classroom. We posit that the Legitimation Code Theory is a useful tool for developing and examining integrated STEM curriculum and its implementation.

Keywords integrated STEM · legitimation code theory · engineering design · curriculum · teacher discourse

Manyof the pressing and intractable challenges facing today's global society are multidisciplinary and require a coordination of knowledge and skills across science, technology, engineering, and mathematics (STEM). Yet, the various STEM disciplines continue to

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"steadfastly defend their sovereign territories" (Sanders, 2009, p. 21), particularly in K-12 classrooms (National Academy of Engineering & National Research Council [NAE/NRC], 2014). To prepare students for broader and deeper understandings of content and disciplinary practices that will serve them throughout their educational and professional lives, recent international science and STEM education reform documents propose an approach to education that focuses on the interconnected nature of the STEM disciplines (e.g., Brunton, 2017; Education Council, 2015; HM Treasury & Department for Business Innovation and Skills, 2014; NAE/NRC, 2014). This new vision of STEM education inspired the implementation of integrated STEM approaches.

There exist a growing number of conceptualizations of integrated STEM education, particularly for the K–12 context (Bryan & Guzey, 2020; Moore et al., 2014; NAE/NRC, 2014, Rennie et al., 2012). Based on a synthesis of the last decade of work in the field to characterize the nature of integrated STEM, we created a framework that consists of five distinguishing elements (Bryan & Guzey, 2020; Bryan et al., 2015). To summarize, when we refer to K-12 "integrated STEM" instruction:

1. One or more *anchor disciplines* make up the learning goals for the lessons/unit.
2. Engineering design is an *integrator* of the anchor disciplines in a unit.
3. Learning is contextualized within a *real-world problem or task* that requires teamwork and communication.
4. Students *justify their designs* by applying content from the anchor discipline(s).
5. The context of instruction emphasizes students' development of the *twenty-first century skills*.

A hallmark of integrated STEM instruction is connecting core content knowledge and practices *across* the disciplines (English, 2016). Students must be afforded opportunities to engage in discipline-specific practices, while at the same time identifying and understanding how individual disciplinary knowledge, skills, and practices inform and support one another (Bryan & Guzey, 2020). Therefore, the scaffolding of discourse during integrated STEM instruction is critical to facilitate students' developing intersubjective understandings of such connections. Furthermore, developing a finer-grained understanding of teachers' discourse strategies in integrated STEM contexts and how these strategies may be supported during instruction is vital to effective preparation of teachers for designing and implementing integrated STEM instruction.

To date, several research studies have explored discursive practices of teachers and students in integrated science and engineering units (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). Discourse studies of integrated STEM instruction have highlighted a range of instructional strategies framed by effective discourse to help students make meaning of science and engineering (Azevedo et al, 2015; Wilson-Lopez & Minichiello, 2017). While these studies contribute to the development of tools and strategies that help students construct meaning in STEM classrooms, further research is needed on teacher discourse that enable or constrain interdisciplinary connections and knowledge-building (Doran et al., 2021; Georgiou, 2016). Integrated STEM education is highly contextual and focuses on connections between and among disciplines; thus, exploring the context-dependence and knowledge-building in the context of interdisciplinary instruction is critical.

Our interest in examining and understanding how teachers' scaffold discourse to support students' learning as they make explicit connections between science and engineering content and practices during integrated STEM instruction led us to consider frameworks for analyzing *semantics and semantic patterns* of teachers' discourse. Specifically, we applied the semantics dimension of the Legitimation Code Theory (LCT) (Maton, 2020). LCT semantics is concerned with context-dependency and meaning-making, and we aimed to identify how teachers use academic language associated with multiple STEM disciplines in order to facilitate students' meaning-making in a context that integrated science and engineering content and practices.

In this paper, we present a study that illustrates our use of LCT (Maton, 2016) as a framework for analyzing a teacher's discourse during integrated STEM instruction. Maton argues that LCT offers methods for exploring the organizing principles of academic disciplines. As noted by educational researchers who have used LCT in science-related studies, "the semantics dimension of LCT regards social fields of practice as semantic structures, which relate to meanings, both cumulatively and individually constructed over time" (Mouton & Archer, 2019 p. 3). Since LCT stresses that the context-specific nature of what is in a text (e.g., curricular resources) and what is said are important for student learning, we chose to also analyze the semantics of the curriculum unit guide that the teacher used to compare the semantic patterns of written curriculum vis-à-vis the teachers' implementation. Our study aimed to address the following research question:

- What semantic patterns are present in a written middle school integrated STEM curriculum unit and a STEM teacher's discourse during its implementation?

Legitimation Code Theory

LCT is a multidimensional framework that builds on the work of Bernstein (1999), who examined how knowledge is produced within academic disciplines by exploring different forms of discourse. 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). Maton (2014a) proposed five dimensions of LCT, namely specialization, semantics, autonomy, temporality, and density. This study focuses on the semantics dimension, specifically semantic gravity. Semantic gravity is a measure of the extent to which meaning is rooted in context (Maton, 2009). For the purpose of exploring the integrated STEM curriculum unit that includes context-embedded tasks and the unit's implementation, our work seeks to identify and describe how scientific concepts, principles, and terminology are presented in written and verbal discourses.

Semantic gravity is measured along a continuum ranging from stronger semantic gravity to weaker semantic gravity. Stronger semantic gravity, denoted with codes SG+ and SG+ +, indicates meaning is context-dependent and difficult to apply to other contexts. Weaker semantic gravity, denoted with codes SG- and SG–, indicates 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 on the broader concept of predator–prey relationships has weaker semantic gravity but a conversation about a specific aquatic predator–prey relationship such as tiger sharks and squid has stronger semantic

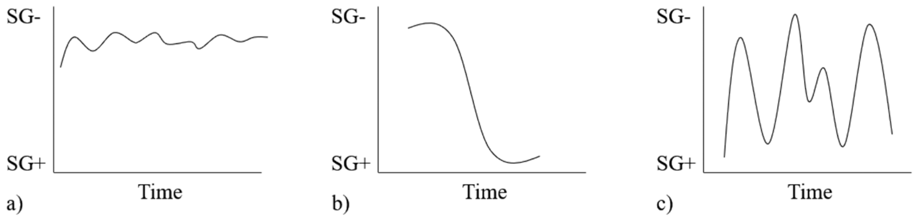

Fig. 1 Three types of semantic patterns: **a** flatlines, **b** escalators, and **c** semantic waves

gravity. Essential to knowledge-building are classroom interactions that oscillate between areas of stronger and weaker semantic gravity.

In addition, Maton (2009, 2020) characterized semantic patterns associated with cumulative and segmented learning. The continuous strengthening and weakening of semantic gravity create what are known as semantic waves, which have been shown to facilitate learning (Maton, 2009, 2014a). Examples of these semantic patterns are presented in Fig. 1. Two semantic patterns that promote segmented learning are flatlines and escalators (Maton, 2009). A flatline occurs when a concept is discussed at approximately the same level of semantic gravity for a prolonged period of time. Alternatively, 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; however, the teacher begins with a concrete example and gradually uses more complex language to arrive at an abstract concept. Escalator patterns suggest that concepts are presented as disconnected ideas, and therefore, students may struggle to understand how concepts are related to one another. Lastly, semantic waves represent the continuous strengthening and weakening of semantic gravity, a pattern that has been shown to enhance learning (Barreto et al., 2021; Maton, 2009, 2014b).

LCT has been used to analyze curriculum, syllabi, assessments, degree programs, teaching practices, and professional development (Clarence, 2017; Jackson, 2016; Mouton & Archer, 2019). While LCT has been used to improve teaching and learning in a vast array of disciplines (e.g., Hood & Hao, 2021), very few studies focused on K-12 science and STEM education (e.g., Mouton & Archer, 2019). In addition, the majority of the previous studies were situated in a university or postgraduate setting (e.g., Georgiou, 2016; Monbec, 2018; Wolmarans, 2021). Given the complexity of teaching and learning within the context of integrated K-12 STEM, we felt it prudent to use LCT to study curriculum materials and teacher discourse as scaffolding tools for students to make connections between content and practices of STEM disciplines.

Methods

This study was part of a longitudinal project that aimed to facilitate middle school science teachers' development of knowledge, skills, and practices for implementing engineering integration in life science instruction. The study utilized a 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.

Participants

Mr. Walsh (pseudonym) taught sixth-grade science at a rural middle school in the Midwest, USA. However, teaching is Mr. Walsh's second career; he previously worked as an environmental engineer, responsible for engineering tasks related to waste and pollution management. At the time of the study, Mr. Walsh had been teaching science for 10 years. We selected Mr. Walsh because of his extensive K-12 teaching experience, his familiarity with teaching engineering design, and his comfort with integrating engineering into the science curriculum.

Mr. Walsh taught in a rural middle/high school with an enrollment of approximately 500 students. The sixth-grade class in which he taught the integrated STEM curriculum unit consisted of 27 students of which 15 were Caucasian females (55.6%) and 12 were Caucasian males (44.4%). Of these 27 students, 20% received free or reduced lunch.

Curriculum Unit

The integrated STEM unit, *Designing a Two-Stage Water Filter*, was developed by the 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. The curriculum unit addresses the five critical elements of integrated STEM education presented earlier (Bryan & Guzey, 2020; Bryan et al., 2015). This unit explicitly integrates science and engineering concepts; each lesson has grade-level appropriate life science and engineering objectives mapped to national and state science education standards. Table 1 presents an overview of the unit.

Data Collection and Analysis

The data for this study included the written curriculum for the *Designing a Two-Stage Water Filter* unit and video recordings of Mr. Walsh's implementation of the unit. Sixteen 50-min class periods were video recorded and transcribed. This study focused on the context-dependent nature of Mr. Walsh's discourse during class interactions. Thus, the transcripts did not include classroom announcements or small-group conversations in which Mr. Walsh was not involved. Mr. Walsh frequently asked questions to elicit student ideas, so the transcripts do provide a snapshot of student dialogue as well.

Using LCT as a framework, we first divided the video transcripts into units of meaning, i.e., passages that convey a single meaning (Maton, 2009). Units of meaning may be at the level of a sentence, a paragraph, or several paragraphs depending on the scope and purpose of the written or verbal discourse. For example, in many instances, Mr. Walsh asked factual questions to assess students' prior knowledge. A factual question as single sentence was coded as an individual unit. In other cases, Mr. Walsh provided familiar real-world examples of the science phenomena under study. These larger discourse segments were longer than a sentence and coded as a single unit. Similarly, the length of discourse segments for the definitions of scientific concepts or principles were varied in the curriculum unit and Mr. Walsh's discourse. Each written or verbal definition of a scientific concept was coded as an individual unit.

We developed a "translation device" (Georgiou, 2016) as shown in Table 2 by adapting the four-point semantic gravity scale used by Wolmarans (2015). The first author

Table 1 Overview of the STEM curriculum

Lesson	Learning objective	Disciplinary practices	Class periods
Lesson 1: Introduction to the design challenge	Determine the design problem, identify the constraints and criteria of the solution for the design problem	Design—problem scoping	1–2
Lesson 2: Water cycle and soil percolation	Describe the effects of abiotic factors on habitat, water cycle, effects of soil types on water percolation; develop a model of how matter (water) is cycled through ecosystems	Inquiry	3–4
Lesson 3: What plants need to live	Plan and conduct investigations to determine how living things use abiotic factors; analyze and interpret data to provide evidence for the relationship between plants and abiotic components	Inquiry	5–7
Lesson 4: Interactions in the ecosystem	Identify the relationship between organisms in an ecosystem; construct an explanation that predicts how changes to biotic factors have effects on ecosystems	Inquiry	8–10
Lesson 5: Creating the water filter	Plan, construct, test, evaluate, and re-design a two-stage water filtration system; apply focal science concepts to find solutions for the design problem	Design—plan, build, test, and evaluate	11–16

Table 2 Descriptions 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."

Table 3 Frequency of each code per lesson in the curriculum

Code	Lesson 1	Lesson 2	Lesson 3	Lesson 4	Lesson 5	Total (%)
SG–	2	3	2	2	0	9 (19)
SG-	2	3	2	7	3	17 (35)
SG+	0	2	1	5	0	8 (17)
SG+ +	3	2	3	3	3	14 (29)
Total	7	10	8	17	6	48 (100)

wcoded 10% of the Lesson 1 data with a researcher who was not involved with the 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.

The code "SG–" represents discourse in the curriculum unit and implementation that presented abstract words or ideas (weaker semantic gravity), such as when Mr. Walsh introduced new science vocabulary terms which are abstract or when the conversation focused on big-picture concepts, such as ecosystems. Discussions about more familiar science ideas are represented by the code "SG-." An SG+code was assigned to discourse in the curriculum unit and implementation in which a more general, everyday example was provided to students. The final code, "SG+ +," was assigned when a specific organism, location, or context was discussed.

We created a semantic profile for both the curriculum unit and Mr. Walsh's implementation of the unit. To create the semantic profiles, the codes for each unit of meaning were plotted in chronological order as a function of time. Weaker semantic gravity is higher on the *y*-axis to represent an increase in the level of abstraction. A line connecting two codes indicates the connectedness and flow of the topics presented in the curriculum or its enactment.

Findings

In this section, we present both the analysis of the integrated STEM curriculum unit and the analysis of Mr. Walsh's discourse during his implementation to examine how context facilitated students' meaning-making in the science classroom. We also compared the semantic profiles of the curriculum and its implementation.

Semantic Patterns in the Curriculum Unit

As shown in Table 3, the degree and frequency of semantic gravity present within each lesson depended on the disciplinary focus (i.e., science or engineering) of that lesson.

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 represent context specific discourse, SG+ +, or specific science discourse, SG-. The goal of these lessons is to understand the details of the design task (SG++) or identify and apply general science concepts (SG-) to the design task. Lesson 5, for example, primarily focuses

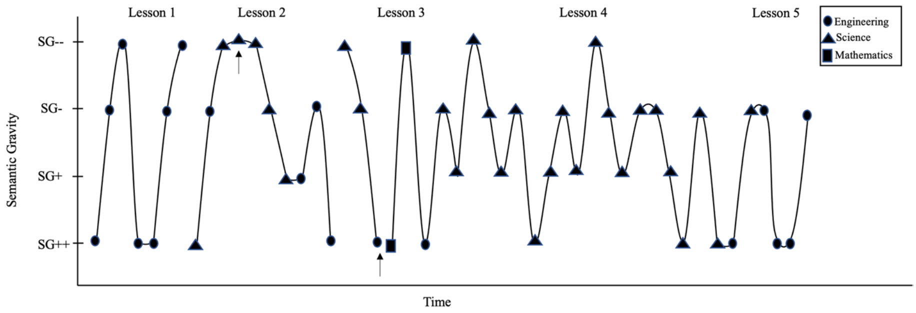

Fig. 2 Semantic profile of the curriculum

on the engineering design challenge—students design, build, and test design solutions, and the teacher facilitates design discussions. The following is an excerpt of a sample/suggested script from Lesson 5 of the curriculum unit that has a stronger 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) (SG++)

This segment of discourse is strongly rooted in the context of the design challenge 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 students in a dialogue as they review the science content that students learned throughout the unit that informed students' design ideas.

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. Lessons 2–4 of the unit focused on teaching new science content; thus, 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 help 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.

Figure 2 shows the semantic profile of the integrated STEM curriculum unit. The semantic profile of the unit contains multiple semantic waves, representing the continual unpacking and repacking of scientific ideas. However, 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 concepts in each of these lessons so students understand the purpose of each lesson and how concepts are related to one another. 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 students' meaning-making.

As shown by the left-most arrow in Fig. 2, this flatline in Lesson 2 indicates times when the curriculum is too abstract for a prolonged period of time. Discourse that is too abstract (a semantic flatline that is higher on the graph) may make it difficult for students to understand the content and how it relates to or affects their everyday lives. On the other hand,

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 (18)
SG-	31	29	27	21	5	113 (41)
SG+	20	16	12	14	0	62 (22)
SG++	19	6	9	16	4	54 (19)
Total	80	65	61	63	10	279 (100)

discourse that primarily contains specific examples (a semantic flatline that is lower on the graph) 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.

A “down escalator” is present in Lesson 3, as indicated by the right-most arrow. 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.

Semantic Patterns in Teacher Discourse

We used the same LCT analysis approach to code Mr. Walsh’s discourse and develop a semantic profile of his discourse during his implementation of the 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. As was 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 Mr. Walsh’s implementation.

Mr. Walsh’s entire implementation of the unit contained 279 units of meaning. Thus, 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. Here, we present the semantic profile of one engineering-based lesson (Lesson 1) and one science-based lesson (Lesson 3). Figure 3, 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.

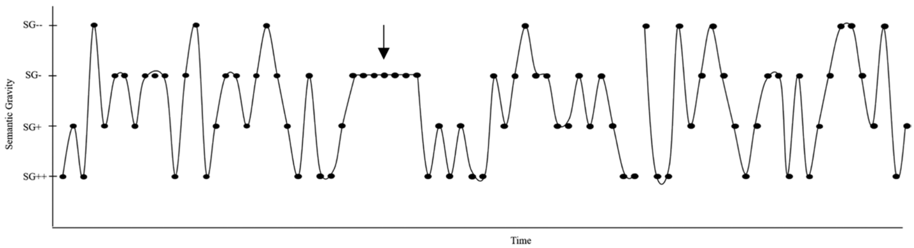

Fig. 3 Semantic profile of Lesson 1 implementation

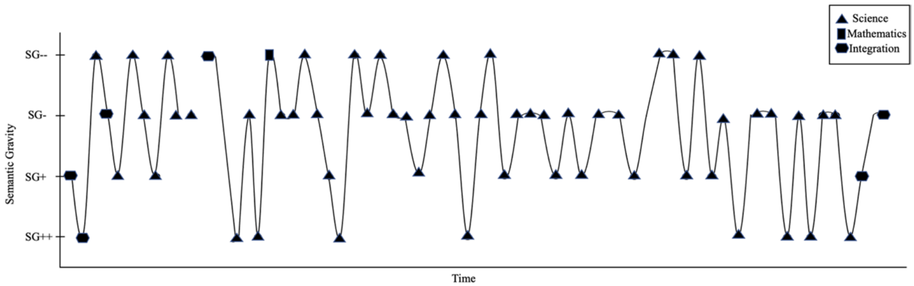

Fig. 4 Semantic profile of Lesson 3 implementation

The semantic waves present within the implementation profile of Lesson 1 illustrate Mr. Walsh's ability to unpack and repack engineering concepts and connect individual ideas to one another. Aside from the flatline in the middle of the lesson (shown by an arrow in Fig. 3), 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 the new term. 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 comes 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-).

Figure 4 shows the semantic profile of Lesson 3, which made up of many semantic waves, with several instances of Mr. Walsh gradually oscillating between SG+ and SG–.

This profile demonstrates Mr. Walsh's tendency to connect science content to real-world examples to help students make sense of the content. In Lesson 3, Mr. Walsh also used interdisciplinary connections to make learning relevant and meaningful to students. 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.

In this section, we demonstrated how LCT was used to create semantic profiles for the curriculum unit and the implementation of each lesson. Analysis of the codes presented in Tables 3 and 4 revealed the similarities and differences in the written curriculum unit and Mr. Walsh's implementation of the unit. The percentage of SG– codes for the curriculum (18%) and its implementation (19%) are quite similar. Mr. Walsh's implementation included the use of more specific science discourse (SG-, 41%) than implied in the curriculum (SG-, 35%). However, the curriculum suggested more unpacking and repacking concepts and explaining abstract ideas using concrete examples (SG+, 17%; SG++, 29%) compared to Mr. Walsh's implementation (SG+, 22%; SG++, 19%). For example, Lesson 2 provides specific instructions for explaining filtration or percolation of water through the soil by using a meaningful, authentic context. However, during the implementation of the lesson, Mr. Walsh led very brief conversations about water cycle, and the discourse focused primarily on terminology or definitions. Identifying these similarities and differences in the semantic profiles of a curriculum unit and its implementation provides data-based information that can be constructive for revising and reshaping the curriculum and instruction to better support students' knowledge-building.

Discussion

LCT provides a framework for identifying semantic patterns present in curriculum and instructional practices (Georgiou, 2016; Jackson, 2016; Maton, 2009, 2020). 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. In this paper, we documented how LCT can be used to analyze an integrated STEM curriculum unit and its implementation in a middle school classroom. Our analysis suggests that LCT is a valuable tool for designing, evaluating, revising, and enhancing integrated STEM curriculum. The analysis of the *Designing a Two-Stage Water Filter* curriculum unit resulted in a semantic profile consisting of multiple semantic waves, indicating that the curriculum unit oscillated between stronger and weaker semantic gravity. Discourse that oscillates between stronger and weaker semantic gravity tends to help students make sense of complex concepts by relating those concepts to more familiar ideas (Maton, 2020). The semantic profile of the curriculum unit also exhibited continuous semantic waves between Lessons 3–5, which indicated that the curriculum explicitly connects the content presented in each lesson. Within each lesson, individual ideas were connected to previously learned content and new content so students could better understand the "big picture." The presence of semantic waves may also help students transfer their learning to new situations. As shown in previous studies, curriculum with a profile consisting of semantic waves provided students the scaffolding they needed to develop disciplinary literacy in the classroom (Maton, 2009, 2014b; Mouton & Archer, 2019).

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 among their students (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"—talk that includes scientific language and everyday language—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 was 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 help make meaning of a specific concept or where he spent more time providing examples and less time connecting them back to the bigger picture. Furthermore, the presence of escalators elucidated instances where he ran out of time and was not able to connect two ideas together. Finally, in several instances, Mr. Walsh missed using more context-specific language as suggested in the curriculum unit. The differences found between the written and enacted curriculum highlighted areas for teacher educators who provide professional development for teachers to better scaffold learning in multidisciplinary contexts where students have to make connections between disciplines.

Interdisciplinary learning is not an easy task (NAE/NRC, 2014). Many students fail to enhance their understanding of the disciplinary concepts and the relationships between concepts while engaging in different disciplinary practices. Students are more likely to develop interdisciplinary understandings and skills when they are provided with more concrete examples and problems rather than solely abstract and uncontextualized definitions. However, appropriate level of complexity and scaffolding instruction are critical for affording students the opportunities they need to unpack and/or make meaning of disciplinary concepts (Wolmarans, 2021). Attention to the semantic patterns of discourse provides valuable insight for enhancing connections between individual disciplines.

Making cross-disciplinary connections is key for integrated STEM education (Bryan & Guzey, 2020; Moore et al., 2014). However, making such connections is complicated since each STEM discipline has unique disciplinary practices, discourse, and ways of creating and sharing new knowledge (NAE/NRC, 2014). For example, science focuses on understanding the natural world and scientific knowledge is being generated through the process of scientific inquiry. Engineering utilizes science to solve problems and the process of engineering design is central to engineering. In integrated science and engineering education, it is often the case that science is the anchor discipline and engineering supports and enhances science learning. In the current study, engineering had a dominant role in Lessons 1 and 5 and science had a dominant role in Lessons 2–4. The semantic profile of lesson implementation revealed the differences in the degree and frequency of semantic gravity present within each lesson. Engineering lessons included relatively the same number of weaker SG and stronger SG codes. Two of the science lessons, Lessons 2 and 3, on the other hand, included more weaker SG codes than stronger SG codes. This finding indicates that concepts and practices from engineering enable for more context-depended instruction. Engineering could contribute to strengthen science knowledge when teachers explain abstract science concepts in the context of engineering or shift between disciplinary science discourse and everyday examples that depend on engineering context.

In light of these findings, future studies might explore how different semantic patterns of teacher discourse facilitate student learning in the science classroom, and particularly in the context of learning science through integrated STEM approaches. A comparative study of semantic profiles of teachers and student learning could add more to our knowledge about the impact of different integrated STEM teaching strategies on learning. To be clear, there is not one specific, "correct" way a semantic profile should look. However, identifying attributes of discourse that foster deeper understanding of a concept or a relationship among concepts may help instructors enhance their planning of sense-making discussions. An effective semantic profile for life science may look different than one for physical science. Similarly, scaffolding student learning in engineering or mathematics may require the use of different semantic patterns in a curriculum or its enactment. Also, creating an alignment profile comparing the semantic gravity of a curriculum and its enactment could highlight areas where the semantic gravity of the teacher discourse varies considerably from the curriculum which would be a useful tool for fidelity of implementation studies or for studies that take a design-based approach to curriculum design and refinement.

Conclusion

In this study, we explored the use of LCT as an analytical framework for examining discourse within an integrated STEM unit. Specifically, we created a semantic profile of the written integrated STEM curriculum unit, which provided a visual representation of how the salient science and engineering ideas/concepts were intended to be presented. Similarly, we created a semantic profile of the teacher's enactment of the curriculum unit, which showed when and how the teacher unpacked and repacked scientific and engineering ideas to facilitate student learning. Integrated STEM involves the *purposeful integration of core disciplinary content and practices of STEM* disciplines and is more intentional than simply teaching two different subjects in one lesson or using one discipline as a tool for teaching another (Bryan & Guzey, 2020). The context-embedded learning tasks, which often have stronger semantic gravity, provide students with opportunities to make connections among STEM disciplines and practices. The power of using LCT to analyze discourse and examine semantic profiles resides in the rich information the sematic profiles provide to enhance the intentional integration of core concepts and practices across disciplines.

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Data Availability The datasets analysed during the current study are available from the corresponding author on request.

Declarations

Conflict of Interest The authors declare no competing interests.

References

Azevedo, F. S., Martalock, P. L., & Keser, T. (2015). The discourse of design-based science classroom activities. *Cultural Studies of Science Education, 10*(2), 285–315. https://doi.org/10.1007/s11422-013-9540-5

Barreto, L., Rodrigues, A., Oliveria, G., Almeida, L., Felix, M., Silva, P., …, & Moriemer, E. (2021). The use of different translation devices to analyze knowledge-building in a university chemistry classroom. *Research in Science Education, 51*, 135-152

Bernstein, B. (1999). Vertical and horizontal discourse: An essay. *British Journal of Sociology of Education, 20*(2), 157–173. https://doi.org/10.1080/01425699995380

Brown, B. A., & Spang, E. (2008). Double talk: Synthesizing everyday and science language in the classroom. *Science Education, 92*(4), 708–732. https://doi.org/10.1002//sce.20251

Brunton, R. (2017). *STEM education policy statement 2017–2026*. Retrieved from https://assets.gov.ie/43627/06a5face02ae4ecd921334833a4687ac.pdf

Bryan, L. A., & Guzey, S. S. (2020). K-12 STEM Education: An overview of perspectives and considerations. *Hellenic Journal of STEM Education, 1*(1), 5–15. https://doi.org/10.12973/hjstem/00110

Bryan, L. A., Moore, T., Johnson, C., & Roehrig, G. (2015). Integrated STEM education. In C. Johnson, E. Peters-Burton, & T. Moore (Eds.), *STEM Road Map: A Framework for Implementing Integrated STEM Education* (pp. 23–37). Routledge.

Clarence, S. (2017). Surfing the waves of learning: Enacting a Semantics analysis of teaching in a first year Law course. *Higher Education Research & Development, 36*(5), 920–933. https://doi.org/10.1080/07294360.2016.1263831

Dawes, L. (2004). Talk and learning in classroom science. *International Journal of Science Education, 26*(6), 677–695. https://doi.org/10.1080/0950069032000097422

Doran, Y. J., Maton, K., & Martin, J. R. (2021). The teaching of science: New insights into knowledge, language and pedagogy. In J. R. Martin & Y. J. Doran (Eds.), *Teaching science: Knowledge, language, pedagogy* (pp. 1–20). Routledge.

Education Council. (2015). *National STEM school education strategy: A comprehensive plan for science, technology, engineering and mathematics education in Australia*. Retrieved from https://www.education.gov.au/education-ministers-meeting/resources/national-stem-school-education-strategy

English, L. (2016). STEM Education K-12: Perspectives on integration. *International Journal of STEM Education, 3*(1), 1–8.

Georgiou, H. (2016). Putting physics knowledge in the hot seat: The semantics of student understandings of thermodynamics. In K. Maton, S. Hood, & S. Shay (Eds.), *Knowledge-building educational studies in Legitimation Code Theory* (pp. 176–192). Routledge.

HM Treasury, & Department for Business Innovation and Skills. (2014). *Our plan for growth: Science and innovation*. Retrieved from https://www.gov.uk/government/publications/our-plan-forgrowth-science-and-innovation

Hood, S., & Hao, J. (2021). Grounded learning: Telling and showing in the language and paralanguage of a science lecture. In K. Maton, J. R. Martin, & Y. J. Doran (Eds.), *Teaching science: Knowledge, language and pedagogy* (pp. 226–256). Routledge.

Jackson, F. (2016). Unraveling high school English literature pedagogic practices: A Legitimation Code Theory analysis. *Language and Education, 30*(6), 536–553. https://doi.org/10.1080/09500782.2016.1177070

Johnston, A. C., Akarsu, M. G., Moore, T., & Guzey, S. S. (2019). Engineering as the integrator: A case study of one middle school science teacher's talk. *Journal of Engineering Education, 108*, 418–440. https://doi.org/10.1002/jee.20286

Kelly, G. J. (2008). Learning science: Discursive practices. In M. Martin-Jones, A. -M. De Mejía,& N. H. Hornberger (Eds.), Encyclopedia of language and education: Vol. 3. Discourse andeducation (pp. 329–340). Springer.

Maton, K. (2009). Cumulative and segmented learning: Exploring the role of curriculum structures in knowledge-building. *British Journal of Sociology of Education, 30*(1), 43–57. https://doi.org/10.1080/01425690802514342

Maton, K. (2014a). *Knowledge and knowers. Towards a realist sociology of education*. Routledge.

Maton, K. (2014b). A TALL order? Legitimation Code Theory for academic language and learning. *Journal of Academic Language and Learning, 8*(3), A34–A48.

Maton, K. (2016). Legitimation Code Theory: Building knowledge about knowledge-building. In K. Maton, S. Hood, & S. Shay (Eds.), *Knowledge-building educational studies in Legitimation Code Theory* (pp. 1–24). Routledge.

Maton, K. (2020). Semantic waves: Context, complexity and academic discourse. In J. Martin, K. Maton, & Y. Doran (Eds.), *Accessing academic discourse: Systemic functional linguistics and legitimation code theory* (pp. 59–85). Routledge.

Monbec, L. (2018). Designing an EAP curriculum for transfer: A focus on knowledge. *Journal of Academic Language and Learning, 12*(2), A88–A101.

Moore, T. J., Stohlmann, M. S., Wang, H. H., Tank, K. M., Glancy, A. W., & Roehrig, G. H. (2014). Implementation and integration of engineering in K-12 STEM education. In Ş Purzer, J. Strobel, & M. E. Cardella (Eds.), *Engineering in pre-college settings: Synthesizing research, policy, and practices* (pp. 35–60). Purdue University Press. https://doi.org/10.2307/j.ctt6wq7bh.7

Mouton, M., & Archer, E. (2019). Legitimation Code Theory to facilitate transition from high school to first-year biology. *Journal of Biological Education, 53*(1), 2–20. https://doi.org/10.1080/00219266.2017.1420681

National Academy of Engineering & National Research Council. (2014). *STEM integration in K-12 Education: Status, prospects, and an agenda for research*. Washington, DC: National Academies Press. https://doi.org/10.17226/18612

Rennie, L., Wallace, J., & Venville, G. (2012). Exploring curriculum integration: Why integrate? In L. Rennie, G. Venville, & J. Wallace (Eds.), *Integrating science, technology, engineering, and mathematics: Issues, reflections, and ways forward* (pp. 1–11). Routledge.

Roth, W. M. (1996). Art and artifact of children's designing: A situated cognition perspective. *The Journal of the Learning Sciences, 5*(2), 129–166. https://doi.org/10.1207/s15327809jls0502_2

Sanders, M. E. (2009). STEM, STEM education, STEMmania. *The Technology Teacher, 68*(4), 20–26.

Valtorta, C. G., & Berland, L. K. (2015). Math, science, and engineering integration in a high school engineering course: A qualitative study. *Journal of Pre-College Engineering Education Research, 5*(1), 15–29. https://doi.org/10.7771/2157-9288.1087

Wilson-Lopez, A., & Minichiello, A. (2017). Disciplinary literacy in engineering. *Journal of Adolescent & Adult Literacy, 61*(1), 7–14. https://doi.org/10.1002/jaal.658

Wolmarans, N. (2015). Navigating boundaries: Moving between context and disciplinary knowledge when learning to design. In R. S. Adams & J. A. Siddiqui (Eds.), *Analyzing design review conversations* (pp. 97–114). Purdue University Press.

Wolmarans, N. (2021). The relationship between specialised disciplinary knowledge and its application in the world. In K. Maton, J. R. Martin, & Y. Doran (Eds.), *Teaching science: Knowledge, language, pedagogy* (pp. 205–225). Routledge.

Yin, R. (1994). *Case study research: Design and methods*. Sage Publication.