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Pedagogical Content Knowledge in STEM

Research to Practice

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Preface

Thomas Kuhn famously compared scientific paradigms to political ones in that there are communities of theory and practice that must be in fundamental agreement for such paradigms to flourish: "this issue of paradigm choice can never be unequivocally settled by logic and experiment alone." In the twenty-first century, we recognize that these agreements are, just as science is, transitory: true until disproven or made obsolete. Science, by its very process, is an evolving set of paradigms for investigating the phenomena of nature, including new ones that emerge and suddenly (in a matter of decades) change everything. This creates a terrible mess for educators. How does one teach a science in constant flux? How do we reconcile the core domains of science (such as chemistry, physics, and biology), when they look at the behavior and substance of matter very differently, at least for now?

Of course, this dilemma is not limited to the pure sciences, but also the soft sciences, engineering, math, and the evolving technological tools for doing science and engineering, what we commonly call "STEM, as well as virtually all other domains of knowledge." In 1984, Lee Shulman saw this challenge as an opportunity to explicitly embrace the problem through specifically targeting domains and topics with clear pathways into pedagogy for each. For the sake of this volume, there is no one-size-fits-all teaching or learning approach to all of STEM. Shulman coined the term *Pedagogical Content Knowledge* (PCK) to indicate that, in order to effectively guide the learning process, practitioners must employ teaching approaches that are particular to the content knowledge for the topic and domain in which they are teaching and that there are, perhaps different ways into deepening engagement with, for instance, redox reactions in chemistry, than there is with ATP synthesis in biology.

PCK has evolved into a diverse area of learning and education research with the potential to transform teaching and learning throughout STEM domains and across learning settings. This volume brings together experts in pedagogical content knowledge to describe cases of bringing PCK into a wide variety of learning settings and the results of those efforts. Some authors chose to present cases describing the structure and process of such deployment, while others describe specific approaches to research PCK in live formal and informal learning environments, and others describe barriers and opportunities for bringing PCK research into practice.

The goal of this work is to give the reader and practitioner a well-rounded sense of the gains being made in STEM teaching and learning through PCK, how the research is informing educational practice, and ultimately inspire practitioners into bringing these ideas into their own thinking about STEM learning.

A variety of approaches to the task are presented in this volume, including descriptions of cases to engage learners in enhanced PCK instruction, research of PCK in learning environments, and addressing the challenges and opportunities of moving PCK from research into practice. Chapter 1 provides an extensive introduction to PCK including a consensus definition. They then provide examples of two methods for measuring teacher PCK. Chapter 2 draws upon Content Knowledge for Teaching (CKT) and addresses means of assessing Disciplinary CKT and Pedagogical CKT. Authors describe a method of measuring CKT-D and CKT-P and their support of student thinking. Chapter 3 addresses the synergy of Personal PCK and Canonical PCK, introducing the possibility of this synergy. Future research as described by the authors may help to contribute more to the field. Chapter 4 introduces barriers and supports for science instruction as described by participants of a professional development program that addresses the development of PCK for the STEM educator. Chapter 5 extends the discussion of PCK to include Mathematics Knowledge for Teaching specific to Visual Representations (MKT-VR). The chapter provides a sound description of MKT-VR and method for measuring the MKT-VR of STEM educators. Chapter 6 looks closely at the role of teacher inquiry in PCK development. Chapter 7 focuses on how to modify a graduate school biology syllabus to advantage PCK. Chapter 8 introduces the reader into the modes of PCK integration across several mathematics courses for students in the MASTER residency program. Chapter 9 provides an overview of how PCK is addressed and measured in the project and the changes occurred across iterations. The MASTER program itself presents an innovative method of preparing preservice STEM educators and providing a variety of contextual learning experiences that support the development of PCK in STEM education. Chapters 10 and 11 describe how experiences in an informal environment can support the development of PCK for teaching inquiry and integration of engineering into mathematics of science instruction. The small pilot group gave indications that the practices described may support the development of inquiry teaching PCK in preservice teachers. In both Chaps 10 and 11, the authors found that the explicit scaffolds offered through the museum partnership improved the practice of participants during the experience. They suggest looking further into how participants integrated the modeling and engineering into their classroom teaching. Chapter 12 looks at the role of an informal learning institution in a PCK-based collaborative residency program. Chapter 13 addresses the practice of argumentation as a piece of the PCK required by STEM educators. In their chapter, they describe the potential impacts of educative curriculum materials (ECM) on the development of PCK with regard to argumentation. In particular, they investigate the distinction between ECM that includes multimedia elements and how they support PCK. Chapter 14 introduces the realm of educative making into PCK. The authors argue that as more maker spaces find their way into schools and other learning environments, the PCK of teachers in educative making moments needs to be further researched and in turn developed. They propose teacher education practice to support a model of maker pedagogical content knowledge (MPCK).

We hope the voices of the many authors represented in this volume will stimulate needed conversation about the challenges in implementing and scaling PCK in the clinic and the role of learning institutions of all kinds in supporting this important idea throughout lifelong learning. While this book represents many dimensions of PCK in STEM, it is merely a point in time, and there is more to discover and new challenges to education to address as interdisciplinary and data-driven science practices and processes find their way more deeply into teaching and learning. Of course, PCK will evolve with it and, we believe, will be as relevant in the twenty-second century as it is for the twenty-first.

Corona, NY, USA
New York, NY, USA

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Part I
PCK Research in Formal Teaching Practice

Chapter 1
Analysis of Practice and Teacher PCK: Inferences from Professional Development Research

Christopher D. Wilson, Molly Stuhlsatz, Connie Hvidsten, and April Gardner

Abstract In this chapter, we describe an approach to professional development grounded in a model of PCK that centers around a teacher's knowledge of how to elicit and respond to student thinking, to engage students in the practices of science, and to develop coherent and effective learning experiences. This approach has been shown to be effective in increasing PCK in both in-service professional development and pre-service teacher education contexts and has resulted in increased student achievement when compared to more traditional approaches. Current and future directions for this work include examining the pathways between teacher professional knowledge and student learning, further development of our approach to measuring PCK using automated analysis of teacher writing, and exploring how to effectively scale up this somewhat resource-intensive approach to teacher learning.

Keywords PCK · Professional development · Lesson analysis · Student learning · Personal PCK and skill · Video analysis · Analysis of practice · Student content knowledge

1.1 Introduction

In this chapter, we describe a professional development approach for developing PCK that involves teachers engaged in analyzing teaching practice using video recordings of classroom sessions. This approach also includes identifying and using instructional strategies that have been shown effective in enhancing student learning.

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1.2 The Introduction of PCK

Studies showing weak or inconclusive links between teachers' content knowledge and student achievement have puzzled researchers for nearly 40 years. In considering the dilemma, Lee Shulman and colleagues rejected the description of teachers "as mere emitters of behavior" and became more concerned with "the motives and implicit reasoning that explained teacher and student behavior" (Shulman 2002). They proposed a "missing paradigm" in educational research in 1986, with the idea of pedagogical content knowledge (PCK). PCK challenged past practices of examining knowledge of subject matter and pedagogy separately. Instead, PCK recognizes the melding of subject matter expertise with pedagogical strategies and knowledge of the learner to produce high-quality classroom practice. For Shulman and the researchers that followed, PCK is a unique teacher knowledge base that allows them to consider the structure and importance of an instructional topic, recognize the features that will make it more or less accessible to students, and justify the selection of teaching practices based on student learning needs.

This idea clarified and generated new ways of thinking about the relationships between teacher knowledge and teacher practice (Shulman 1987). Shulman's description of PCK resonated with many educational researchers and initiated much research on professional teacher knowledge. Over the next 25 years, science education researchers enthusiastically studied PCK (Abell 2008; Borko and Livingston 1989; Cochran et al. 1993; Gess-Newsome 1999; Grossman 1990; Hashweh 1987; Heller et al. 2004; Kind 2009; Loughran et al. 2001; Magnusson et al. 1999; Padilla et al. 2008; Park and Oliver 2008; Rollnick et al. 2008; Schneider and Plasman 2011; Van Driel et al. 1998). However, because the PCK construct was based on a conceptualization rather than empirical study, researchers were free to reconceptualize the idea of PCK. The outcome of this array of research over the ensuing years was divergence in the interpretation and understanding of PCK. In an address to PCK researchers in 2012, Shulman himself (2015) noted:

> In some ways I feel a little uncomfortable talking authoritatively about pedagogical content knowledge now. I feel like the biological father of a baby that was raised in its infancy and then given away for adoption or foster care when it was about five years old. During the years that followed, the youngster was raised by many parents and played with many peers. Now that it has survived adolescence and reached emergent adulthood, most of you know far more about PCK that I possibly could because you have been living with, developing, elaborating, revising, and applying that set of ideas in serious research and pedagogical work.

Following Shulman's introduction of the PCK construct, other researchers included pedagogical content knowledge as one of the knowledge bases for teaching. The most complete descriptions from these early years consisted of four components: general pedagogical knowledge, subject matter knowledge, PCK, and knowledge of context (Grossman 1990). Magnusson et al. (1999) started with this description to develop a model of PCK for science teaching. Their model describes five components of PCK: orientations to teaching science, knowledge of science curricula, knowledge of assessment of scientific literacy, knowledge of students' understanding of science, and knowledge of instructional strategies. Many subsequent science education research studies have used the Magnusson model as originally described or with modifications based on the perspectives and findings of the studies, including making teaching orientation a backdrop rather than a component of PCK (Friedrichsen et al. 2012). This shift gave more emphasis to the relationships among the components in the Magnusson model (Park and Oliver 2008; van Driel and Henze 2012) and adding knowledge of how to sequence ideas (Smith and Banilower 2012). Other researchers have described PCK for science teaching as an integration of content knowledge, pedagogical knowledge, and contextual knowledge (Gess-Newsome 1999), PCK as completely distinct from pedagogical knowledge and content knowledge (Kirschner et al. 2012), or PCK as a transformation of knowledge of student context, knowledge of student ideas about concepts, subject matter knowledge, and content knowledge (Rollnick and Mavhunga 2012).

1.3 PCK Summits and Consensus Definition

The growing divergence among the models of PCK used by science education researchers was the impetus for the first "PCK Summit" held in the fall of 2012 (Carlson et al. 2015). Researchers of PCK in science and mathematics teaching gathered to compare and negotiate their differing models, with the goal of developing a consensus model of PCK. Despite the divergence of PCK models used by these researchers, they were able to identify commonalities among them. All included content or subject matter knowledge and aspects of pedagogical knowledge, such as knowledge of instructional strategies, assessment, or curricula. Many also included understanding of the school or student context. Among science education researchers, there was general agreement that PCK is topic-specific, rather than domain-specific. That is, there is not a general PCK for teaching physics, biology, or chemistry, but PCK for teaching acceleration, photosynthesis, or covalent bonds.

One confounding issue for participants was whether PCK is a knowledge base that can be assessed through paper-and-pencil tests or interviews, or a skill that can be assessed only through classroom observations, or both. Another problematic issue was whether PCK is canonical – a knowledge base that can be taught – or personal and must be gained through experience and reflection. The PCK Summit participants agreed on the following definition of personal PCK and PCK and skill (Gess-Newsome 2015):

- Personal PCK is the knowledge of, reasoning behind, and planning for teaching a particular topic in a particular way for a particular purpose to particular students for enhanced student outcomes.
- Personal PCK and skill is the act of teaching a particular topic in a particular way for a particular purpose to particular students for enhanced student outcomes.

The consensus model resulting from the Summit includes PCK as one of several knowledge bases within teacher professional knowledge and skill. It includes both topic-specific professional knowledge (which might be considered a canonical form of PCK) and personal PCK, which is developed through experience and described above. As the name "teacher professional knowledge and skill" implies, the model includes knowledge that is held by an individual as well as skill in enacting that knowledge. See Gess-Newsome (2015) for a detailed description of the components of this model and the relationships among them.

1.4 Approaches to Enhancing PCK Among Teachers

Loughran et al. (2012) developed Content Representations (CoRes) as a tool for capturing teachers' PCK. The CoRes scaffolds and documents teachers' thinking about specific science topics by asking them to identify the "big ideas" associated with a topic and responding to several prompts about each of these concepts, such as what students should learn related to a big idea, why they should learn that, what students typically find challenging about the concept, and teaching strategies that are effective for helping students learn. Researchers who have used CoRes found the tool to be useful not only for collecting examples of expert PCK but also as a means of enhancing or accelerating the development of more sophisticated PCK among beginning science teachers (Bertram 2014; Hume 2010; Williams 2012). Other approaches for enhancing PCK among science teachers involve specially designed professional development programs. For example, Gess-Newsome et al. (2017) designed a 2-year, curriculum-based professional development intervention that successfully increased biology teachers' PCK. Daehler et al. (2015) described the development of a science teacher professional development program to develop PCK that includes science investigations coupled with examination of teaching cases and reflections about connections to their students and classrooms.

1.5 Science Teachers Learning Through Lesson Analysis (STeLLA)

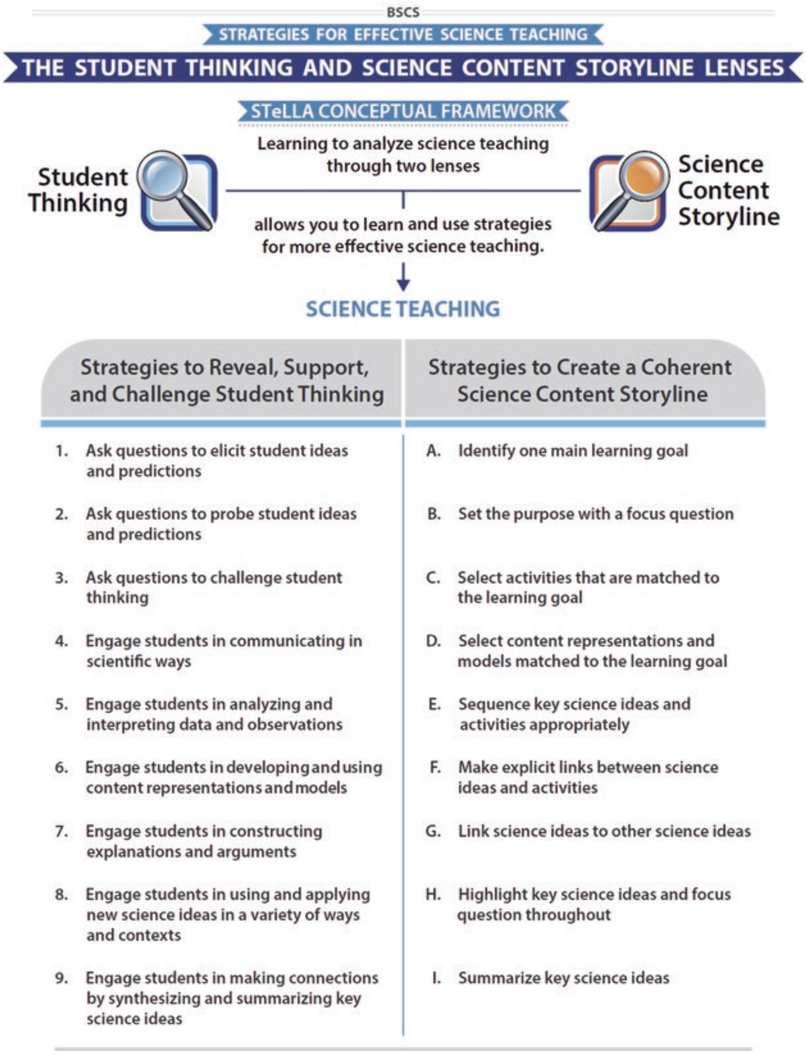
Science Teachers Learning Through Lesson Analysis (STeLLA) is a series of professional development and teacher preparation programs grounded in research on how teachers learn and built around core science teaching practices delineated in the STeLLA conceptual framework (Roth et al. 2011; Taylor et al. 2016). Initially, STeLLA described a 1-year professional development program for upper elementary teachers (STeLLA 1 was an initial test of the efficacy of the approach, whereas STeLLA 2 tested the approach in a randomized controlled experiment described later in this chapter). The STeLLA approach has now been scaled up and is used in both in-service and pre-service settings for teachers of kindergarten through 12th grade, in face-to-face, online, and leadership development contexts.

The essential features of the STeLLA approach that lead to enhanced teacher PCK include (1) the goals for teacher learning that intertwine increasing pedagogical knowledge with increasing science content knowledge, (2) the structure of the program that scaffolds teacher learning in ways that lead from greater support for teachers to greater independence and accountability, and (3) the context of teacher learning featuring analysis of grade- and content-specific classroom videos.

1.5.1 STeLLA Teacher Learning Goals

In programs using the STeLLA approach, teachers learn to analyze science teaching through two lenses – a "Student Thinking Lens" that focuses teachers' attention on ways to reveal, support, and challenge student thinking and a "Science Content Storyline Lens" that focuses teachers' attention on the coherence and connections that students can build as they learn science (Fig. 1.1). These two lenses are instantiated through 18 strategies that support teachers as they develop student thinking and coherent storyline-centered approaches to teaching science in their particular context.

In addition to the STeLLA lenses and strategies, the STeLLA approach features science content learning goals for teachers that focus on a deep understanding of two science content areas taught at the grade level they teach. Teachers deepen their understanding of content through activities and experiences that model teaching and learning of science content using the STeLLA lenses and strategies. For example, teachers in a summer institute may participate as learners in a science activity led by PD leaders who model the use of the STeLLA strategies by asking questions that elicit, probe, or challenge teacher thinking (STeLLA strategies 1, 2, and 3). They engage in analyzing data, using models, or developing explanations and arguments about phenomena related to their grade-level standards (STeLLA strategies 5, 6, and 7). The sequence of science activities they encounter will reflect a carefully designed conceptual flow (STeLLA Science Content Storyline strategies) with opportunities for teachers to make links between science ideas and the science content-based activities they complete. The activities teachers engage in during a summer institute are similar to activities they will lead with their own students, but designed to deepen their understanding of the science as adult learners. Teachers further deepen their understanding of these science concepts as they study the STeLLA lesson plans provided for their teaching and the common ideas and unscientific ways of thinking they might encounter when teaching this content to their students. In addition, teachers collaboratively analyze video of students discussing their ideas related to the science content or reflect on authentic student artifacts. Each of these experiences provides an opportunity for teachers to learn how to effectively use teaching strategies in ways that enhance teaching of specific science content within a particular classroom situation and to transfer this knowledge into their own teaching practice.



BSCS

STRATEGIES FOR EFFECTIVE SCIENCE TEACHING

THE STUDENT THINKING AND SCIENCE CONTENT STORYLINE LENSES

STeLLA CONCEPTUAL FRAMEWORK

Student Thinking

Learning to analyze science teaching through two lenses

allows you to learn and use strategies for more effective science teaching.

Science Content Storyline

SCIENCE TEACHING

Strategies to Reveal, Support, and Challenge Student Thinking	Strategies to Create a Coherent Science Content Storyline
1. Ask questions to elicit student ideas and predictions	A. Identify one main learning goal
2. Ask questions to probe student ideas and predictions	B. Set the purpose with a focus question
3. Ask questions to challenge student thinking	C. Select activities that are matched to the learning goal
4. Engage students in communicating in scientific ways	D. Select content representations and models matched to the learning goal
5. Engage students in analyzing and interpreting data and observations	E. Sequence key science ideas and activities appropriately
6. Engage students in developing and using content representations and models	F. Make explicit links between science ideas and activities
7. Engage students in constructing explanations and arguments	G. Link science ideas to other science ideas
8. Engage students in using and applying new science ideas in a variety of ways and contexts	H. Highlight key science ideas and focus question throughout
9. Engage students in making connections by synthesizing and summarizing key science ideas	I. Summarize key science ideas

Fig. 1.1 The STeLLA lenses and strategies

1.5.2 STeLLA Program Structure

The structure of the STeLLA approach is grounded in situated cognition learning theory and a cognitive apprenticeship model of instruction (Collins 2006; Lave and Wenger 1999). Teacher learning is situated in the contexts that the knowledge will be used – classrooms. Each aspect of the teacher learning experience is centered on experiences that enhance their classroom teaching: analyzing classroom video (discussed in the next section), studying lesson plans or student artifacts, engaging in science activities, or reflecting on their own teaching experiences. The program is structured to begin with learning about science content and effective pedagogy from those with expertise in the STeLLA approach and continues with experiences that slowly fade the support of experts and turn greater independence of use to the participating teachers. Expertise at the beginning of the professional development comes in two forms. First, the professional development leaders provide expertise by planning a sequence of learning, facilitating activities, selecting classroom video for analysis, and guiding conversations among teachers. Second, classroom video featured during lesson analysis sessions features experienced teachers modeling the use of STeLLA lenses and strategies with their students. Although these experienced teachers are not present during the STeLLA sessions, they contribute their expertise to the participants by sharing their classroom practice, culture, and students with STeLLA participants.

In the STeLLA approach, guidance and support from experts slowly fade as teachers take on more and more of the responsibility for independently adopting and enacting the STeLLA strategies. After being introduced to the strategies and seeing them in action in video, teacher participants use a prepared set of STeLLA lessons that embed student thinking and Science Content Storyline strategies. Each teacher is filmed while teaching a portion of these lessons, and short clips are selected by a STeLLA facilitator for the small group to analyze. Participating teachers, at this point in the program, are very familiar with analyzing video from other teachers' classrooms and can now use the process to support and challenge one another and to negotiate deeper levels of understanding about the content, the strategies, and enactment in each participant's context.

In the final phase of the STeLLA approach, teachers experience the entire process of planning and enacting lessons that demonstrate their knowledge and use of the STeLLA lenses and strategies by collaboratively planning an instructional unit in a new science content area. STeLLA PD facilitators provide tools and processes that guide this planning and enactment, but step back from their role as leaders as the teachers step up to the challenge. The STeLLA program structure embodies the cognitive apprenticeship learning model by (1) working with experts and learning from the classroom video of more experienced STeLLA teachers, (2) trying out the STeLLA approach for themselves using prepared lesson plans and reflecting within a small group using video of their own initial attempts at using the strategies, and (3) planning new lessons with STeLLA peers with less input, guidance, or expertise from the PD leaders.

1.5.3 The Context of Teacher Learning: Video Analysis

The core teacher learning activity in all programs using the STeLLA approach is analysis of practice using grade-specific classroom video. Watching classroom video provides an opportunity for participants to see the same segment of classroom instruction and discuss the clip to negotiate a common understanding and language for communicating about teaching and learning. Videos provide a means of slowing down the action and focusing on specific aspects of the instruction for analysis. They can be watched more than once and focus on different elements of the teaching or student ideas being expressed. One of the design principles of the STeLLA approach is to provide written transcripts of each clip with time stamps so that teachers can cite evidence from the transcript to support claims they are making about the teaching strategies they see, the ideas students have about the science, or the particular times where teachers missed an opportunity to capitalize on student thinking to guide learning.

In line with situated cognition theory of teacher learning, it is essential that teachers analyze video featuring science content and classrooms at their grade level. This assures that each teacher is working in a meaningful, authentic context. The STeLLA leaders create video cases and select clips that will engage teachers in developing their initial understandings of (a) the science content, (b) the STeLLA teaching strategies, and (c) the video analysis process. Later in the program, teachers analyze video clips from their own and their colleagues' classrooms. Through these familiar contexts, teachers discuss their own students' unique ways of thinking about the content and ways to address the needs of their students in learning science content.

Using the STeLLA approach to teacher learning, program structure, and video analysis, teachers develop a level of PCK that links effective teaching practices to science content taught at their grade level. Participants analyze and reflect on their own use of the STeLLA strategies with their own students to develop a deeply contextualized understanding of the impact the STeLLA strategies can have on student learning. They have opportunities to try out the STeLLA lenses and strategies with a high degree of support that fades over time as they enact effective practices with greater independence and flexibility in their own classrooms.

1.6 Measuring PCK

1.6.1 The Need to Measure PCK

As PCK emerged as an important construct in science education, so did the need to measure it. As with the STeLLA studies described here, PCK is an intended outcome of many studies of professional development and teacher education interventions, and thus valid and reliable measures are needed. Such measures also have formative value during professional development, providing PD leaders with information on what participants do and do not know. Further, recent movements to develop national indicators in math and science education have recognized the importance of measuring teachers' knowledge of how to effectively teach their content (NRC 2013). That is, in order to monitor progress toward national recommendations for successful K-12 STEM education, we need to be able to measure growth in teachers' professional knowledge. Finally, measuring PCK is important because "assessments operationalize constructs" (William 2010). Instrument development work across science education has been foundational in developing frameworks that establish the structure of previously fuzzy concepts and making empirical observation possible. In doing so, the value of the construct to the field is increased, because if one cannot effectively measure something, it is unlikely to be valued or planned as an outcome of interventions.

1.6.2 Approaches to Measuring PCK

It has been said that as a field, we've been better at developing PCK than measuring it, which in part is due to a lack of consensus about the construct (Smith and Banilower 2015). While that is undoubtedly the case, several promising approaches have continued to be developed and refined, especially as the consensus model from the PCK Summit gains traction. Most measures situate their approach in the assertion that since PCK is the professional knowledge of teachers, it is visible in the professional work of teachers, which involves planning, teaching, and reflecting. *Planning measures* include instruments like the CoReS (Content Representations) and PaP-eRs (Pedagogical and Professional Experience Repertoires) developed by Loughran and colleagues (Loughran et al. 2012). These measures require teachers to write about the topics they are going to teach and what their lessons will involve and to describe reasons for those instructional decisions. *Teaching measures* use teachers' classroom practice as evidence of their PCK and use classroom observations or video to collect data. Finally, *reflecting measures* occur following instruction and involve teachers discussing the reasons for instructional decisions, sometimes with reference back to incidents in classroom video.

1.6.3 Measuring PCK Through Analysis of Practice

Our approach to measuring PCK diverges from this planning-teaching-reflecting cycle, in that a teacher's analysis of another teacher's classroom video is used as evidence of their PCK. While one could argue that such analysis falls outside of the regular professional work of teachers, and is therefore not professional knowledge one should expect a teacher to have, we believe it reasonable to expect that if a teacher has high PCK, they should be able to identify and describe effective science instruction and to identify student understanding from student talk. The instrument involves teachers watching a series of 5- to 10-min video clips, chosen to reveal different aspects of PCK. Teachers are asked to write about the teaching and learning visible in each video and provide analytic comments. Each response is scored using a rubric that codes for attention to the 16 STeLLA strategies, as well 8 distal codes that address more general aspects of PCK such as content accuracy, student thinking, and instructional coherence. Each code is scored 0 (no mention of the strategy), 1 (strategy is mentioned but not elaborated), or 2 (an elaborated discussion of the strategy is provided). This approach to measuring PCK emerged from the analysis-of-practice focus of the STeLLA model described above. We conclude this chapter by describing two studies that have used this instrument to measure the impact of teacher education and professional development on teacher PCK.

1.6.4 Two Studies Examining the Impact of Analysis of Practice on Teacher PCK

1.6.4.1 A Cluster Randomized Trial of In-Service Elementary Teachers

In this study, we tested the STeLLA professional development program in a cluster randomized trial with 140 fourth and fifth grade teacher participants in Colorado. Teachers were randomly assigned at the school level to either receive the STeLLA Lesson Analysis program or receive the same number of hours (88.5) of professional development focused entirely on deepening their content knowledge. This comparison was chosen because many studies and national reports argue that elementary teachers require this science content-focused PD to teach science more effectively. The structure of the STeLLA PD program is described above. We collected teacher responses to a science content assessment and the video analysis task before and after the program, as well as pretest and posttest student content assessments. The post-intervention science achievement for teachers and students was significantly higher in the STeLLA program than in the content deepening program (controlled for pre-intervention achievement). At the student level, the *p* value was 0.001, with a corresponding effect size of 0.68 (Hedges g) on a measure of students' science achievement (Taylor et al. 2016).

1.6.4.2 ViSTA Plus – A Quasi-experiment in Pre-service Teacher Education

The ViSTA Plus (Videocases for Science Teaching Analysis Plus) project was a 3-year study that followed a cohort of pre-service teachers from the science methods course, into student teaching, and finally through the first year of teaching. Methods courses from two universities in the Southwestern United States were assigned to either the ViSTA Plus treatment condition or a business-as-usual condition. In ViSTA Plus, we took the STeLLA framework, tools, and resources and adapted them for elementary pre-service teachers. The program includes a semester-long analysis-of-practice methods course that introduced pre-service teachers to STeLLA strategies and video-based lesson analysis and prepares them for participation in study groups that continued to meet synchronously online during student teaching and the first year of teaching.

The practice-focused science methods course is organized around the STeLLA conceptual framework and is intended to immerse pre-service teachers in learning in the context of the science classroom from the beginning of the program. First, pre-service teachers analyze videos and student work from experienced teachers' classrooms to support their learning about science and about the STeLLA Student Thinking and Science Content Storyline lenses and about the STeLLA teaching strategies. During student teaching, they teach model lesson plans embodying the STeLLA lenses and strategies and participate in lesson analysis study groups. The study group work continues during the first year of teaching as teams of teachers collaboratively design a series of grade-specific lessons and teach them in their own classrooms and again analyze and learn from one another's enactment of the lessons in synchronous online study groups. Similar to the STeLLA 2 study, we asked the ViSTA Plus teachers to teach a STeLLA-focused lesson sequence with the students in their student teaching classrooms and first year classrooms and comparison teachers to teach lessons with matched learning goals. Teacher content knowledge and PCK were assessed at four time points over the course of the study: pre-methods course, post-methods course, post-student teaching, and post-first year teaching. Due to significant attrition in the final stages of the project, only data from the first three time points is presented here. The students of the ViSTA Plus teachers were assessed on their science content knowledge before and after each teaching unit.

1.7 Findings: Teacher PCK

As we described above, teacher PCK was measured using a video analysis task measure in the STeLLA2 and ViSTA Plus studies. Growth on this outcome was observed for teachers in both treatment and comparison conditions over the course of the interventions. STeLLA and ViSTA Plus teachers outperformed the comparison condition teachers in both studies (Fig. 1.2a and b). Of particular interest, in the

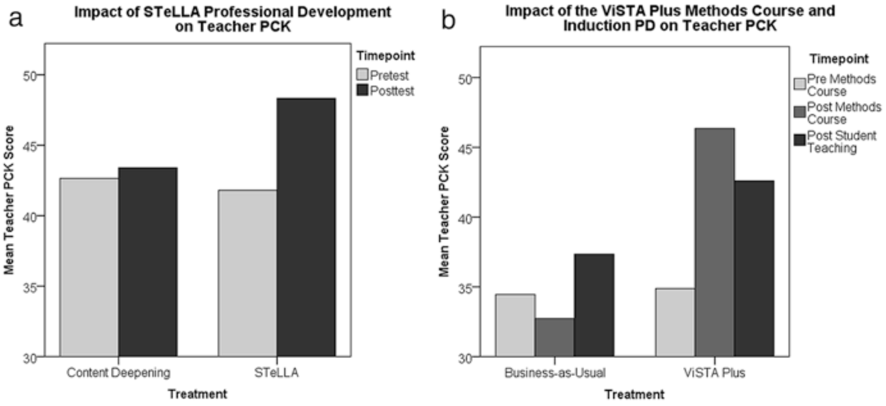


Fig. 1.2 (**a**) and (**b**) The impact of lesson analysis professional development on teacher PCK in the STeLLA2 and ViSTA Plus studies

ViSTA Plus study of pre-service teachers, we observed the ViSTA Plus teachers increased their PCK significantly during their methods course, whereas teachers in the traditional methods course did not make significant gains in PCK until their student teaching experience. This finding speaks to the value of bringing classroom video and lesson analysis into the methods course, situating learning in the classroom context, and the development of PCK requiring professional experiences.

1.8 Findings: Connecting PCK to Student Content Knowledge

In both studies, the treatment condition significantly impacted student content knowledge (Taylor et al. 2016; Wilson et al. 2017), which led to the question – to what extent was teacher PCK predictive of student learning? In both studies, PCK was a positive but not a significant mediator in models predicting student learning, after the impact of the treatment had been accounted for. The problem here might be one of power, in that both studies were powered to find differences in treatments with respect to teacher and student outcomes, not the relationship between the outcomes. We will continue to explore this relationship, since we believe PCK to be an important factor in providing students with effective learning experiences.

1.9 Conclusion and Future Directions

The theme of this book is the translation of PCK research into practice. In this chapter, we described an approach to professional development grounded in a model of PCK that centers around a teacher's knowledge of how to elicit and respond to student thinking, to engage students in the practices of science, and to develop coherent and effective learning experiences. This approach has been shown to be effective in increasing PCK in both in-service professional development and pre-service teacher education contexts and has resulted in increased student achievement when compared to more traditional approaches. Current and future directions for this work include examining the pathways between teacher professional knowledge and student learning, further development of our approach to measuring PCK using automated analysis of teacher writing, and exploring how to effectively scale up this somewhat resource-intensive approach to teacher learning.

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Chapter 2
The Intertwined Roles of Teacher Content Knowledge and Knowledge of Scientific Practices in Support of a Science Learning Community

Lane Seeley, Eugenia Etkina, and Stamatis Vokos

Abstract In this chapter we envision the science classroom as an authentic scientific community. In this vision, student ideas can influence the trajectory of scientific investigation. Teachers serve as experts and guides, but they also can learn alongside their students. To do this, they need to listen to the students and be able to build on students' original ideas to help them learn. What knowledge does a teacher draw on in such a classroom? In this chapter we empirically investigate some ways in which a teacher can utilize both knowledge of the subject matter and knowledge of science practices to respond productively to student thinking. We present data from a large study of knowledge for teaching energy. The subjects of this study were high school physics teachers. We found that in some instructional situations, teachers with insufficient content knowledge cannot productively respond to student reasoning. We also found cases where teachers can compensate for lack of content knowledge if they are skilled in science practices. To explain our findings, we hypothesize the existence of two types of content knowledge: foundational content knowledge and elaborative content knowledge. Furthermore, we suggest that foundational content knowledge along with knowledge of scientific practices can allow teachers to compensate for insufficient elaborative content knowledge. We discuss the implications of our hypothesis for future research and for the preparation and professional development of physics teachers.

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2.1 Introduction

> Ms. Cordova is preparing for her high school physics class tomorrow. She has noticed that her students have used the terms for various forms of energy, but the evidence she has collected suggests that so far, only kinetic energy and gravitational potential energy are being associated reliably with observable indicators. As she was leaving class today, a student group mentioned to Ms. Cordova that during a process in which a kicked ball rolls to a stop, its kinetic energy gradually decreases because its speed decreases, and therefore it must be transforming into potential energy. "It's potential kinetic energy," one of the students in the group exclaimed as she went out the door.
>
> Ms. Cordova ponders various instructional moves to respond productively to the students' ideas. She notes the students' facility with connecting kinetic energy to its indicator—the speed of the ball. She appreciates the group's intellectual commitment to the idea that energy conservation requires that the decrease in a form of energy in a system be accounted. She is realizing that the imperceptibility of temperature changes in interacting surfaces in many physical processes does not lend itself to students' thinking about thermal energy as a likely increasing form of energy that compensates for a form of energy that is decreasing perceptibly. She is concerned that if the class does not recognize the role of thermal energy in lots of physical phenomena, her students might not be able to connect their school learning of "conservation of energy" to sociopolitical issues associated with efforts to "conserve energy" (Daane et al. 2014) or even to energy learning in other science disciplines.

The preceding vignette is inspired by multiple classroom discussions in which learners spontaneously bring up the phrase, "potential kinetic energy." To respond productively to student ideas, Ms. Cordova needs to marshal knowledge that is strongly dependent on the specific topic her students are learning. In this example, she needs to know enough (and be curious about her students' ideas) to notice the disciplinary substance of the offhand comment her students made. She needs to know that the energy of the ball, the floor, and the air will remain constant as no energy is flowing into or out of the system of the three objects and that the interaction between the ball and the ground converts the kinetic energy of the ball into thermal energy of the ball, the floor, and the air. She also needs to know that in many mechanical contexts, temperature changes are too small to have been experienced by her students in their daily lives. She needs to know of mesoscopic and microscopic models for friction (Besson and Viennot 2004) that can help her students develop a causal picture for the "heating up" associated with surfaces rubbing against each other; she also needs to be aware that learners tend to conflate models of processes at different scales (microscopic/macroscopic), whereas even seasoned energy learners have a hard time separating cleanly effects that involve both ordered macroscopic motion (e.g., the "wind" produced by the ball moving through the air) and disordered microscopic motion (e.g., during the dying-down of air currents).