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Interdisciplinary Knowledge for Teaching: A Model for Epistemic Support in Elementary Classrooms

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Research and national standards, such as the Next Generation Science Standards (NGSS) in the United States, promote the development and implementation of K-12 interdisciplinary curricula integrating the disciplines of science, technology, engineering, mathematics, and computer science (STEM+CS). However, little research has explored how teachers provide epistemic support in interdisciplinary contexts or the factors that inform teachers' epistemic support in STEM+CS activities. The goal of this paper is to articulate how interdisciplinary instruction complicates epistemic knowledge and resources needed for teachers' instructional decision-making. Toward these ends, this paper builds upon existing models of teachers' instructional decision-making in individual STEM+CS disciplines to highlight specific challenges and opportunities of interdisciplinary approaches on classroom epistemic supports. First, we offer considerations as to how teachers can provide epistemic support for students to engage in disciplinary practices across mathematics, science, engineering, and computer science. We then support these considerations using examples from our studies in elementary classrooms using integrated STEM+CS curriculum materials. We focus on an elementary school context, as elementary teachers necessarily integrate disciplines as part of their teaching practice when enacting NGSS-aligned curricula. Further, we argue that as STEM+CS interdisciplinary curricula in the form of NGSS-aligned, project-based units become more prevalent in elementary settings, careful attention and support needs to be given to help teachers not only engage their students in disciplinary practices across STEM+CS disciplines, but also to understand why and how these disciplinary practices should be used. Implications include recommendations for the design of professional learning experiences and curriculum materials.

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I. INTRODUCTION

Research promotes the development and implementation of K-12 interdisciplinary curricula integrating the disciplines of science, technology, engineering, mathematics, and computer science (henceforth STEM+CS). These studies illustrate the potential of integrating disciplines to improve students' disciplinary content knowledge, problem solving skills, and retention in STEM+CS classes and careers (Fllis & Fouts, 2001; King & Wiseman, 2001; Smith & Karr-Kidwell, 2000) and provide relevant and engaging classroom learning experiences (Frykholm & Glasson, 2005; Koirala & Bowman, 2003). Interdisciplinary STEM+CS approaches also provide opportunities for students to build epistemic knowledge, which is the understanding of how and why to engage in disciplinary practices, as well as the habits of mind and the nature of the individual disciplines (Berland et al., 2016). Epistemic knowledge is important for making connections between disciplines and to understand the ways of knowing the practices that are unique to a discipline (e.g., Lazenby et al., 2020). However, little research has explored how teachers provide epistemic support in interdisciplinary contexts or the factors that inform teachers' epistemic support in STEM+CS activities.

The goal of this paper is to articulate how interdisciplinary instruction complicates epistemic knowledge and resources needed for teachers' instructional decision-making. Toward this end, this paper describes existing models of teachers' instructional decision-making with individual STEM+CS disciplines to highlight specific challenges and opportunities of interdisciplinary approaches on classroom epistemic supports. We offer an expanded model of teachers' knowledge and decision-making for interdisciplinary instruction with classroom examples from elementary school settings, as elementary teachers often integrate disciplines as part of their teaching practice. We then offer considerations as to how teachers can provide epistemic support for students to engage in disciplinary practices across mathematics, science, engineering, and computer science.

II. RATIONALE

To provide background on the complexities of interdisciplinary instruction, we explore prior literature that focuses on supporting students' epistemic development and highlights challenges to implementing STEM+CS curricula, and review existing models of teacher instructional decision-making.

1. SUPPORTING STUDENTS' EPISTEMIC DEVELOPMENT

Epistemic knowledge for a specific discipline involves understanding how and why one engages in the practices of that discipline (Berland et al., 2016). In classroom contexts, students can develop epistemic knowledge by engaging in learning communities in which students construct knowledge by engaging in the practices of a discipline (e.g., Lave & Wenger, 1991) and learning the ways of thinking and reasoning inherent to that discipline (Sandoval & Reiser, 2004). For example, when students engage in the practices of mathematics, science, engineering, or computer science communities, then they are not only building knowledge within these disciplines but are also creating an understanding of the disciplinary ways of thinking and the nature of mathematical, scientific, engineering, and computer science knowledge (e.g., Ganesh & Schnittka, 2014; Pantoya et al., 2015). Thus, epistemic knowledge is important for all students to recognize in order to increase student interest and performance within STEM+CS disciplines (Moore et al., 2014).

Teachers have an important role in supporting students to develop this epistemic knowledge within individual disciplines. Prior research shows that teachers' epistemic support can guide students to engage in disciplinary practices (e.g., Christodoulou & Osborne, 2014; González-Howard & McNeill, 2019), that this support can be provided to students in a variety of ways at different times (Russ, 2018), and that students use their epistemic knowledge to guide the way in which they engage in practices (Ruppert et al., 2019). For example, teachers can communicate to students "what constitutes knowledge or learning in the immediate moment" (Russ, 2018; p. 99) or explicitly tell students about the broader disciplinary goals for specific practices (Gray & Rogan-Klyve, 2018). Students then can take on agency to actively make decisions about building knowledge and engaging in practices in alignment to disciplinary goals (Miller et al., 2018; Stroupe et al., 2019).

Particularly, this epistemic support can be through teachers helping students make explicit connections to disciplinary practices, supporting students to learn about the unique nature of a discipline (i.e., what are the ways of knowing in that discipline, understanding why practices are important in that field, and building students' awareness of what one needs to do in order to further knowledge in that discipline; e.g., Kelly, 2008). For example, disciplinary epistemic knowledge in mathematics includes understanding that mathematics uses logic and deduction from foundational principles to derive new mathematical relations (e.g., Chevallard, 2006; Sierpinska & Lerman, 1996). During problem solving or model-based instruction, mathematics teachers can explicitly connect what students do in the classroom to authentic mathematical practices. In science, epistemic knowledge includes understanding that science answers questions about the natural world and is tentative and subjective (e.g., Abd-El-Khalick & Leaderman, 2000; Lederman, 1992). Science teachers can use examples such as relativity or the changing guidance for COVID-19 to help students understand how scientists refine their understanding based on new evidence and ideas as well as how culture impacts science. In engineering, epistemic knowledge includes understanding that engineering develops solutions that address human wants and needs at the individual, community, and global level (e.g., Moore et al., 2014). Teachers can support students to develop this understanding through reflecting upon how their own designs and design processes address human needs. In computer science, epistemic knowledge includes understanding how and why computers work and how to shape computers' impact on society (e.g., K-12 Computer Science Framework, 2016). Teachers can help students develop epistemic knowledge of computer science through discussion and debate of relevant examples such as bias in algorithms. However, for students to build epistemic knowledge such that they can, and choose to, regularly engage in disciplinary practices across contexts in alignment to a discipline, teachers' epistemic supports must be prioritized and consistent both across different contexts and over time (Ke & Schwarz, 2021; Russ 2018). In summary, teachers can help students develop sophisticated epistemic knowledge of disciplines by purposefully and consistently highlighting the different ways that each discipline generates and refines disciplinary knowledge.

In this paper, we specifically characterize epistemic supports in classrooms as the ways that teachers support students' epistemic knowledge (Lederman et al., 1998). Following the literature (e.g., Berland et al., 2016; Lederman et al., 1998; McNeill & Krajcik, 2008; Sandoval et al., 2004), we discuss two primary types of epistemic supports to account for both through our framework: *pragmatic* and *disciplinary*. We define *pragmatic epistemic supports* as supports that help students engage in specific disciplinary practices. Examples include teachers supporting students to plan and carry out investigations in science or to define problems in engineering. For instance, teachers can engage students in a discussion about the appropriate design of an investigation or prompt students to identify constraints that help define an engineering problem. Examples can also be interdisciplinary, such as supporting students to test potential designs using computational models (e.g., Dasgupta et al, 2017) or to use algorithms to model scientific phenomena (e.g., Hutchins et al., 2020). We define *disciplinary epistemic supports* as supports that help students to understand the nature of the discipline and how and why disciplinary practices advance knowledge in the discipline. *Disciplinary epistemic supports* make connections between the classroom activities and the authentic engagement with disciplinary practices (e.g., Berland et al., 2016; Sandoval, 2004). For instance, teachers can support students to develop disciplinary-based epistemic knowledge of engineering by making explicit connections from students' engineering design activities to how professional engineers solve real-world problems. Teachers can also support students to understand how and why practices are used. For example, teachers can frame argumentation as a community practice in science rather than an individualistic practice (e.g., Gonzales-Howard & McNeill, 2019). This framing uses the development of group understanding as an epistemic reason for how to engage in the specific practice of argumentation. Thus, *pragmatic epistemic support* involves engaging in disciplinary practices while *disciplinary epistemic support* involves understanding the nature of the discipline.

2. INTERDISCIPLINARY STEM+CS CURRICULAR CHALLENGES

Research demonstrates the potential of integrated STEM+CS approaches to improve students' disciplinary content knowledge, problem solving skills, and retention in STEM+CS classes and careers (Fllis & Fouts, 2001; King & Wiseman, 2001; Smith & Karr-Kidwell, 2000). However, prior research also highlights difficulties that teachers face when trying to implement interdisciplinary, STEM+CS curricula. First, instead of consensus about what counts as interdisciplinary at the elementary level, research shows that there are many accepted definitions and models of interdisciplinary STEM+CS (e.g., Breiner et al. 2012; Estapa et al., 2017; Johnson et al., 2020; NRC, 2014; Roehrig et al. 2012). These models are often context-dependent, dependent on stakeholders (Breiner et al., 2012), or tied to policy enactment (Bybee, 2013) instead of focusing on providing a clear definition and goals for stakeholders implementing STEM+CS curricula. For example, instruction that integrates science and engineering can mainly focus on science with the engineering activities involved as a way to further science understanding. Alternatively, they could focus on engineering with only relevant science concepts taught as a way for students to complete the engineering challenge. Similarly, integrating mathematics and computer science can center on mathematics with the computer science activities serving to help students engage in mathematical practices, or lessons may focus on computer science with mathematics in service of creating a program. With integrated curricula between two or more STEM+CS disciplines (Sanders, 2009), this vagueness may lead to teachers struggling to adequately incorporate each discipline as intended by a curriculum (Shaughnessy, 2013).

In this paper, we define interdisciplinary as building connections between disciplines and real-world problems within one classroom (Stohlmann et al., 2011). We also consider a spectrum of integration. Specifically, we extend the definition of integration from Furner and Kumar (2007), "teaching math entirely as a part of science, math as a language and tool for teaching science, or teaching science entirely as a part of math" (Furner & Kumar, 2007, p. 187) to include all combinations of the four disciplines of science, engineering, mathematics, and computer science. Note, this is different from elementary teachers being responsible for teaching separate disciplinary-based content throughout the day. Instead, interdisciplinary instruction places each discipline in a primary, supporting, or mutually complementary role where the disciplines build upon one another. Interdisciplinary instruction can consist of two or more disciplines integrated at a time, working in service of each other with teachers helping to make connections between the disciplines explicit to the students.

While research has examined the ways in which teachers support students' epistemic knowledge in individual STEM+CS disciplines (Lin & Chan, 2018; Tan et al., 2019), little research has explored teachers' epistemic supports in interdisciplinary contexts. Interdisciplinary instruction offers unique affordances and challenges to help students develop epistemic understanding. Affordances include offering students the opportunity to engage in shared disciplinary practices in ways that mirror authentic practice and underscore the ways that disciplines complement each other. For example, integrating computational modeling into science lessons enables students to understand how scientists use computation to investigate the natural world. Integrating engineering into science can help students see how engineers use science to solve real-world problems, or how scientists apply scientific principles to engineering technologies needed to answer their own research questions. Epistemic supports in interdisciplinary instruction can also give students opportunities to compare and contrast epistemic knowledge across disciplines, which may enable students to develop deeper understandings of each (e.g., Tytler et al., 2019). For example, when students engage in both science and engineering, teachers can encourage students to compare how science investigates the natural world, while engineers focus on the designed world.

However, STEM+CS interdisciplinary instruction can also be challenging for teachers, especially in elementary classrooms where teachers are expected to teach all disciplines to their students but may not have a background or training in any of the STEM+CS disciplines. Moreover, increasing content demands and a focus on the implementation of national frameworks will compel elementary teachers to integrate the teaching of multiple disciplines (e.g., NGSS; NGSS Lead States, 2013; Common Core Mathematics; K-12 CS Framework).

STEM+CS integration has the potential to be successful, in part because of practices that are common across STEM+CS disciplines (such as modeling, argumentation, and working with data). However, these shared practices further highlight the need for teachers to be able to provide students with epistemic support, so that students can understand and appreciate the unique roles of these practices in advancing knowledge both within and across disciplines. This is particularly important for elementary teachers, as exposure to STEM+CS in elementary contexts strongly relates to students' identity development and potential interest in STEM+CS courses and careers (Morgan et al., 2016). Additionally, integrated STEM+CS instruction is intrinsically challenging, as disciplines have their own epistemic knowledge and practices, but practices may also be shared (or similar) across disciplines.

To teach interdisciplinary content, teachers must then have the knowledge and skills not only to meaningfully teach each involved discipline (Furner & Kumar, 2007) but also know how each discipline (including specific content, practices, and epistemologies) relates to the others. This knowledge includes disciplinary epistemic knowledge about the habits of mind, ways of thinking, and practices within each discipline and how each is similar or different from the others. Further, teachers need to support students to engage in the content and practices of multiple disciplines and intentionally make connections among disciplines (Duschl et al., 2016).

Even with high quality, standards-aligned, interdisciplinary curricula, teachers' beliefs, goals, or epistemic understanding of a single discipline may influence how students understand and engage in disciplinary practices in other disciplines. For many teachers, interdisciplinary teaching may be challenging as teachers may have different levels of prior experience in each discipline, especially with engineering or computer science. Teachers may consider content from disciplines that they do not typically teach (i.e., engineering or computer science) as skills rather than disciplinary content, affecting how the less familiar discipline is implemented in comparison to more traditional content (Estapa et al., 2017). Particularly for elementary teachers, who may not have a formal training in each discipline, there is the potential to create new knowledge gaps and challenges (Stinson et al., 2009). For example, teachers can have difficulties predicting how long lessons will last, knowing how to best guide students in their work, and maintaining confidence in their teaching (Stohlmann et al., 2011). Further, more research is needed to better understand how these challenges for the teachers may affect students' learning within interdisciplinary contexts across disciplines (Crotty et al., 2017; Mehalik et al., 2008; Wendell & Rogers, 2013). For example, a scientific concept that is appropriate for elementary school students may rely on more advanced mathematics concepts (Lilly, Fick et al., 2020), which the teachers may or may not have the disciplinary knowledge to support. Thus, we argue that a refined model of teacher knowledge and instructional decision-making is needed to further investigate how teachers provide epistemic support for students *in situ* during interdisciplinary activities to identify factors that may influence teachers' instructional decision-making around epistemic support.

3. EXISTING MODELS OF TEACHER INSTRUCTIONAL DECISION-MAKING

Many models, both discipline-general and discipline-specific, exist that articulate various elements of teachers' decision-making in classrooms (e.g., Hamre et al., 2013; Schoenfeld, 2018; Shulman, 1986). For example, discipline-general frameworks such as Grossman (1990) and Marks (1990) describe elements such as knowledge of students' understanding, knowledge of curriculum, knowledge of instructional strategies, and knowledge of purposes as central to teaching, and knowledge of media for instruction as central to teachers' decision-making in the classroom. These discipline-general frameworks are intended to universally describe teaching across contexts. In contrast, discipline-specific frameworks articulate what is needed for instructional decisions in a specific discipline. For example, mathematical knowledge for teaching (Ball et al., 2008) breaks down content knowledge into content knowledge of mathematics in common settings other than teaching, specialized content knowledge that is unique to teaching mathematics, and horizon content knowledge of how distinct concepts connect together. Mathematical knowledge for teaching also consists of knowledge of content and students, knowledge of content and teaching, and knowledge of content and curriculum. However, there are few, if any, frameworks that explicitly address needs for teaching interdisciplinary instruction.

In this paper, we have chosen Gess-Newsome's (2015; Figure 1) discipline-general model as a starting point to inform a model of interdisciplinary teaching because it (1) provides insight into the role of professional knowledge and educative resources on teachers' classroom practice and (2) unifies discipline-specific and discipline-general frameworks. Here we describe in detail the components of Gess-Newsome's model that have the most salient implications for supporting instructional decision making in interdisciplinary contexts, with a particular focus on epistemic supports.

Teacher professional knowledge bases (TPKB) are formal resources and knowledge created by experts in the field for practice (e.g., Cochran-Smith & Lytle, 1992). TPKB includes but is not limited to knowledge about assessment, pedagogy, content, students, and curricula. Knowledge of assessment can include understanding the design and purposes of formative and summative assessment and how to use results to modify instruction. Pedagogical knowledge includes strategies to differentiate, engage, and manage students. Content knowledge includes national or state standards, such as the NGSS, which involve integrating disciplinary core ideas, science practices, and crosscutting concepts. Knowledge of students involves understanding students' cognitive and physical development and disabilities, and how to build upon individual students' assets and community resources. Curricular knowledge includes goals, structures, sequence, and the ability to critique curriculum for coherence. TPKB typically encompasses knowledge from a specific discipline but can conceivably be broadened to include knowledge both within and across multiple disciplines. TPKB exists outside of the teacher and is codified by experts or other national policies.

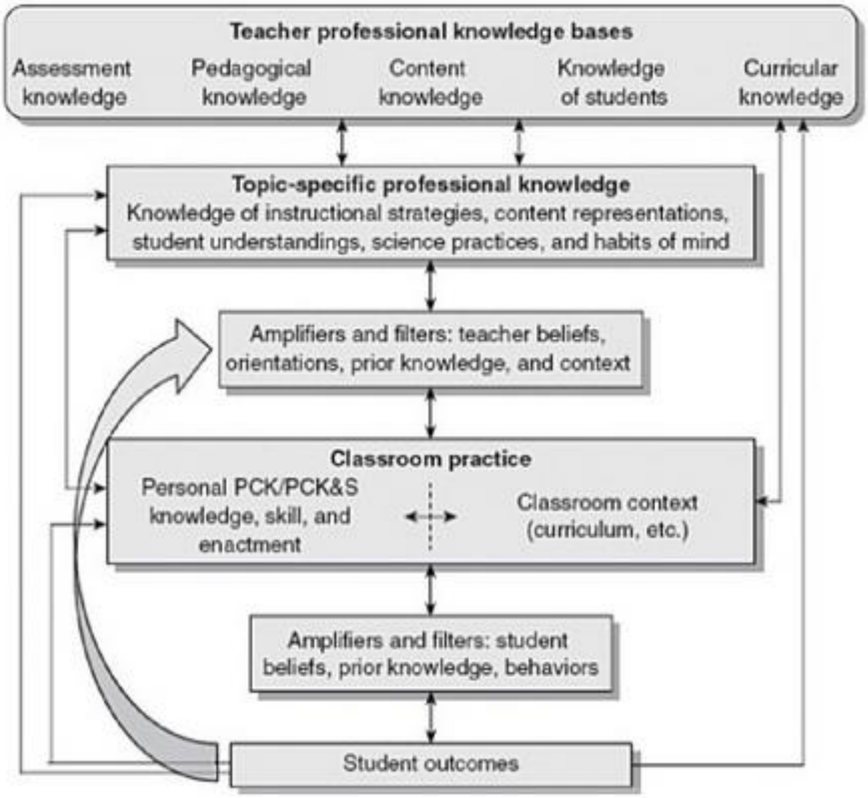

Figure 1. Model of teacher professional knowledge and skill and influences on classroom practice and student outcomes. Reproduced from Gess-Newsome (2015).

Topic-specific professional knowledge (TSPK) involves applying these knowledge bases to specific content with students at a particular grade band. Although TSPK is similar in nature to pedagogical content knowledge (Gess-Newsome, 1999), like TPKB, TSPK is defined as existing outside of the mind of individual teachers, codified by experts, and available for use and study by teachers. TSPK involves knowing appropriate instructional strategies, relevant content representations, the organization of content around big ideas or anchoring questions/problems, knowing potential alternative student ideas, and knowing how to integrate content, practices, and habits of mind within a lesson or unit. Importantly, TSPK can be identified by researchers and serve as the basis for learning experiences specific to grade level and content for teachers.

While TSPK could be well-defined for topics that exist within the boundaries of a specific discipline, it may be ill-defined and/or highly complex for topics that draw from multiple disciplines. For example, with fifth-grade students studying the science concept of urban water runoff, TSPK involves connecting the topic to an engineering design challenge, such as “How can we reduce water runoff at our school?” In order to model urban water runoff, students draw from prior, school-based knowledge in mathematics to quantify the model, then engage in a computer science lesson so that they can create a program that models the runoff computationally. To fully support the modeling practice across the disciplines of science, engineering, mathematics, and computer science, teachers must hold TSPK in each of these disciplines. This support may be difficult to provide, as concepts and skills needed for the design challenge may draw from different grade bands across disciplines.

As illustrated in Figure 1, both TPKB and TSPK pass through *teachers’ amplifiers and filters*, such as teachers’ beliefs, orientations, prior knowledge, and broader learning context. Teachers’ beliefs include their own ways of thinking and attitudes about teaching, the disciplines that they teach, and about the students that they teach (Muijs & Reynolds, 2002). For example, teachers may believe they should sometimes promote student discovery of new knowledge rather than receive information only through direct instruction or perceive variation in their students’ capability to engage in specific curricular activities. These beliefs can have an impact on teachers’ effectiveness and the opportunities that students have to engage in disciplinary practices (Askew et al., 1997). Teachers have agency to choose, reject, adapt, or modify professional knowledge that they implement in their own classrooms. For example, teachers with beliefs about the importance of schooling to promote social justice may choose to emphasize drawing upon student assets and community resources within instruction. Teachers with orientations toward student-centered instruction might choose to use students’ existing ideas and potential alternative ideas as a basis for learning activities. Teachers with a deep personal understanding of content knowledge may use different instructional supports for different topics. Contextual variables such as access to high quality professional development opportunities and school policies and practices can also amplify or filter teachers' use of professional knowledge bases and strategies.

As part of *classroom practice*, teachers make both planned and in-the-moment instructional moves that draw upon their own pedagogical content knowledge and skills and are based within specific classroom settings for specific content and learners. Gess-Newsome (2015) defines pedagogical content knowledge and skill (PCK&S) as a kind of *reflection in action* (Schön, 1983) where teachers enact planned instruction but necessarily monitor student involvement and make instructional changes based on what they notice in their classrooms. PCK&S is tacit, dynamic, and can be inferred by researchers based on what they see of teachers' classroom practice. PCK&S specifically highlights teachers' *skills* to enact appropriate strategies, as some teachers may have the knowledge about instructional strategies but may not have the skill to implement strategies in practice. This limitation may be especially salient in interdisciplinary context. For example, teachers may have the skill to enact a strategy in mathematics but not computer science. To address this limitation, we introduce epistemic PCK&S to the model, encompassing the PCK&S teachers draw from in the classroom to support students' epistemic knowledge across disciplines.

Finally, teachers' instructional moves pass through *students' amplifiers and filters* as they promote student outcomes of interest. For example, a student will have varying experiences, proficiency, and interest in different STEM+CS disciplines. This student's engagement with the lesson and instructional materials will depend on this prior knowledge, having subsequent impacts on their learning outcomes across the disciplines.

4. CHARACTERIZING INTERDISCIPLINARY TEACHER PROFESSIONAL KNOWLEDGE

We build from Gess-Newsome's model to highlight the intricacies and challenges of epistemic supports within interdisciplinary curricula through our model of interdisciplinary-epistemic teacher knowledge (Figure 2). Existing models highlight the importance of PCK&S within a single discipline but do not explicitly acknowledge the impact of interdisciplinary contexts on the professional and personal knowledge that teachers need to enact interdisciplinary curricula. We specifically focus on elements that may influence how teachers choose to provide epistemic support for students in interdisciplinary contexts; the professional knowledge of TPKB and TSPK as well as how teacher beliefs and context can amplify and filter both TPKB and TSPK in classroom contexts. Clarifying established models with respect to both interdisciplinary contexts and epistemic supports is important, as each different discipline in an interdisciplinary curriculum has unique epistemic knowledge and practices which presents challenges for teachers. By doing so, we aim to provide insight into the kinds of available professional knowledge, learning experiences, and supporting resources that teachers may need in order to provide epistemic support for students in interdisciplinary contexts.

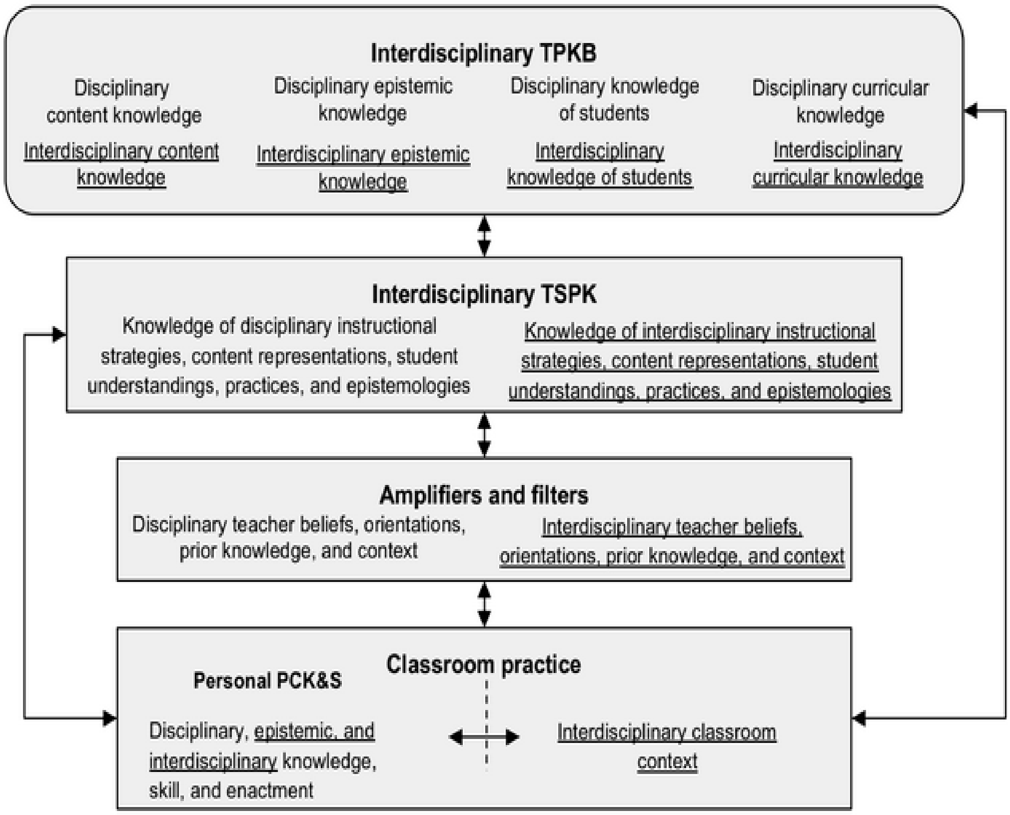

Figure 2. Interdisciplinary-Epistemic Teacher Knowledge: An elaborated model describing a framework of interdisciplinary teacher knowledge for epistemic support and instructional decision-making in classrooms, with added concepts underlined for clarity.

1) Interdisciplinary TPKB

Teachers need discipline-specific content knowledge in the form of understanding the concepts, practices, and the nature of each discipline in order to offer students opportunities to engage authentically with a discipline. In interdisciplinary contexts, teachers need to understand each discipline as well as how concepts, practices, and epistemic knowledge connect or contrast across disciplines.

(1) DISCIPLINARY AND INTERDISCIPLINARY CONTENT KNOWLEDGE

National frameworks for mathematics (National Council of Teachers of Mathematics, 2014), science (Framework for K-12 Science Education; National Research Council, 2012), engineering (K-12 Engineering Framework; American Society for Engineering Education (ASEE, 2020), and computer science (K-12 Computer Science Framework, 2016) establish disciplinary concepts that students should know at each grade level. For interdisciplinary projects, such as those aligned to the NGSS, elementary science teachers are expected to integrate disciplines (i.e., science, engineering, mathematics, and computer science) by supporting students to engage in disciplinary-specific practices, core ideas, and crosscutting concepts. To enact such projects, teachers should then ideally understand concepts in each discipline, what concepts precede and follow, as well as how concepts may connect with each other across disciplines (e.g., interdisciplinary content knowledge). In elementary settings, elementary science teachers enacting NGSS-aligned curricula may need support to understand connections between disciplinary concepts across mathematics, science, engineering, and computer science. For example, elementary teachers may come into their classrooms with limited mathematics (e.g., Browning et al., 2014; Foss & Kleinsasser et al., 1996) and science (e.g., Appleton, 2008; Menon & Sadler, 2016) conceptual knowledge. Additionally, elementary teachers may need targeted support for engineering and computer science concepts since these disciplines are not part of the standard curriculum and teachers typically have very little experience with engineering or computer science in preservice teacher programs (e.g., Wendell, 2014; Yadav et al., 2017). In addition to understanding the disciplinary concepts in isolation, teachers may also need support to understand how concepts in different disciplines may connect or build upon each other. For example, the mathematics concept of analyzing patterns and relationships overlaps with abstraction in computer science; mathematical models using algebraic expressions to represent real-life situations can also connect to representing science phenomena and engineering concepts mathematically.

Disciplinary content knowledge also involves understanding the disciplinary processes and practices. Table 1 provides an overview of different practices for each discipline according to national frameworks used in the United States.

Table 1. Disciplinary practices for mathematics, science, engineering, and computer science as defined in national frameworks.

Mathematics (Common Core)	**Science (NRC, 2012)**	**Engineering (ASEE, 2020; NRC, 2012)**	**Computer Science (K12CS.org)**
● Make sense of problems and persevere in solving them ● Reason abstractly and quantitatively ● Construct viable arguments and critique the reasoning of others ● Model with mathematics ● Use appropriate tools strategically ● Attend to precision ● Look for and make use of structure ● Look for and express regularity in repeated reasoning	● Asking questions ● Developing and using models ● Planning and carrying out investigations ● Analyzing and interpreting data ● Using mathematics and computational thinking ● Constructing explanations ● Engaging in argument from evidence ● Obtaining, evaluating, and communicating information	● Engineering ● Materials processing ● Quantitative analysis ● Professionalism ● Defining problems ● Developing and using models ● Planning and carrying out investigations ● Analyzing and interpreting data ● Using mathematics and computational thinking ● Designing solutions ● Engaging in argument from evidence ● Obtaining, evaluating, and communicating information	● Fostering an inclusive culture ● Collaborating around computing ● Recognizing and defining computational problems ● Developing and using abstractions ● Creating computational artifacts ● Testing and refining computational artifacts ● Communicating about computing

Similar to disciplinary concepts, teachers implementing interdisciplinary curricula need to have interdisciplinary knowledge of practices both within and across disciplines. Some practices are similar across disciplines. For example, communicating ideas (such as through argumentation) is explicitly described across mathematics, science, engineering, and computer science. In some cases, practices in one discipline refer directly to other disciplines. For example, using mathematics and computational thinking constitutes a distinct scientific and engineering practice in the NGSS, reflecting instances where scientists and engineers use mathematical and computational tools and techniques to achieve their goals. To help practitioners make these connections, some frameworks articulate connections between practices across disciplines (e.g., K-12 Computer Science Framework, 2016). However, teachers may not be aware of, have access to, or have the support to make use of these knowledge bases.

(2) DISCIPLINARY AND INTERDISCIPLINARY EPISTEMIC KNOWLEDGE

Teachers need to understand not only the epistemic knowledge of each discipline but also interdisciplinary epistemic knowledge, or how disciplines are similar and different. For example, mathematics and computation are used across fields and disciplines, but each have their own epistemic goals and habits of mind (Table 1). Although the NGSS integrate science and engineering practices into one set, science and engineering are two different fields with two different goals: science investigates the natural world and engineering seeks to solve human problems in the designed world. Engineering also creates technologies that help advance scientific discovery, while science explains principles that can be applied to novel engineering solutions. These kinds of relationships are important for teachers to understand and emphasize in the teaching of interdisciplinary curricula.

(3) DISCIPLINARY AND INTERDISCIPLINARY KNOWLEDGE OF STUDENTS

Teachers' knowledge about their students includes understanding students' individualized learning needs to offer differentiated instruction as well as how to incorporate students' assets and resources (i.e., prior knowledge, personal skills; Gess-Newsome, 2015). Teachers also need to have knowledge of their students, assets, and resources in interdisciplinary contexts. Implications of teachers' knowledge of learners in interdisciplinary settings may include that teachers may have different levels of knowledge of students for different disciplines. For example, teachers may be aware of the expected mathematics backgrounds of most students following specific learning trajectories at their school but be unaware of the computer science backgrounds that some students may have access to outside of formal school settings. It is then difficult for teachers to make assumptions about what every student "knows" or has been exposed to, and teachers may or may not be able to connect to students' assets within each discipline. For example, some teachers may be better able to support students to bring in their existing assets into science instruction than into mathematics or computer science instruction.

Additionally, elementary teachers are also tasked to implement NGSS-aligned projects into inclusive classrooms (Librea-Carden et al., 2021) that typically include students with disabilities, students without disabilities, a special education teacher, and a general education teacher. Although special education teachers can provide essential supports for students with disabilities, they often have limited preparation in STEM+CS (e.g., Taylor & Villanueva, 2017). To provide opportunities for students with disabilities to engage in NGSS-aligned projects, general teachers typically need support to provide students with the explicit support that they may need to engage with the inquiry-based activities included in the project (e.g., Cook et al., 2009; Therrien et al., 2017).

(4) DISCIPLINARY AND INTERDISCIPLINARY KNOWLEDGE OF CURRICULUM

Knowledge of the curriculum is a teacher's understanding of the objectives and scope and sequence of a disciplinary curriculum along with the ability to assess the soundness of the curriculum (Gess-Newsome, 2015). A deep interdisciplinary knowledge of curriculum helps teachers to better adapt the curriculum to fit the needs of their students while maintaining fidelity to specific aspects of the curriculum (i.e., authenticity, rigor). Implications of teachers' not having adequate interdisciplinary knowledge of curriculum include that teachers may or may not be able to support connections that curriculum activities make between different disciplines or draw upon high-quality interdisciplinary resources for teaching.

2) Disciplinary and Interdisciplinary TSPK

Interdisciplinary instruction has ramifications for teachers' knowledge of instructional strategies, content representations, student understandings, disciplinary practices, and epistemologies within TSPK.

(1) INSTRUCTIONAL STRATEGIES

Different disciplines have different professional specifications of TSPK, and teachers need to understand not only the disciplinary instructional strategies but also the nuances and differences of instructional strategies across disciplines. For example, prior research in pedagogical knowledge for supporting mathematical, student-centered discussions includes anticipating, monitoring, selecting, sequencing, and connecting moves (Stein et al., 2008). To push whole-class discussions to build on student thinking, teachers must have a high level of mathematical pedagogical knowledge to be able to consider both correct and incorrect mathematical strategies that students may use, consider students' mathematical thinking and solution strategies, and consider the order of presenting student ideas (e.g., from concrete to abstract and popular to less popular; Stein et al., 2008). However, science has instructional strategies to elicit student ideas in discussion that focus on introducing a scientific phenomena through an anchoring activity, eliciting hypotheses, and pressing for possible explanations to uncover students' partial, alternative, and everyday understandings of the target concept (Windshitl et al., 2012). In interdisciplinary lessons, what may begin as a discussion about science phenomena may then transition into a mathematical discussion. The ability to engage in teaching practices within other disciplines would then require teachers to have knowledge of instructional strategies across disciplines, how strategies may connect and weave together across disciplines, as well as how to plan and anticipate interdisciplinary connections.

(2) CONTENT REPRESENTATIONS

Similarly, part of interdisciplinary TSPK is understanding how content representations are both similar and different across disciplines. For instance, teachers may choose to emphasize data tables to connect data collection and analysis practices across mathematics, engineering, and science disciplines. However, without a strong understanding of what representations are valuable and how they are used in the different disciplines, teachers may miss learning opportunities for students. For example, not understanding if or how a data table is useful for building a computational model may limit a teachers' use of data tables for testing and debugging computational models with students.

(3) STUDENT UNDERSTANDINGS

TSPK of student understandings in interdisciplinary settings involves teachers' knowledge of potential challenges and alternative ideas for specific topics within each discipline, as well as how alternative ideas in one discipline may affect learning of specific topics in other disciplines. For example, students that may struggle with the mathematical concept of a ratio may then also struggle with the scientific concept of an absorption ratio, and then subsequently struggle to use the absorption ratio variable in a computational expression.

(4) INTEGRATING CONTENT, PRACTICES, AND EPISTEMOLOGIES

Interdisciplinary TSPK involves knowledge of integrating specific content topics with particular practices and understanding how these content-practice combinations connect to different epistemic concepts. For instance, in science, the NGSS outline performance expectations that students should be able to achieve at the end of a grade level or band. These performance expectations weave together disciplinary core ideas, science and engineering practices, and crosscutting concepts. However, the NGSS provide little guidance to teachers on how to meet those expectations in classroom instruction. Thus, teachers need to select and choose how and when to use particular practices and crosscutting concepts to help students learn particular core ideas, which includes choosing when and how to "use mathematics and computational thinking" as part of their lessons. In interdisciplinary instruction, teachers need to be able to weave together specific concepts, practices, and epistemic knowledge in each discipline and across disciplines for specific learning objectives. Instead of general knowledge like TPKB, TSPK involves knowing how to integrate these pieces across disciplines for a particular lesson or unit.

Unintended consequences or challenges in implementing integrated curricula involve intricacies in making these choices for specific topics. For example, supporting students to engage in computational practices that are appropriate for elementary school students may require students to use more advanced mathematics concepts (Lilly, Fick et al., 2020). Additionally, teachers may need support to know what aspects of epistemic knowledge connect to specific disciplinary content and practices. For example, professional development can help teachers understand the nature of computer science as a field and why it is important for activities to include testing and debugging while students develop computational models in science classes. Thus, it is important to consider how concepts, practices, and epistemic knowledge are integrated into specific lessons within interdisciplinary instruction (Duschl et al., 2016).

3) Disciplinary and Interdisciplinary Amplifiers and Filters: Teacher Beliefs and Self-Efficacy

In interdisciplinary contexts, teachers' beliefs can be disciplinary-specific in that teachers may have different beliefs and considerations of self-efficacy for different disciplines, different instructional approaches, or different self-efficacy for supporting students with individualized learning needs within different disciplines. For example, teachers may hold different beliefs about the importance of written communication in mathematics than in science, teachers' beliefs about their students' abilities may or may not vary from one discipline to another, and teachers may have beliefs regarding the capabilities of certain students to engage in specific disciplinary practices. For example, assuming that students who face challenges in mathematics would necessarily face challenges in engineering or that students with individualized needs are not capable of engaging in computer programming could result in inequitable STEM+CS opportunities for students, particularly for students from certain social or economic backgrounds (Therrien et al., 2011).

Teachers' interdisciplinary beliefs and self-efficacy may also affect implementation of interdisciplinary projects. These beliefs may cause teachers to provide unbalanced epistemic supports across disciplines or alter curricular activities in ways that reflect their self-efficacy in each discipline. For example, teachers may choose which curricular materials to implement or emphasize epistemic knowledge of disciplines that they feel more familiar with. Or teachers may not believe specific disciplines to be as important to devote time to, because of a lack of associated state-mandated testing for that discipline, their own perceptions of the level of rigor required to engage in that discipline, or if they think that a discipline should or should not be given attention within their classroom or specific course.

4) Classroom Practice: Disciplinary, Epistemic, and Interdisciplinary PCK&S

We build upon Gess-Newsome's view of personal PCK&S and explicitly highlight the role of epistemic and interdisciplinary knowledge, skill, and enactment within classroom practice (epistemic PCK&S). We align with the conception of PCK&S as what is evident in teachers' instructional decision-making and intentional moves during instruction, which may be different from teachers' stated knowledge. For example, although teachers may have access and training in interdisciplinary instructional strategies for specific topics, they may or may not use them in an interdisciplinary classroom context, even when curricular resources include these connections (Alfieri et al., 2015). Additionally, teachers may need additional support to maintain rigor across the integration of concepts during instruction. For example, the integration of mathematics into other subjects does not ensure that students will learn mathematics, as students can struggle to communicate their mathematical ideas within interdisciplinary contexts, and there may need to be in-the-moment changes to the design of lessons to maintain student engagement (Alfieri et al., 2015). An interdisciplinary model of teacher knowledge and instructional decision-making should therefore address how teachers integrate disciplines during classroom practice to help students engage in and make connections across disciplines (Duschl et al., 2016). We also acknowledge that classroom practice is based on the learning context, which includes the community in which teachers teach (i.e., school-wide or departmental policies, how to access personnel support for students with individualized needs) as well as the state and/or school-specific standards that they are responsible for teaching.

III. VIGNETTES OF INTERDISCIPLINARY INSTRUCTION

To illustrate how the model identifies opportunities and challenges to teachers' interdisciplinary decision-making, we discuss vignettes from our studies of two teachers (identified by the pseudonyms Mr. Skelton and Ms. Banet) implementing an NSF-funded, STEM+CS interdisciplinary project (e.g., Lilly et al., 2021). In the Water Runoff Challenge (WRC), teachers challenged students to redesign surface materials around their school to reduce water runoff. Within this project, teachers supported students to solve an authentic and relevant problem of water runoff in their recess areas and soccer fields by developing conceptual scientific models of water runoff through hands-on investigations, generating different designs of their school grounds, and then creating a computational model to test and compare their designs. In this way, the teachers helped students to engaged in engineering to solve the runoff problem at their school, science to explore why there was runoff after heavy rains for different materials, mathematics to calculate numerical values of water runoff and discover patterns and rules for the amounts of water absorbed and runoff based on total rainfall, and computer science to create the computational models based on the mathematical rules (Chiu et al., 2019; Lilly, McAlister et al., 2020).

The WRC has been implemented at the same school with the same teachers over three years in various classroom contexts. We focus on two classroom contexts: an Inclusive Class, in which a large proportion of students have individualized educational plans, and a General Class, in which a large proportion of students are also in advanced mathematics classes. We draw from data in the first year of implementation, including teacher surveys, interviews, artifacts, classroom observations, and transcripts of classroom video, to provide examples and highlight important considerations for how teachers provide epistemic supports in interdisciplinary contexts. We focus on verbal supports in the examples as a specific lens for clarity. The next section elaborates existing models of instructional decision-making by identifying special considerations of interdisciplinary instruction on TPKB and TSPK, as amplified and filtered through teacher beliefs, prior knowledge, and context, and the impact of these considerations on teachers' epistemic support in classroom practice. Thus, through the provided examples, we make connections between the teacher knowledge bases and types of support (i.e., *pragmatic* or *disciplinary*) and argue that these knowledge bases impact teachers' ability to give *pragmatic* and *disciplinary* support to students.

1. EPISTEMIC PCK&S IN INTERDISCIPLINARY CLASSROOM PRACTICE

PCK&S can inform teachers' epistemic support for students during classroom instruction by providing students with connections between the disciplinary practices that they are engaging in and the broader discipline. For example, Mr. Skelton explained to students,

> In science a lot of times we'll do the same experiment lots and lots and lots of times and we'll get slightly different bits of information. We take an average because we want to find where is the center point, right?

In this episode, Mr. Skelton provides disciplinary epistemic support in a science-focused lesson where students engage in a science disciplinary practice (planning and carrying out investigations) while using the mathematical concept of average. He does this by connecting the immediate activity (computing the average of an empirical dataset) to the discipline of science by indicating that scientific data necessarily includes variation that must be accounted for mathematically.

While this example illustrates a targeted and specific support, the epistemic support could have been elaborated in numerous ways, such as discussing the reasons for the occurrence of variation or being more precise about the nature of average than characterizing it as a "center point." This may exemplify a missed opportunity for the teacher to support understanding of the mathematical concept of average, considering what average really means, connecting to related data practices in mathematics, and discussing why a scientist would want to take an average. These follow-up conversations would have built further on scientific knowledge and its connection to a foundational mathematics concept used frequently in science. It is unclear whether this specific epistemic knowledge connecting scientific variation and average is part of Mr. Skelton's PCK&S. This connection would be a strong candidate to be addressed in teachers' professional learning experiences designed to support the integration of science and mathematics.

2. INTERDISCIPLINARY TPKB, EPISTEMIC KNOWLEDGE, AND CLASSROOM PRACTICE

The ability of teachers to adapt instruction based on their *knowledge of students* can enable them to create additional opportunities for epistemic support. For example, in the first year of the WRC, the teachers used their knowledge of their students to add an activity for a class section with a large proportion of students with individualized educational plans (Inclusive Class). In this added activity, students went outside to their recess area during a rain event to take observations and generate evidence of the water runoff problem at their school. This additional lesson gave the teachers opportunities to provide *pragmatic epistemic support* of the science practice of planning and carrying out investigations. Additionally, the teachers were able to give students *disciplinary epistemic support* to help students understand the ways that the water runoff related to their previous activities. For example, the teachers stated that they considered the lesson important as students "were able to connect pieces of the curriculum" and the activity "reminded them of why we are doing all this in the first place."

However, incomplete knowledge of students combined with teacher beliefs about the capabilities of students can result in different opportunities for students. In the WRC, students were supposed to create their own computational models to test their designs. Students in both class sections, the Inclusive Class and the General Class, struggled to do so. When students in the General Class initially struggled with this, the teachers had the students work together in pairs and then share their codes through whole-class discussion to debug the coding together as a class and compare variations in their codes. When students in the Inclusive Class initially struggled with this, the teachers quickly restructured the activity to offer students support. They did this by providing *pragmatic* support that verbally led students step-by-step through the programming and, ultimately, gave students the final computer code rather than supporting students to create their own. While this in-the-moment support saved time and perhaps stress for the students in the Inclusive Class, it also meant that they were not given the same opportunity as students in the General Class to engage in computer science practices in the ways in which the curriculum intended or opportunities to build epistemic knowledge around computer science practices. For example, when given the code, the students in the Inclusive Class then did not receive *disciplinary* verbal support about the importance of debugging within the iterative process of creating a code or how different variations of codes can be used to create computational models. From the teachers' beliefs about the mathematics backgrounds of the Inclusive Class, relative to the General Class, the teachers may have believed that students in the Inclusive Class needed more direct support in computer programming rather than being capable of working through challenges with the coding. Thus, knowledge of students may not be as helpful if teachers are not able, or do not know how, to provide additional scaffolding or differentiation for their students that still enables engagement with the disciplinary practices.

We recognize that the teachers were trying to modify the curriculum based on their understanding of student needs. However, in implementation, they may then have also been limiting opportunities for certain students to engage in the disciplinary practices that the curriculum fore fronted. Further, the teachers both recognized their modifications across the curriculum. Mr. Skelton said, "We used direct instruction more than suggested with [the Inclusive Class], leading them through the initial values and change rules" and "we guided students in [the Inclusive Class] through the engineering design more so than the lesson suggested." Further, Ms. Banet acknowledged that her modifications to the curriculum "short changed" students in the Inclusive Class in that some of the aspects most suggested by the curriculum, student-centered engagement in disciplinary practices, were not always met. Thus, if the teachers had placed the two class sections on more equal footing in computer science, been able to recognize potential struggles and plan their responses, or had strategies for providing *pragmatic* and *disciplinary* support that still enabled engagement in the disciplinary practices, then they might not have short changed students in the Inclusive Class. The teachers may then need help to gain an understanding of how to support students based on their knowledge of the students that would enable them to build students' epistemic knowledge and adapt curriculum activities as needed without sacrificing curricular goals.

3. KNOWLEDGE OF CONTENT

Knowledge of the content can also influence how teachers enact epistemic supports in interdisciplinary classrooms. Teachers reported struggling to support students in disciplines with which they were less familiar such as computer science and engineering. At times, this came from the teachers finding these skills difficult. For example, Ms. Banet discussed having trouble helping students to generate and debug code for a computational model. She felt that this had a negative impact on her students, saying,

> There were a couple of times where the students' programs were malfunctioning, and I didn't know how to help other than having them close out their program and bring up a whole new copy. A couple of girls, they didn't know why it wasn't running the program ... and they ended up having to start over because I didn't know what else to do.

Here, the teacher's lack of knowledge of the disciplinary practice of debugging led to her feeling that she was unable to support her students in computer science activities that included this practice. In an interdisciplinary STEM+CS curriculum unit, challenges with coding potentially have downstream impacts on other disciplines. In this case, an incomplete or buggy computational model would create subsequent challenges for students to use the model to make scientific predictions and test engineering designs. This example illustrates how support to build teachers' epistemic knowledge is necessary so that teachers implementing interdisciplinary curricula understand how a computer science disciplinary practice such as debugging can have impacts across multiple disciplines for classroom teaching in interdisciplinary contexts.

4. INTERDISCIPLINARY TSPK AND CLASSROOM PRACTICE

Applying disciplinary knowledge to specific content with students in a particular grade level can lead teachers to verbally support activities differently for different groups of students. We describe an example where students in two different class sections were supported differently to understand mathematical models of the scientific concept of absorption ratio. In this example, the concept of ratios is not a typical fifth-grade concept at this school and was being introduced as part of the WRC. It is not unusual in interdisciplinary work for students to be challenged to learn necessary concepts and skills in the moment or for the grade-appropriateness of the concepts and skills needed to be misaligned across disciplines (Schmidt & Houang, 2007). In this example, the science phenomenon was driving which mathematical concepts were included (Lilly, Fick et al., 2020), and the focus on authentic science understanding then involved more complex mathematical concepts. Despite all being fifth graders, a large proportion of students in the General Class were also in accelerated mathematics classes and, thus, had prior knowledge of the concept of ratios due to their accelerated coursework; however, students in the Inclusive Class did not have this prior knowledge. The teachers knew this about their students and so structured a modeling activity differently to be more appropriate for students based on their "grade level" awareness of the mathematical concept.

In the General Class, the teachers gave students the opportunity to make their own mathematical models and then discussed these student mathematical models together as a class.

In the whole-class discussion, Mr. Skelton made two different student mathematical models a point of discussion to help students understand the connection between additive and multiplicative properties. He further continued *disciplinary epistemic support*, saying,

> So you could have done it either way, which is a really important point when you're coding. There's not always one solution. As a matter of fact, there's often lots of different solutions. So if you've got here a different way, that's wonderful.

We note that the teacher may have actually meant algorithm here, instead of solution. This is important to clarify as this kind of disciplinary knowledge would have made the connection between the nature of an algorithm across the disciplines of mathematics and computer science clear to students. Further, the teachers' language also risks conflating "solution" with engineering solution, which is not applicable here. Still, the teacher attempted to help students draw connections between the mathematical modeling that they were engaged in and the computational modeling that they would soon do.

In contrast, in the Inclusive Class, the teachers led the students through developing the mathematical model of absorption ratio together through a whole-class discussion. There was no epistemic support of different algorithms as the students all followed the teachers' directions to create the same model. Thus, the teachers led students in the Inclusive Class through a specific algorithm through a whole-class discussion rather than enabling students to create their own mathematical models and produce various answers as was done in the General Class. This meant that students in the General Class had the opportunity to consider connections between the disciplinary idea that multiple algorithms can be used to solve a problem in both mathematics and computer science while students in the Inclusive Class did not.

While this example illustrates how two class sections were differently, and perhaps inequitably, supported toward engaging in disciplinary practices, the teachers were implementing the curriculum and supporting students to the best of their abilities based on their knowledge of students. This type of planned differentiation was not evident in the lessons focused on computational thinking. As shown in a previous example, teachers approached computer programming in the computer science-focused lessons in the same way with both groups of students. After realizing that students in the Inclusive Class were struggling, they then changed their supports to try to meet their needs. So for a mathematics-focused activity, the teachers differentiated the structure of the activity based on their knowledge of the students' in mathematics. While for computer science-focused activities, activities were approached with the same structure until the teachers realized students in the Inclusive Class were struggling.

Thus, for both disciplines where teachers have and do not have knowledge of their learners, teachers may just need help to be able to maintain rigor and the student-centered nature of activities when providing support, particularly for students with individualized needs. The teachers recognized this need; they reported recognizing how the potential differences in prior mathematical knowledge may have affected their students' ability to understand the science concepts, discussed this difference in prior knowledge as an inequity, and then pointed out their own challenges in equitably supporting students across class sections in integrated activities.

5. AMPLIFIERS AND FILTERS: INTERDISCIPLINARY TEACHER BELIEFS AND CLASSROOM PRACTICE

Teachers made changes to the enacted interdisciplinary instruction based on their beliefs about students, beliefs about the importance of specific domains, and the classroom contexts and constraints of time. Specifically, the teachers made substantial changes to the enacted curriculum for the Inclusive Class. Teachers modified activities by skipping questions, truncating or removing activities, and modifying activities to be done as a class rather than the intended individual work. For example, referring to a computer science-focused portion of the project, Ms. Banet reflected that, "Due to time, we cut out all the math in the notebook. So the kids didn't do pages, the last page we did was 18 and then we had them skip to page 26. We cut out all of that." This shows that when faced with pacing concerns, the teachers chose to remove aspects of mathematical content and crucial practices of testing computer artifacts. Yet these curricular activities were important for creating and coding conceptual models, which the teachers may not have prioritized or realized with limited disciplinary knowledge and/or beliefs about the importance of these activities within the progression within the WRC. In particular, without interdisciplinary TPKB in the form of knowledgeable about how information would build and what activities were most important for students to be able to understand concepts and engage in activities later in the curriculum for those disciplines, teachers may have pulled upon their limited PCK&S to cut activities that were important because their beliefs about their students' abilities when enacting those in-the-moment activities seemed the most concerning obstacle to overcome.

Implications of teachers needing interdisciplinary PCK&S also include the ways that this may affect teachers' epistemic supports. For example, teachers may have different ways to engage students in practices by either letting them just try an activity or heavily scaffolding an activity. For example, in comparing *pragmatic* support between class contexts for science-focused concepts, we found that the Inclusive Class received less support aimed to engage prior knowledge than students in the General Class. This difference is evident in the verbal support given to the General Class to help them make predictions:

> So today we're actually going to explore that a little further, about what happens when water hits different surfaces. We decided that your engineering design was going to withstand one inch of rainfall per hour. Your answer is just going to be a prediction, I believe grass will do what with water when water hits it. Don't forget the why part to your predictions, the part that says because. So you're using any prior knowledge you have about grass or concrete to explain your claim or prediction that you're making.

In these statements, teachers' *pragmatic* verbal support helped students to recall prior knowledge regarding design constraints and different surface materials, helped students to make sense of what a prediction is, and included instructions for how to create their prediction. In contrast, here is the support that students in the Inclusive Class were given:

> Go ahead and pull up 4.1. Give me a thumbs up when you've made a prediction about what will happen when rainfall hits grass and when it hits concrete.

This verbal support only included support directly for making predictions, which showed that the students in the Inclusive Class received different *pragmatic* verbal support to make predictions.

The teachers' beliefs about students and their own self-efficacy regarding their ability to provide support for students with disabilities also affected teachers' support of student engagement in disciplinary practices. For example, Mr. Skelton reflected that he struggled with "being able to recognize then act on the varying scaffolding needs between class sections that effectively meets the needs of students" and needed additional support to maintain rigor for students in the Inclusive Class. Specifically in regard to the computer science-focused activities, he said that "differentiating for ability level was a struggle for me" and suggested that he could have used additional professional development to prepare for "differentiating this for varied learners."

These challenges, coupled with lower reported expectations and beliefs about the ability of students in the Inclusive Class to engage in disciplinary practices, may have led the teachers to differently support students. For example, Mr. Skelton said that the Inclusive Class was "successful in carrying out the first experiment after watching me do it" but the General Class was "successful in designing the experiment and carrying out the modeled experiment" and students in the Inclusive Class were successful at "capturing images of how water affects surfaces, and predicting which surface would absorb more water" while students in the General

Class were successful at “understanding permeability versus impermeability and calculating absorption rates.” In implementation, the teachers’ verbal support was also different. For example, Ms. Banet said to the General Class,

> We learned about different materials and their absorption is how their absorption rate and the rainfall relate. And then we talked about how the more absorbent a surface is the less water will flow on top, and then the higher the absorption, the more water it absorbs. So the absorption rate gets determined by how much water is absorbed by the grass and how much rainfall that we actually have.

In contrast, she told the Inclusive Class “the water represents rainfall. Whatever is on top of the soil is what was not absorbed, that's your runoff. And duration is the total time.” Thus, students were not receiving the same verbal support to understand and engage with disciplinary practices, and teachers’ beliefs of students may influence the ways that they structure their verbal support and affect the opportunities that students have to engage in integrated activities.

In these examples, the teachers are providing epistemic supports in science, engineering, and computer science-focused lessons based on their prior knowledge about students’ placement in specific class sections, which was based on students’ prior mathematics proficiency and individualized needs. Yet, prior knowledge about students should also be interdisciplinary such that teachers’ prior knowledge about student achievement in one discipline should not necessarily inform how a teacher provides support in another discipline. Further, students’ needs in one discipline may not dictate their needs in a different discipline. Thus, the more teachers know about their students’ prior knowledge and needs across disciplines, the better they can epistemically support their students accordingly to engage in disciplinary practices as well as to understand the nature of each discipline and the connections between disciplines.

IV. IMPLICATIONS AND CONCLUSIONS

With interdisciplinary curricula, teachers are tasked not only to weave together the concepts and practices of each discipline but also to represent the epistemic knowledge of each discipline. This may be particularly difficult for disciplines that teachers may not have specific training or backgrounds in, and the level of support that teachers require to mitigate these challenges could vary for each teacher based on their own goals; pedagogical, content, and epistemic knowledge; knowledge of students; and beliefs (Figure 2). Considering epistemic knowledge, elementary teachers who do not have prior experience in teaching engineering or computer science may need support to integrate epistemic knowledge s of these disciplines (i.e., engineering design and computational thinking) into their elementary science or mathematics classrooms.

Our model of interdisciplinary-epistemic teacher knowledge provides guidance for professional learning experiences for elementary teachers through which they could build upon their own prior experiences and knowledge toward more successfully implementing interdisciplinary curricula (Baker & Galanti, 2017). Teachers may need specific support to identify, access, and understand TPKB for the interdisciplinary curricula that they are implementing. Professional learning experiences can help teachers explore and understand disciplinary concepts, practices, and cross-cutting ideas as well as help teachers compare and connect practices and epistemic knowledge across disciplines. For example, in the WRC project, teachers were provided with explicit guidance on the NGSS and how students can learn science concepts by engaging in engineering and computational thinking practices.

In addition, elementary teachers who do not have prior experience in teaching engineering or computer science may need support to integrate epistemic knowledge of these disciplines into their elementary science or mathematics classrooms. Professional learning experiences should include explicit opportunities for teachers to learn disciplinary epistemic knowledge. Such support could also include explicit explanations of connections between disciplines that teachers could then make clear to their students (Estapa et al., 2017). For example, in the WRC project, teachers were provided with explicit support to understand the differences between epistemic knowledge in science and engineering, as well as how computation can be used as a tool within both disciplines.

Providing teachers with opportunities to develop knowledge of interdisciplinary curricula can involve engaging teachers in the curricular activities as students and supporting reflection and discussion around the activities (e.g., Borko, 2004; Guskey & Yoon, 2009; Garet et al., 2001). For example, in the WRC project, teachers engaged in all of the lessons as students to develop understanding of how the curricular unit weaved together content and practices across domains. Teachers were also asked to reflect upon and discuss specific supports within the teachers' guide materials that called out connections across disciplines.

Professional learning experiences can also provide teachers with opportunities to develop and strengthen TSPK. Professional learning opportunities can help provide teachers with interdisciplinary instructional strategies and support teachers to develop understanding of content representations across disciplines. For example, WRC professional development activities helped teachers understand representations of systems across science, engineering, and computational settings. Interdisciplinary TSPK for student understanding can be supported through professional learning experiences. For example, professional development can provide common student challenges and alternative ideas for specific topics within interdisciplinary instruction, as well as how alternative ideas in one discipline may affect learning of other concepts in other disciplines. In the WRC project, careful attention should be given to how alternative student understanding of concepts such as ratios and variables may affect students' ability to develop and use computational models.

Further, our model of interdisciplinary-epistemic teacher knowledge provides guidance to address teacher beliefs in interdisciplinary instruction. Professional learning experiences can help teachers maintain confidence in their teaching (e.g., Stohlmann et al., 2011) and address beliefs such as considering content from disciplines that they do not typically teach (e.g., engineering or computer science) to be skills rather than academic content. Professional learning experiences can also provide explicit goals of interdisciplinary efforts to help teachers develop orientations and beliefs towards the need to engage students in interdisciplinary instruction (e.g., Berland 2014; Estapa et al., 2017; National Research Council 2014; Roehrig et al., 2012). For example, teachers in the WRC were provided with explicit goals of integrating science, mathematics, engineering, and computer science into an NGSS-aligned, STEM+CS project within elementary science classrooms to help students see the natural connections and dependencies among disciplines.

Our framework also highlights the need for teacher learning opportunities to access and understand PCK&S, and especially epistemic PCK&S, during interdisciplinary classroom instruction. Professional learning experiences can provide teachers with opportunities to reflect upon their implemented interdisciplinary lessons and examine the kinds of epistemic supports that were used with different class contexts or different groups of learners to help identify and tease apart potential influences (e.g., TPKB, TSPK, beliefs, PCK&S). For example, WRC teachers engaged in daily and weekly reflections about what happened during instruction, and engaged in weekly discussions with the researchers to debrief and plan for the next week of instruction.

However, it may not be feasible for teachers to have professional learning opportunities that address all potential aspects of all relevant disciplines in interdisciplinary instruction. As such, curriculum designers can provide support specific to the interdisciplinary curriculum being enacted. First, curriculum designers can choose a specific, coherent, and constrained (e.g., not too many) set of concepts and practices as the focus of the unit. For instance, given the wide range of disciplinary practices, curriculum designers can make a single practice (such as modeling) the primary focus to highlight connections across disciplines. Having too many focal concepts and practices may place too great of a burden on teachers to provide cross-disciplinary supports. Second, epistemic supports can be designed directly into student facing materials, relieving teachers of the need to enact these supports at their discretion. For example, class slides or student notebooks can provide starter discussion prompts that aim to further epistemic knowledge. Third, classroom epistemic supports can also be made explicit in supporting curricular materials, such as a teachers' guide, videos, or instructional slides. For example, to help teachers develop TPKB, the WRC teachers' guide provided "briefs" about the nature of engineering, science, and computer science disciplines and had call-outs to these briefs during relevant lessons. To help teachers develop TSPK and PCK&S, the WRC provided videos of how to engage students in planning and carrying out investigations as well as how to support students to develop their computational models.

This paper illustrates how interdisciplinary instruction offers specific challenges and opportunities to help students not only engage in disciplinary practices but also develop disciplinary epistemic knowledge. As STEM+CS interdisciplinary instruction becomes more common in elementary settings, careful attention and support needs to be given to help teachers to support their students to engage in disciplinary practices, comprehend why and how these disciplinary practices should be used, and understand, as well as draw connections between, epistemic knowledge of each of the disciplines.

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