Chapter 3
A Framework for Examining Teachers' Practical Knowledge for STEM Teaching

Kennedy Kam Ho Chan, Yi-Fen Yeh and Ying-Shao Hsu

3.1 Introduction

Around the world, there is an increasing call for providing K–12 students with quality science, technology, engineering, and mathematics (STEM) education to ensure that students will be able to engage and pursue STEM-related issues and careers (Metcalf, 2010; National Academy of Engineering & National Research Council, 2014). STEM education calls for new ways of teaching that go beyond the teaching of a particular discipline to teaching that involves an integration of different disciplines (Kelly & Knowles, 2016; Wang, Moore, Roehrig, & Park, 2011). Although what a teacher needs to know and be able to do in general for effective teaching and learning has been a subject of scholarly research (e.g., Cochran-Smith & Lytle, 1999; Guerriero, 2017; Verloop, van Driel, & Meijer, 2001), relatively less effort has been put into articulating the knowledge teachers need for effective STEM teaching (see exceptions: Allen, Webb, & Matthews, 2016; Saxton et al., 2014; Srikoom, Faikhamta, & Hanuscin, 2018). This leads to the central question: What knowledge does a teacher need for effective STEM teaching that leads to the valued student outcomes in STEM education? In this chapter, we pursue this question and propose a theoretical framework for examining and analyzing teachers' knowledge of STEM teaching. To achieve this goal, we first review the literature on STEM education to

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identify STEM literacy and elements of effective STEM teaching. We then review the teacher knowledge literature to identify facets of knowledge needed for effective STEM teaching.

3.2 Integrated STEM Education

Around the globe, policy-makers, educators, industrial leaders, and business entrepreneurs have highlighted the critical importance of expanding and improving STEM education at the K–12 level. The call for STEM education goes beyond merely studying the four STEM subjects in isolated silos to tightening the connections within, between, and among these subjects in an integrated way that (a) reflects the nature of the work of most STEM professionals and (b) engages the interdisciplinary nature of most STEM issues. STEM education is advocated not only for workforce demands in science or engineering fields but also for the pursuit of informed citizenship: *STEM Literacy for All*. Unlike conventional approaches for developing talents in the science or engineering fields, STEM education focuses more on integrative learning experiences (Sanders, 2009) and soft skills development such as communication and teamwork (Hobbs, Clark, & Plant, 2018). It is worth pointing out that STEM should be viewed as a distinctive subject that is underpinned with some disciplinary features from each of the constituent disciplines. Yet, STEM is not a mere assembly of the four separate disciplines; rather, it should be viewed as a meta-discipline—a new discipline that is formed from the integration of other disciplines (Kennedy & Odell, 2014). As a meta-discipline, STEM is a cohesive entity that is greater than the sum of its parts, that is, the four respective disciplines.

3.2.1 STEM Literacy

STEM literacy can be conceptualized as comprising “the conceptual understanding and procedural skills and abilities for individuals to address STEM-related personal, social, and global issues” (Bybee, 2010, p. 31). Following PISA’s framework for science, reading, and mathematical literacy, Bybee proposed that STEM competencies include three aspects, namely, identifying STEM issues, explaining issues from STEM perspectives, and using STEM information. These competencies reflect features of STEM projects like context-dependent, practice-based (i.e., meaningful implication of knowledge and skills in practices), creativity pursued as well as both the disciplinary knowledge and generic thinking abilities involved. STEM-related issues can be real-life situations or problems to solve, which explains why STEM literacy should be viewed as educational outcomes most students should achieve.

A meta-level STEM literacy is also worthy of pursuit, especially when real-life situations and problems are so complicated that there is often no single or easy solution. Viewed from this perspective, STEM literacy should not be merely viewed as a composite of *S*, *T*, *E*, and *M* literacies. Rather, core competence should entail learners developing literacy in terms of how problem-solvers activate what has been learned from various disciplines and then create feasible solutions in the context of problem-solving. Yeh, Hsu, Wu, Yang, and Lin (under review) proposed five competencies that are critical to problem-solving but are primitively incubated in separate disciplines. These competencies are analogical reasoning, contextualization, quantitative thinking, prediction, and reflective ability. Taking contextualization as an example, problem solvers first need to decontextualize problems into what is familiar such as processing calculation. The solution prototypes then need to be recontextualized using the right languages for the audience targeted for the follow-up mass production or marketing. Contextualization and decontextualization can involve problem definition and rationale expression of design in the engineering field (Atman et al., 2007). However, it should be noted that transfer of learning is not easily or automatically achieved (Dixon & Brown, 2012; Johnson, Dixon, Daugherty, & Lawanto, 2011). It is believed that these meta-level competencies can be greatly nurtured in STEM-related or problem-solving tasks if they can be purposefully emphasized with disciplinary connections.

Zollman (2012) added nuances to the idea of STEM literacy when he urged that three domains of STEM literacy be strengthened, under the ultimate goal of "STEM literacy for learning [rather than] learning for STEM literacy" (p. 12). Apart from knowledge and skills to address STEM issues, he contends that reflection helps learners improve their solutions as well as become quicker and better thinkers for any new challenges in the future. The ability to self-regulate determines how efficient students may be in strategic problem-solving (e.g., making plans or collaborating with others), which allows them to better understand themselves and build their self-identity from exploration. Finally, students' STEM literacy elaborates the stages of thinking of actions, linking between movements, and automatically refining performance. The three domains (i.e., cognition, affection, and psychomotor) contribute to the ultimate objectives for STEM education: *STEM literacy for continual learning* (Zollman, 2012). Therefore, STEM literacy encompasses not only knowledge and skills requisite for problem-solving but also a set of generic skills and learning dispositions that enable life-long learning. Students who attain and keep enhancing their meta-disciplinary STEM literacy will be the successful candidates to fulfill the STEM pipeline demands and future careers.

In summary, STEM literacy builds on *S*, *T*, *E*, and *M* literacies—but what matters the most is how students use and integrate their related knowledge and competencies from the respective disciplines adequately and flexibly to solve problems encountered or create products to satisfy needs. To develop such an interdisciplinary (or trans-disciplinary) literacy demands not just knowledge or competency development, it is critical that students develop interdisciplinary ways of thinking as well as persistent but sustainable ways of learning.

3.2.2 Effective STEM Teaching

Vasquez, Sneider, and Comer (2013) identified a continuum of levels of STEM integration in terms of interconnection between the respective STEM disciplines. *Multidisciplinary* involves learning the core concepts and skills separately in each discipline but situating them in a common theme. *Interdisciplinary* entails learning closely-linked concepts and skills from two or more disciplines for deepening the learning of those concepts and skills. *Transdisciplinary* involves the application of concepts or skills from more than two disciplines to real-life problems or projects. Despite the varied perspectives of STEM integration, there appear to be commonalities in effective STEM teaching. First, effective STEM teaching should have an explicit focus on content integration across the disciplines (e.g., Ring, Dare, Crotty, & Roehrig, 2017). Second, effective STEM teaching should not only focus on the development of content knowledge but also foster skills development such as innovative problem-solving and inquiry skills (e.g., Wang et al., 2011). It logically follows that effective STEM teaching foregrounds the use of student-centered pedagogies such as inquiry and problem-based learning approaches (e.g., Breiner, Harkness, Johnson, & Koehler, 2012; Sanders, 2009) and the use of real-life contexts (Breiner et al., 2012). Moore, Johnson, Peters-Burton, and Guzey (2015) developed a STEM integration framework for effective teaching that succinctly identifies six essential elements: a personally meaningful, motivating, and engaging context; engineering design challenges; learning from failure through redesign; embedding mathematics and/or science content; use of student-centered pedagogies; and an emphasis on teamwork and communication.

The above review suggests that effective STEM teaching demands that teachers teach in a completely new way from traditional, teacher-directed, content teaching. What teacher knowledge is required to support this new way of teaching? The following sections address this question by first reviewing teacher knowledge literature and then proposing the nature and composition of knowledge required for effective STEM teaching.

3.2.3 Teacher Knowledge for Effective Teaching

What teachers need to know for effective teaching has attracted scholarly attention for many decades (e.g., Cochran-Smith & Lytle, 1999; Shulman, 1986; Verloop et al., 2001). We define teacher knowledge as the sum of knowledge a teacher possesses that guides his/her actions (Carter, 1990). A teacher may consciously or unconsciously use or refrain from using some of his/her knowledge of teaching.

Shulman (1986, 1987) proposed that teacher professional knowledge is comprised of seven categories: content knowledge, general pedagogical knowledge, curriculum knowledge, pedagogical content knowledge (PCK), knowledge of learners and their characteristics, knowledge of educational contexts, and knowledge of educational ends, purposes, and values. Shulman's work is influential for at least two reasons. First, it reinforces the notion that teachers are professionals with a unique province of professional knowledge that is not shared by others (i.e., content specialists). Second, it highlights that teachers' knowledge comprises not only knowledge that is generic in nature (i.e., applicable to different subject domains) but also the knowledge that is specific to the teaching of a particular body of content.

Although Shulman's ideas were well received, many debates about the nature and composition of teacher knowledge continue to exist in the field (e.g., Chan & Hume, 2019). A group of researchers working in the area of science teacher knowledge met in 2012 to propose a consensus model for teacher professional knowledge and skills (Gess-Newsome, 2015). The model (Fig. 3.1) makes explicit several characteristics of teacher professional knowledge. First, this model differentiates two different facets of teacher knowledge: general knowledge bases for teaching and topic-specific professional knowledge. The former is generic across topics and includes knowledge categories such as assessment knowledge, pedagogical knowledge, etc. The

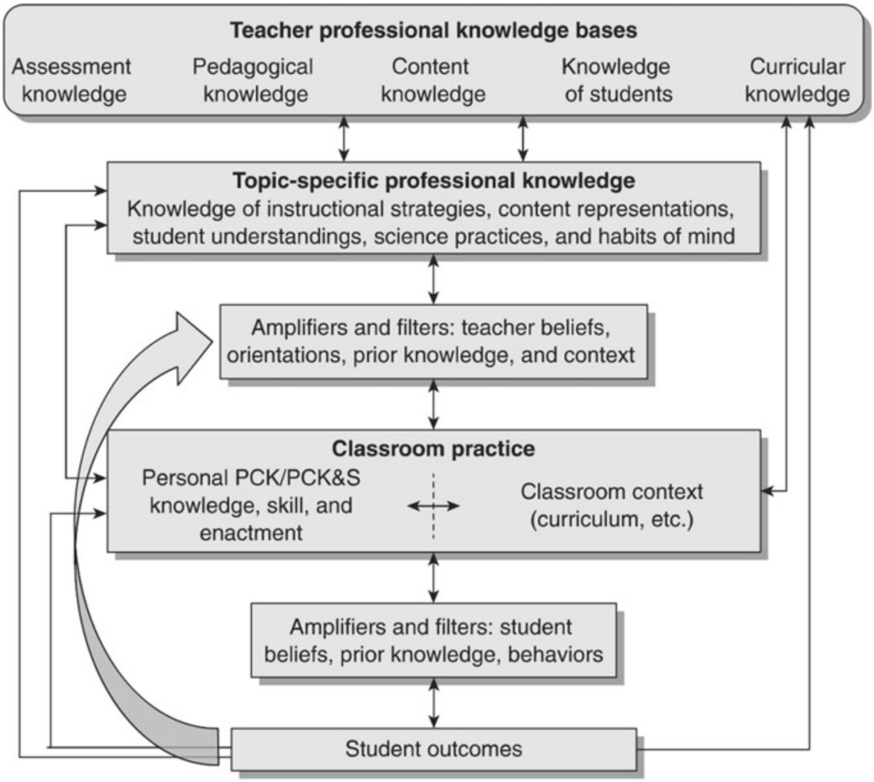


Fig. 3.1 Adapted from "A Model of Teacher Professional Knowledge and Skill including PCK" by J. Gess-Newsome, 2015, in *Reexamining pedagogical content knowledge in science education* (p. 31). Copyright 2015 by Routledge Publishing

latter includes topic-specific knowledge for teaching a particular topic. Second, the model distinguishes between canonical and personal knowledge. Canonical knowledge is generated by research or best practice, which can have a normative function while personal knowledge is private and idiosyncratic in nature, which is developed from a teacher's classroom experience. Cochran-Smith and Lytle (1999) indicated that canonical knowledge can be regarded as knowledge *for* practice whereas personal knowledge is knowledge *of* the practice. Moreover, the consensus model highlights that a teacher's classroom practices are informed by topic-specific professional knowledge and general knowledge bases for teaching and that the teacher's beliefs serve as a filter or amplifier that mediates the translation of knowledge into classroom practices.

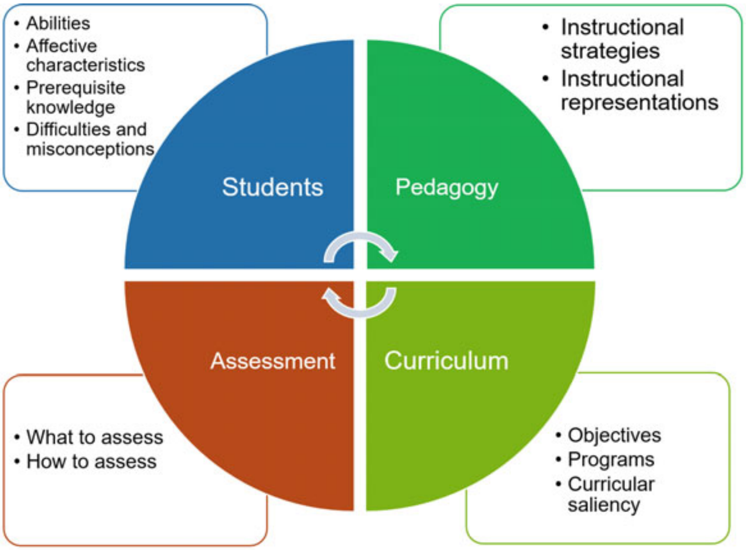
3.3 Teacher Knowledge for Effective STEM Teaching

We see effective STEM teaching as comprising a set of teaching practices (e.g., engaging students in motivating contexts, use of student-centered pedagogies) informed by teachers' knowledge. We assert that the knowledge required for effective STEM teaching is broad and multifaceted. Different types of teacher knowledge integrate to inform a teacher's decisions for planning, enactment, and reflection on his/her STEM instruction. In other words, teachers' knowledge informs teachers' planning, real-time monitoring, and adjustment as well as post hoc reflection. Teachers' beliefs about STEM integration (e.g., Wang et al., 2011), for example, can serve as a filter or amplifier to mediate the translation of knowledge into the teachers' practices.

We are interested in using the consensus model for characterizing teachers' personal knowledge, which we call teachers' practical knowledge for STEM teaching. Teachers' practical knowledge is personal, context-bound, and guides teachers' action in concrete and specific situations (van Driel, Beijaard, & Verloop, 2001). Therefore, teachers are generators of their own practical knowledge through reflection on their classroom practices—STEM teaching is supported by both topic-specific and generic teacher knowledge. Like others (e.g., Davis & Krajcik, 2005), we believe that teachers need discipline-specific knowledge to be able to "help students understand the authentic activities of a discipline, the ways knowledge is developed in a particular field, and the beliefs that represent a sophisticated understanding of how the field works" (p. 5). Hence, teachers need different types of knowledge that may be topic-specific (i.e., specific to teaching a particular concept), discipline-specific (i.e., specific to teaching STEM discipline or a particular *S*, *T*, *E*, *M* discipline), or domain-general (i.e., general knowledge about teaching) for effective STEM teaching. Although some scholars have conceptualized teacher knowledge for STEM teaching as STEM PCK or PCK for STEM (e.g., Allen et al., 2016; Saxton et al., 2014; Srikoom et al., 2018), we are reluctant to using this label because we believe that knowledge required for effective STEM teaching embraces (a) some elements that are related to student skills development (e.g., teaching of problem-solving skills) and (b) other elements that are content-specific (e.g., teaching of disciplinary content). We also argue that STEM teaching goes beyond aiming at merely teaching students a particular body of content to concepts from different disciplines and their interconnections. Hence, we prefer the term *Practical Knowledge for STEM Teaching*.

To conceptualize the composition of teachers' knowledge for teaching STEM, we drew on the consensus model and prior work (e.g., Allen et al., 2016, Magnusson et al., 1999; Saxton et al., 2014). Our analysis suggests that, apart from content knowledge, there are four important knowledge components, namely, assessment, pedagogy, curriculum, and students (Fig. 3.2). These knowledge components may be topic-specific, domain-specific, or domain-general in nature.

We envisage that the quality of teachers' knowledge also differs as a result of several factors, such as teachers' years of STEM teaching experience and their formal education. Expert teachers are characterized by a rich and elaborated knowledge base (Borko & Livingston, 1989; Leinhardt & Greeno, 1986). Moreover, experts are known to have a flexible knowledge base that allows rapid retrieval of knowledge for teaching performance. Their knowledge goes beyond *knowing that* to *knowing how* and *knowing why*. In other words, experts do not adhere to context-free rules but are



Nature of Knowledge:
Specificity (Domain-general, discipline specific, topic-specific, concept-specific)
Quantity (From low in quantity to rich in quantity)
Concreteness (From vague and general to concrete and specific in details)

Fig. 3.2 Teacher knowledge for effective STEM teaching able to apply the principles in practices based on the situations (Dreyfus & Dreyfus, 1986). As such, expert STEM teachers would not only have knowledge for teaching STEM that is greater in quantity but also of higher quality. The knowledge is more detailed, more contextualized, and situated in different teaching cases and real-life teaching examples.

To summarize, our conceptualization of teachers' practical knowledge for effective STEM teaching (details in Fig. 3.2) takes into account the major components of teacher knowledge and acknowledges that the knowledge may exist in varying degrees of specificity (i.e., topic-specific, domain-specific, generic), quantity, and quality (i.e., concreteness). The four components are knowledge about assessment, knowledge of pedagogy, knowledge about curricula, and knowledge about students. It is noteworthy that the components of knowledge serve only for analytic purposes. In reality, the boundaries between knowledge components are fuzzy and teachers draw on these knowledge components as a whole in an integrated fashion to inform their planning, enactment, and reflection on their STEM instruction. Teachers' beliefs (e.g., their beliefs about STEM integration) may mediate the translation of their knowledge into actual classroom practices.

3.4 Interview Protocols for Investigating Teacher Knowledge

A variety of tools and strategies have been used to investigate teachers' professional knowledge (e.g., Baxter & Lederman, 1999; Black & Halliwell, 2000). Data collection instruments include questionnaires, surveys, interviews, and classroom observations (e.g., Chan & Hume, 2019; van Driel, Berry, & Meirink, 2015). Each instrument has its own unique affordances and limitations. Acknowledging the inherent challenges of measuring teachers' cognition (Kagan, 1990), we propose, as a starting point, the use of semistructured interviews to elicit teachers' knowledge for teaching STEM.

The interview protocol (Table 3.1) is structured into three sections. The first part elicits teachers' conceptions about STEM education as well as their beliefs about the purposes of STEM education. We believe that how a teacher conceptualizes STEM education greatly influences their STEM instruction. Based on the consensus model, we see teachers' beliefs as an important amplifier and filter in mediating teachers' use of knowledge. The second part probes the teachers' knowledge for STEM teaching in terms of the four teacher knowledge components (i.e., curriculum, assessment, students, and pedagogy). The questions specifically prompt teachers to differentiate between teaching that focuses only on disciplinary content from STEM teaching that entails not only content but also interconnections between/amongst concepts and skills from different disciplines. Teachers are asked to provide examples to illustrate their ideas as far as possible. This provides a window into how they draw on their knowledge to design curriculum and tailor instructions in classrooms. The third

Table 3.1 Interview protocol to elicit a teacher's knowledge for STEM teaching

Part 1: Teacher's views about STEM education and purposes of STEM education

1. What are the first words or phrases that come to your mind when you hear the word "STEM"?
2. How do you define "STEM"?
3. Why do you want to implement STEM education?
4. What do you think are the important elements for STEM literacy?

Part 2: Teacher's knowledge for teaching STEM

5. (a) What learning objectives or goals do you set for your students in STEM education?
(b) What learning objectives or goals do you think your students set for themselves?
6. To achieve the goals, how do you design and implement your courses?
7. What learning difficulties do you think your students have about STEM?
8. How can you know whether your students have achieved the learning objectives in STEM?
9. What are the challenges that you encounter when you do STEM education? How do you deal with them?
10. What do you think are the differences when you teach disciplinary content and STEM courses?
(a) Do you use different strategies?
(b) How do students respond to these two types of instruction?
(c) Do you use different assessments?
(d) How is the curriculum different?

Part 3: Teacher's professional development experience related to STEM

11. What professional development do you think STEM teachers need to be equipped with?
12. How do you build up your professional learning in STEM education?
13. Have you attended any teacher learning communities? Do you think it helpful in equipping yourself to teach STEM?
14. Is there anything that you think the government, the schools, or the university can do to improve the quality of STEM education?

part of the interview examines the teachers' professional development experiences related to STEM. The questions prompt teachers to reflect on their professional development experiences to identify perceived needs in their future professional development. Such information may be useful for professional developers to design powerful learning environments to promote teachers' STEM teaching.

It is hoped that through analyses of the voices, stories, and examples shared by teachers with varying STEM teaching experience, we will be able to elicit, capture, and document the critical knowledge for STEM teaching. Specifically, we would like to characterize the nature and content of knowledge for STEM teaching and identify patterns among teachers that surpass the idiosyncratic level of individual stories and narratives.

3.5 Conclusion

This chapter has engaged the question of what teacher knowledge is requisite for effective STEM teaching. We approached this question by reviewing the learning outcomes (i.e., STEM literacy) advocated in STEM education. We identified several key elements of effective STEM teaching and theorized the knowledge that supports practices conducive to effective STEM teaching through a review of the STEM education and teacher knowledge literature. We ended by explicating the design of an interview protocol that serves as a tool to elicit teacher knowledge for STEM teaching. The proposed teacher knowledge framework can serve as a useful analytic tool for researchers to characterize the nature and content of teacher knowledge that informs effective STEM teaching. The interview protocol will also reveal the professional development needs of teachers for effective STEM teaching from the voices of the teachers. The chapters that follow will exemplify the findings based on an empirical investigation of teachers using these tools in different Asian countries.

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