# CONNECTING PEDAGOGICAL CONTENT KNOWLEDGE (PCK) TO TEACHING PRACTICE: INVESTIGATING PHYSICS TEACHERS' ENACTED PCK, PERSONAL PCK, AND ENGAGEMENT WITH STUDENT IDEAS IN CLASSROOM DISCUSSIONS

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**ABSTRACT**

CONNECTING PEDAGOGICAL CONTENT KNOWLEDGE (PCK) TO TEACHING PRACTICE: INVESTIGATING PHYSICS TEACHERS' ENACTED PCK, PERSONAL PCK, AND ENGAGEMENT WITH STUDENT IDEAS IN CLASSROOM DISCUSSIONS

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Responsiveness to student ideas—attending to the ideas that students express in classroom interactions and providing appropriate instructional supports in response—is essential for effective science teaching and learning. Although researchers have proposed pedagogical content knowledge (PCK) as an important intellectual resource for teachers' responsiveness to student ideas, it is not yet clear how PCK supports teachers' responsiveness, especially in the context of moment-to-moment classroom interactions. In this study, I use the constructs of enacted PCK (ePCK) and personal PCK (pPCK) to explore how PCK is related to teachers' engagement with student ideas during classroom discussions. In particular, this study focuses on discussions about force and motion in five high-school physics classrooms to investigate the relationship between ePCK and teachers' engagement with student ideas and the relationship between ePCK and pPCK. First, I analyzed video recordings of teachers' classroom discussions for evidence of ePCK and for the quality of teachers' engagement with student ideas, as reflected in their responses to student ideas. In classroom discussions rated as low engagement, I found limited evidence of ePCK; in contrast, in classroom discussions rated as high engagement, teachers displayed ePCK in a variety of different ways. High levels of teacher engagement appeared to be additionally supported by less content-specific teacher moves. Second, I analyzed video recordings of post-unit video-stimulated teacher interviews for evidence of pPCK, as reflected in teachers' reasoning about video clips of these same classroom discussions. I found

three levels of pPCK in terms of quality of interpretations of student ideas and connections between instructional strategies and student ideas. Third, I compared ePCK, as evidenced in classroom observations and pPCK, as evidenced in video-stimulated interviews for the same discussion. I found three potential relationships between ePCK and pPCK in classroom discussions: 1) congruence between ePCK and pPCK; 2) incongruence between ePCK and pPCK; and 3) through reflection, generation of pPCK that is then available to inform ePCK in future classroom discussions. I conclude with the contributions to the literature and the implications for teacher education.

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# Chapter 1. Introduction

Responsiveness to student ideas—attending to the ideas that students express in classroom interactions and providing appropriate instructional supports in response—is essential for effective science teaching and learning (Grossman, Hammerness, & McDonald, 2009; McDonald, Kazemi, Kavanagh, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012). Students come to school with considerable knowledge of and experiences with the physical world, as well as skills that can support scientific inquiry. These resources, constructed through everyday life, can serve as an important foundation for students' understanding of scientific concepts, as well as participation in the practices of science. In contrast to a traditional view of education in which teachers deliver content with little consideration of student ideas, new visions of science education imagine teachers leveraging and building from the ideas, experiences, and other resources that students bring to the classroom (National Research Council, 2007; 2012). In particular, teachers are expected to listen closely to what students say and do in the midst of instruction and to mediate between students' ideas and the goal(s) of a science lesson through ongoing interactions. This vision of teaching depends heavily on teachers' responsiveness to student ideas.

Responsiveness to student ideas depends on teachers' knowledge, dispositions, and goals for instruction (Robertson, Atkins, Leven, & Richards, 2016; Schoenfeld, 2011; van Es & Sherin, 2002). In particular, teachers' content-specific knowledge for teaching—i.e., pedagogical content knowledge (PCK; Shulman, 1986)—is considered crucial for teachers' responsiveness to student ideas (Ball, 1993; Ball, Thames, & Phelps, 2008; Bell & Cowie, 2001, Bennett, 2011; Black, Harrison, Lee, Marshall, & Wiliam, 2004; Falk, 2012; Hammer, 1997, Heritage, 2007; H Heritage, Kim, Vendlinski, & Herman, 2009). Defined as the "special amalgam of content and pedagogy" (Shulman, 1987, p. 8), PCK represents a unique body of knowledge that distinguishes a teacher of a subject from either a content specialist or a teacher of a different subject. PCK is a teacher's professional understanding of how to transform content knowledge to be pedagogically meaningful to students. Although not explicitly identified as such, Shulman's description of PCK consisted of two main components: knowledge of what ideas students are likely to have regarding a topic (e.g., student common preconceptions or alternative conceptions) and knowledge of what instructional strategies might be useful to support students' understanding of a topic (e.g., useful metaphors, content representations, or demonstrations). Responsiveness requires teachers to draw upon PCK because teachers need to recognize the significance of student ideas with respect to the discipline (knowledge of student ideas) and to respond in ways that help students make connections between their ideas and disciplinary ideas (knowledge of instructional strategies)

Although researchers have proposed PCK as an important intellectual resource for teachers' responsiveness to student ideas, it is not yet clear how PCK supports teachers' responsiveness, especially in the context of moment-to-moment classroom interactions. Research has tended to focus on characterizing teachers' responsiveness to student ideas or on articulating specific teaching moves that contribute to responsiveness, with less focus on specific aspects of PCK that might support responsiveness. A small number of studies have investigated the role of PCK either in teachers' formative assessment practices, as elicited by their analysis of student work (e.g., Falk, 2012), or in teachers' noticing, as elicited by their analysis of video clips (e.g., Meschede, Fiebranz, Kornelia, & Steffensky, 2017) or vignettes (e.g., Dreher & Kuntze, 2015), but there are few empirical studies of the relationship between PCK and teachers' responsiveness to students' ideas in the moment of instruction.

Investigation of the relationship between PCK and teacher responsiveness would help to resolve a long-standing challenge: connecting PCK and teaching practice. Although researchers, starting with Shulman (1987), have posited a relationship between PCK and practice, definitive empirical evidence of this relationship has remained elusive. Many studies of PCK have remained at the descriptive level, rather than producing a clear model for the relationship between PCK and teaching practice (Abell, 2008; Fischer, Borowkski, & Tepner, 2012; van Driel, Berry, & Meirink, 2014). A focus on the relationship between PCK and responsiveness to student ideas would help us understand how PCK is related to the interactive parts of instruction. It is these interactive parts that directly affect student learning. Well-designed instructional plans and faithful enactment of those plans is still important for ensuring productive learning opportunities, but there is evidence that students benefit, in particular, from teachers' responsiveness to their ideas. Student learning is enhanced when teachers attend and respond to student learning during instruction (K. T. Anderson, Zuiker, Taasoobshirazi, & Hickey, 2007; Black & Wiliam, 1998; Pierson, 2008).

One challenge in studying the relationship between teachers' PCK and teaching practice is that there are different—and often vague—conceptualizations of PCK, making it difficult to draw comparisons across studies (Abell, 2007; 2008; Chan & Hume, 2019; Fischer et al., 2012; van Driel et al., 2014). Different models of PCK propose different components of PCK. While Shulman's model identifies knowledge of student ideas and knowledge of instructional strategies, other models add additional components such as conceptions of educational purpose and knowledge of curriculum (Grossman,1990), knowledge of assessment (Tamir, 1988), or all three of these components (Magnusson, Krajcik, & Borko, 1999). In addition, studies may investigate different *forms* of PCK. Some studies focus on *declarative* PCK, "factual knowledge that can easily be expressed in sentences or indicative propositions" (Schmelzing et al., 2013, p. 1371), eliciting PCK through teachers' performance on written assessments, surveys, or teachers' verbal reports. In contrast, other studies focus on *procedural* PCK—"the ability to do something" (Schmelzing et al., 2013, p. 1373)—observing teachers' practice to capture the aspects of PCK that are actually used in teaching practice. However, few clarify what forms of PCK were investigated, making comparison of findings among studies difficult (Chan & Hume, 2019).

Recently, a group of international science education researchers gathered to review existing studies of science teachers' PCK and discuss variations among different conceptualizations of PCK, and corresponding methodologies for capturing PCK. The resulting model— the Refined Consensus Model (RCM; Carlson & Daehler, 2019) of PCK—was intended to allow the research community to exchange and develop ideas based on a common, shared foundation. The RCM differentiates three "realms" of PCK: *collective PCK (cPCK)*, *personal PCK (pPCK),* and *enacted PCK (ePCK)*. The realm of cPCK represents the specialized professional knowledge that is accumulated and shared by a group of science education professionals. An individual teacher's pPCK refers to a store of knowledge that the teacher has accumulated and possesses with respect to teaching particular content to a particular group of students in a particular context. ePCK refers to the knowledge and skills that an individual teacher utilizes when engaging in the act of instruction, which includes planning, teaching, and reflecting.

The constructs of ePCK and pPCK appear useful for understanding the relationship between PCK and teaching practice. First, teachers act for a variety of reasons, but ePCK focuses only on the aspects of the practice that have do to with PCK (i.e., knowledge of student ideas and knowledge of instructional strategies addressing those ideas). Second, the relationship between ePCK and pPCK helps us to identify what aspects of personal knowledge (pPCK) get translated into practice (ePCK). According to RCM, no matter how much personal knowledge a teacher possesses (i.e., pPCK), only a portion of the knowledge that is available and relevant to the situation informs ePCK in a given moment. The relationship between ePCK and pPCK may help us to reveal parts of pPCK that are most closely related to ePCK and, thus, to teaching practice. Despite their potential for illuminating the relationship between PCK and practice, the constructs of ePCK and pPCK have not yet been well explored, due to their relatively recent introduction to the research literature. While there have been some attempts to reconceptualize previous studies in terms of ePCK and pPCK (e.g., Alonzo, Berry, & Nilsson, 2019; Carlson et al., 2019; Park & Suh, 2019) and researchers have begun to conduct studies framed in terms of ePCK and pPCK (e.g., Carpendale & Hume, 2019), empirical studies using the constructs of ePCK and pPCK and exploring the relationships between ePCK and pPCK are needed to explore the utility of these constructs in different settings.

In this dissertation, I attempt to address the challenge of connecting PCK and teaching practice by exploring ePCK, pPCK, and the relationship between ePCK and pPCK. Among various aspects of teaching practice, I focused on classroom discussions, an interactive part of instruction that gives teachers the opportunity to demonstrate their responsiveness to student ideas. Within classroom discussions, I focused on how teachers engage with student ideas elicited in classroom discussions and explored how ePCK is used to accomplish this engagement with student ideas. This investigation will inform the field about the relationship between one aspect of teaching practice and one aspect of PCK. Understanding this relationship informs our understanding of teachers' responsiveness to student ideas in real-time classroom interactions and, more broadly, the relationship between PCK and teaching practice.

## Research Questions

The purpose of my research is to investigate five physics teachers' ePCK, associated pPCK, and the relationships between their ePCK and pPCK and between ePCK and teachers' engagement with student ideas. In particular, I focused on classroom discussions about force and motion to examine ePCK, pPCK, and teachers' engagement. I characterized the teachers' engagement with student ideas and ePCK, as reflected in their classroom discussions, and the teachers' associated pPCK, as reflected in video-stimulated interviews in which they reasoned about video clips from their classroom discussions. I then explored the relationship between ePCK and teachers' engagement and the relationship between the ePCK and pPCK I had identified. Three research questions guided my inquiry:

1. What aspects of ePCK are evident from physics teachers' interactions with students in classroom discussions about force and motion? How is ePCK related to teachers' engagement with student ideas?
2. What aspects of pPCK are evident from physics teachers' reasoning about classroom discussions about force and motion in video-stimulated interviews?
3. For classroom discussions about force and motion, how is physics teachers' ePCK and pPCK related?

## Overview of Chapters

I present my study in the remaining chapters. In chapter 2, I review the areas of literature that informed my study. In chapter 3, I describe the context of the research and the methods I used to answer my research questions. Chapters 4, 5, and 6 describe the findings of my study. In chapter 4, I characterize teachers' engagement with student ideas and evidence of ePCK, as reflected in classroom observations. In chapter 5, I present evidence of teachers' pPCK, as revealed in video-stimulated interviews. In chapter 6, I compare teachers' ePCK and associated pPCK to explore the relationship between ePCK and pPCK. In chapter 7, I discuss implications of this study and future direction.

# Chapter 2. Literature Review

In this chapter, I discuss the areas of literature that informed my study. I first discuss the literature on teachers' responsiveness to student ideas and argue for further exploration of a possible relationship between teachers' responsiveness and PCK. Then, I move to discuss PCK, an important intellectual resource for teachers' responsiveness to student ideas. I describe Shulman's definition of PCK and other researchers' elaboration of the construct. Next, I discuss studies on the relationship between PCK and teaching practice. I describe two different conceptualizations of PCK and discuss how each portrays the relationship between PCK and practice. I then discuss the Refined Consensus Model (RCM; Carlson & Daehler, 2019) of PCK that incorporates the two conceptualizations of PCK and suggests a third way to see the relationship between PCK and practice. I argue that the RCM provides a fruitful way to investigate how PCK underlies practice, particularly through the constructs of *enacted PCK* (ePCK) and *personal PCK* (pPCK) and the relationship between ePCK and pPCK.

## Teachers' Responsiveness to Student Ideas

Responsiveness to student ideas appears in literature framed in terms of teacher noticing, formative assessment, and discourse studies (Furtak, Bakeman, & Buell, 2018; Lineback, 2015; Richards & Robertson, 2016). These areas of research provide different insights into teachers' responsiveness. Research on teacher noticing has uncovered what teachers notice about student ideas and how they interpret the noticed aspects. Studies on formative assessment have revealed the ways that teachers actually take action in response to student ideas. Discourse studies have identified teachers' discourse moves that seem responsive to student ideas expressed in classroom interactions. Below describe each area of scholarship and then discuss research on the relationship between PCK and responsiveness.

**Teacher Noticing.** Teachers' responsiveness to student ideas depends heavily on what aspects of student ideas get noticed and how the noticed aspects are interpreted (Jacobs, Lamb, & Philipp, 2010; Jacobs, Lamb, Philipp, & Schappelle, 2011)—i.e., teachers' attention to student ideas. Although the literature on teacher noticing focuses primarily on mathematics education, this work provides insight into teachers' attention to student ideas across subjects.

The definition of noticing varies across studies (Sherin, Russ, & Colestock, 2011). Some researchers see noticing as the initial process of identifying significant aspects of a complex classroom activity (e.g., Star & Stickland, 2008; Star, Lynch, & Perova, 2011). These studies examine what teachers do and do not attend to when viewing classroom activity. Other researchers view noticing as not only including the initial process of attending to particular features of classroom activity but as also involving interpretations of these noticed features (e.g., Sherin & van Es, 2005; van Es & Sherin, 2002; van Es & Sherin, 2008). This view has been the most widely adopted in the literature. In van Es and Sherin (2002), *noticing* is defined as having the following three components: a) "identify what is noteworthy about a particular situation" (p. 573), b) "using what one knows about the context to reason about situations" (p. 574), and c) "make connections between specific events and the broader ideas they represent" (p. 574). Finally, going beyond the processes of attending to and reasoning about classroom activity, another group of researchers holds a broader notion of teacher noticing that includes a third process: teachers' planning an instructional response to what was noticed and reasoned about (e.g., Jacobs et al., 2010; Jacobs et al., 2011; Santagata, 2011; Santagata, Zannoni, & Stigler, 2007). For example, Jacobs and colleagues include "intended responding" (Jacobs et al., 2010, p.

173)—deciding how to respond, not actually putting a plan into action—as part of noticing practice.

Studies of teachers' noticing usually use videotapes of classroom instruction. Teachers are asked to watch (selected segments of) videotaped lessons from their own or others' classrooms and describe what they notice. Teachers are sometimes provided with software to help them to navigate and document their analyses (e.g., Santagata, 2009; Santagata et al., 2007; Sherin & van Es, 2005; van Es & Sherin, 2002). This kind of software is used to capture individual teachers' noticing. In contrast, some researchers examine group's noticing instead (or in addition to) that of individual teachers (e.g., Sherin, Linsenmeier, & van Es, 2009; van Es & Sherin, 2010; van Es, 2011). Using a "video-club" model in which teachers regularly meet to watch and discuss videos together, these studies characterize the group's noticing and track changes in noticing over time.

Among a broad range of features that teachers identify as noteworthy in classroom activity, some researchers focus, in particular, on teachers' noticing of and responding to student ideas (Jacobs et al., 2010; Jacobs et al., 2011; Santataga, 2011; Santagata et al. 2007; Sherin et al., 2009; van Es, 2011; van Es & Sherin, 2010). When watching a classroom video, teachers tend to attend to the teacher in the video, describing the teacher's pedagogy, guessing the teacher's intention, and sometimes suggesting alternative instruction; teachers tend to pay relatively little attention to evidence of student ideas (Sherin & Han, 2004; Sherin & van Es, 2005; van Es, 2011). Therefore, some work on teacher noticing includes interventions designed to shift teachers' attention towards student ideas (Santagata, 2011; Sherin & Han, 2004; Sherin et al., 2009; Sherin & van Es, 2005; van Es, 2011; van Es & Sherin, 2010). Once student ideas have been noticed, teachers may still have difficulty interpreting students' thinking and reasoning.

When attending to student ideas, teachers tend to focus on the correctness of students' responses or general/superficial aspects of student ideas, instead of trying to understand students' sense-making (Jacobs et al., 2010; Jacobs et al., 2011; Santagata, 2009; Sherin & Han, 2004; Sherin & van Es, 2005; van Es, 2011). Attending to student ideas is necessary, but not sufficient for deciding how to respond (Jacobs et al., 2010; Jacobs et al., 2011). Jacobs and colleagues (2010; 2011) examined mathematics teachers' reasonings about a video including evidence of student ideas and found that teachers who were able to propose instructional responses with extensive consideration of the student ideas also were able to attend to student ideas. However, teachers who were able to attend to student ideas did not necessarily propose instructional responses tailored to the student ideas. In summary, noticing literature provides insight into cognitive processes that precede teachers' responsiveness.

**Formative Assessment.** Formative assessment is a process used by teachers and students during the course of instruction to gather evidence of student learning and take action based on the information to improve student learning (Black & Wiliam, 1998; Formative Assessment for Students and Teachers State Collaborative on Assessment and Student Standards, 2018). This is in contrast to summative assessment, which is focused on determining students' achievement after instruction (National Research Council, 2001). Rather than waiting for final reports of student achievement when there is little chance to support student learning, formative assessment focuses on improving students' learning by attending to students' needs immediately (Shavelson et al., 2008). As an on-going, interactive process to improve student learning, formative assessment may not be separate from the processes of teaching and learning (McManus, 2008).

Researchers have described teachers' formative assessment practices in terms of an iterative process of eliciting, recognizing, interpreting, and responding to student ideas (Cowie &

Bell, 1999; Ruiz-Primo & Furtak, 2007). The formative assessment process generally begins with eliciting information about student ideas. Teachers gather information about student ideas in various ways—e.g., employing quick quizzes or curriculum-embedded assessment tasks (Furtak & Ruiz-Primo, 2008; Shavelson et al., 2008); observing students' ideas and explanations in science notebooks (Alonzo, 2008) or in journals (Shepardson & Britsch, 2000); listening to student ideas, questions, and conversations in whole class/small group discussions (Black & Wiliam, 1998, Bell & Cowie, 2001; Wiliam, 2008); and observing students' performance during class activities (Bell & Cowie, 2001). Once the information about student ideas becomes available, teachers recognize particular aspects of student ideas as noteworthy and then interpret the noticed aspects. According to Bell and Cowie (2001), teachers interpret information about student learning by comparing it to expected levels of understanding at a particular age group (*norm-referenced interpretation*), by comparing it to certain criteria such as the completion of tasks or demonstration of scientific understanding (*criteria-referenced interpretation*), or by comparing to students' own previous achievement (*ipsative interpretation*). Finally, teachers use their interpretations as the basis for responding to student ideas with the aim of improving student learning. Teachers may ask follow-up questions that probe the reasoning behind students' responses and help students reflect and advance their own learning (Black & Wiliam, 1998), adjust subsequent instruction to be tailored to specific learning needs (Cowie & Bell, 1999), or provide feedback that describes the quality of student work and what needs to be done to improve (Sadler, 1989).

Analyzing and responding to student thinking can take place on multiple time scales (Cowie & Bell, 1999; Furtak, 2006; Shavelson et al., 2008). On one hand, while teachers gather information about student learning during instruction, analysis of and action based on the gathered information can take place after instruction. For example, after instruction, teachers often analyze written work that students completed during class, making changes to instructional plans and/or providing written feedback to students. A teacher would be engaging in formative assessment if, after school, she reflected on an unexpected student idea that arose during instruction and made changes to her instructional plans for the next day. On the other hand, teachers can analyze and respond to student ideas in the moment of instruction. When student ideas are revealed during instruction, teachers may respond to the ideas by providing immediate feedback or by making instantaneous modifications to instruction in order to meet students' learning needs (Cowie & Bell, 1999; Furtak, 2006; Shavelson et al., 2008). Teachers may analyze what students think in the moment and then take action immediately—for example, by providing another explanation or example, engaging the student in further dialog, or showing a demonstration.

**Discourse Studies.** Compared to literature on teacher noticing and on formative assessment, literature on classroom discourse provides insights into particular discourse moves that teachers use when responding to students' ideas during classroom discussions (Richards & Robertson, 2016). The individual studies discussed below provide the bases for the coding schemes used in my research.

Studies have investigated the range of discourse moves utilized by teachers during classroom interactions, exploring differences in terms of responsiveness to students' ideas. Pierson (2008) looked at the patterns of teachers' follow-up moves in secondary mathematics classroom discourse and investigated the degree of the teachers' responsiveness, which she defined as "the extent to which teachers 'take up' students' thinking and focus on student ideas in their moment-to-moment interactions" (p. 25). She identified three levels of teachers' responsiveness to students' ideas: Low, Medium, and High. Whereas Low and Medium responsiveness were characterized by follow-up moves that are not responsive (e.g., evaluative remarks) or minimally responsive (e.g., reformulating a part of students' answer to deliver content), respectively, High responsiveness was characterized by follow-up moves that appear to reflect attempts to explore and engage with the substance of students' ideas. High responsiveness is further differentiated into High I and High II, depending on whether the teacher's thinking is highlighted (e.g., addressing a misconception with extensive feedback) or the student's thinking is highlighted (e.g., requesting that a student further explain or clarify her/his idea), respectively.

Lineback (2015) investigated an elementary teacher's science classroom and explored different types of *redirection*, a teacher's attempt to change the focus of students' attention. Specifically, Lineback examined teacher talk turns and differentiated types of redirection in terms of responsiveness to student ideas. She identified a range of teacher talk moves from *minimal* (e.g., evaluative remarks)—a less responsive redirection—to *elaboration* (e.g., asking a student to clarify or expand her/his thinking) or *consideration* (e.g., inviting other students to comment on a student's contribution)— more responsive redirections.

Some studies focused specifically on particular discourse practices that researchers deem responsive to students' ideas (Lau, 2010; Michaels & O'Connor, 1993; 2012; Richards, 2013; van Zee & Minstrell, 1997). van Zee and Minstrell (1997) described the *reflective toss*, a particular type of teacher question/statement that focuses on "'catching' the meaning of the student's prior utterance and 'throwing' responsibility for thinking back to the students, not only to the individual student doing the talking, but also to all of the students in the class" (p. 229). This pattern can be contrasted with traditional teacher questions in Initiation-Response-Evaluation (I-R-E) sequences (Mehan, 1979) or triadic dialogue (Lemke, 1990) that focus on evaluating (in)correctness of student answers. Reflective tosses are flexible and dynamic (rather than predetermined or planned) because teachers need to adjust their questioning to students' emerging ideas about a topic in the moment.

Michaels and O'Connor (1993) focused on *revoicing* and explored how this discourse strategy coordinates social participation structures and academic task structures. Revoicing refers to a teacher's move that makes "a warranted inference" (p. 323) based on the student's contribution. According to Michaels and O'Connor (1993), revoicing allows the teacher to recast the academic content implied in the student's contribution and relate the student's contribution to the larger, conventional knowledge structure of the discipline. Moreover, the student is given responsibility to validate the inference (or reformulation) in the next talk turn. Going beyond *revoicing*, Michaels and O'Connor (2012) further articulated a set of follow-up moves that teachers can use to facilitate productive discussions in science classrooms, such as asking for clarification/example, asking students to choose a position, asking for reasoning, and challenging a student idea.

Lau's (2010) and Richards's (2013) dissertation work identified a set of teacher utterances that evidence teachers' responsiveness to student ideas. Some of these utterances included *building on student ideas, identifying similarities/differences between students' ideas*, and *returning to a student's idea in a later time*.

## Pedagogical Content Knowledge

Shulman introduced the concept of *pedagogical content knowledge* (PCK; 1986, 1987) as part of his effort to describe the knowledge base of teaching. He claimed that high-quality instruction requires an elaborate knowledge base that can support teachers' instructional reasoning and practices. Shulman (1987) described seven domains of knowledge for professional teaching: subject matter knowledge, general pedagogical knowledge, curricular knowledge, PCK, knowledge of learners and their characteristics, knowledge of educational contexts, and knowledge of educational values and purposes. While all of these categories of teacher knowledge are important, he particularly emphasized specialized knowledge for teaching subject matter—i.e., PCK. He viewed quality teaching as going beyond executing a set of generic skills and behaviors and argued for the central role of PCK in supporting quality teaching.

Defined as "special amalgam of content and pedagogy" (Shulman, 1987, p. 8), PCK represents "the capacity of a teacher to transform content knowledge into forms that are pedagogically powerful and yet adaptive to the variations in ability and background presented by the students" (p. 15). PCK is considered to be "uniquely the province of teachers, their own special form of professional understanding" (Shulman, 1987, p. 8). PCK distinguishes a teacher of a subject from a content expert, as well as from a teacher of a different subject (Mark, 1990). PCK is closely related to—but still distinguished from—other knowledge domains for teaching. In particular, PCK is viewed as being transformed from content knowledge, pedagogical knowledge, and contextual knowledge (Grossman, 1990; Magnusson, Krajcik, & Borko, 1999; Van Dijk & Kattman, 2007; van Driel, Berry, & Meirink, 2014). As noted by Magnusson et al. (1990), this is a reciprocal relationship: "[PCK] is the result of a transformation of subject matter, pedagogy, and context, but… the resulting knowledge can spur development of the base knowledge domains in turn" (p. 96).

**Components of PCK.** Although Shulman did not identify them explicitly, he indicated that two components constitute PCK: knowledge of student ideas and knowledge of instructional strategies (van Driel, Verloop, & de Vos, 1998). Shulman (1986) described the first component of PCK as "an understanding of what makes the learning of specific topics easy or difficult: the conceptions and preconceptions that students of different ages and backgrounds bring with them to the learning of those most frequently taught topics and lessons" (p. 9)—i.e., knowledge of student ideas. This component of PCK includes teachers' understanding of a) common student ideas—the ideas that students frequently bring to the classroom regarding particular topics, which include what others have called (*pre)conceptions*, *misconceptions*[1], or *alternative conceptions*—and b) areas of students' difficulties—the aspects of topics, concepts, or activities that students might have trouble with (Marks, 1990).

Shulman (1986) described the second component of PCK as including "for the most regularly taught topics in one's subject area … the ways of representing and formulating the subject that make it comprehensible to others" (p. 9)—i.e., knowledge of instructional strategies (Park & Oliver, 2008). This component of PCK entails teachers' knowledge of a) ways to represent a particular idea or concept in pedagogically useful forms—e.g., analogies, illustrations, examples, explanations, or models—and b) activities, tasks, or tools that can be used for students' learning of particular topics—e.g., investigation, experiments, demonstrations, and simulations (Magnusson et al., 1999). Teachers' responses to specific student ideas is also considered part of this component of PCK (Park & Oliver, 2008).

Researchers have elaborated the construct of PCK by describing additional components (van Driel et al., 1998). For example, in addition to Shulman's two components of PCK, Grossman (1990) identified conceptions of educational purpose (e.g., goals for teaching science) and knowledge of curriculum (e.g., horizontal curriculum relationships across subject areas within a grade, vertical relationships across grade levels within a subject area, or alternative curriculum materials for a given topic within a grade). Tamir (1988) included knowledge of

[1] In this study, the term misconceptions is sometimes used as a shorthand for what people have described alternative conceptions, preconceptions, or common sense. This is consistent with teachers' language, but—while using this term—I recognize that students' ideas make sense based on their experiences in the world and are important resources for their learning.

assessment (e.g., tests and evaluation methods) as an important additional component of PCK. Magnusson et al. (1999) expanded Shulman's model by including all of the additional components identified by Grossman (1990) and Tamir (1988); their model is widely adopted in the field. Although the components of PCK vary across models, Shulman's two components—knowledge of student ideas and knowledge of instructional representations and strategies—are found in all models of PCK (van Driel et al., 1998). In addition, research has shown that these two components play a critical role in making connections among other components to form coherent PCK (Park & Chen, 2012).

**Characteristics of PCK.** Research has revealed a number of characteristics of PCK. Three are particularly relevant to my study. First, although some researchers argue for generic PCK that could be applicable across different disciplines (cf. Fernández-Balboa & Stiehl, 1995), researchers appear to have reached some agreement that PCK is discipline-specific. Veal and MaKinster (1999) identified three levels of specificity for PCK: general, domain-specific, and topic-specific. General PCK focuses on broader understanding of pedagogical concepts or skills specific to a particular discipline or subject. For example, there are instructional strategies specific to teaching science—such as inquiry-oriented instruction or project-based learning—and teachers' understanding of these strategies—as science PCK—is distinguished from math PCK or history PCK (Magnusson et al., 1999). Domain-specific PCK focuses on teachers' knowledge specific to a particular domain within a discipline. This level acknowledges that PCK for teaching physics is different from PCK for teaching chemistry, for example. Topic-specific PCK focuses on knowledge for teaching a particular topic or concept within a domain. For example, in physics the knowledge for teaching the topic of force and motion is different from the knowledge for teaching the topic of electricity.

Second, content knowledge is a prerequisite for PCK (van Driel et al., 2014). Studies have shown that teachers with strong content knowledge tend to be more aware of common student ideas and relevant instructional strategies to address those ideas (e.g., Davis, 2003; van Driel, de Jong, & Verloop, 2002) while weak content knowledge limits teachers' PCK (e.g., Käpylä, Heikkinen, & Asunta, 2009; L. R. Sanders, Borko, Lockard, 1993; M. Sanders, 1993; Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008). It is, however, important to note that while content knowledge is necessary, it is not sufficient for PCK development (Davidowitz & Potgieter, 2016; Depaepe et al., 2015). PCK is also influenced by other factors, such as teachers' orientation toward science teaching, amount of teaching experience, and classroom context (Magnusson et al., 1999).

Third, PCK is practical knowledge, developed from and used in teachers' own classroom practice as they attempt to address problems that arise in practice (Connelly & Clandinin, 1985; Elbaz, 1983). Thus, PCK is bounded by the situation, context, and tasks that teachers confront in the classroom (Carter & Doyle, 1987; Leinhardt, 1988). As knowledge developed from personal classroom experience (Geddis, Onslow, Beynon, & Oesch, 1993; Lee & Luft, 2008; Mulholland & Wallace, 2005; van Driel et al., 2002), PCK is closely related to teaching practice and thus is often tacit (Baxter & Lederman, 1999; Fenstermacher,1994; Schön, 1983). The work of teaching is concerned with instructional practice and action, not articulation of the knowledge that teachers may be drawing upon (Kind, 2009).

## PCK and Teaching Practice

One of the ultimate goals for PCK research is to understand how PCK is related to teaching practice. Researchers have posited a relationship between PCK and teaching practice. Shulman (1987) argued that "the usefulness of [PCK] lies in its value for judgment and action"

(p. 14). Abell (2008) emphasized that "PCK is not merely the amount of knowledge in a number of component categories, it is also about the quality of that knowledge and how it is put into action" (p. 1410). More specifically, researchers have theorized a relationship between PCK and teachers' responsiveness to student ideas (e.g., Ball, 1993; Ball, Thames, & Phelps, 2008; Bell & Cowie, 2001, Bennett, 2011; Black, Harrison, Lee, Marshall, & Wiliam, 2004; Falk, 2012; Hammer, 1997, Heritage, 2007; Heritage, Kim, Vendlinski, & Herman, 2009). However, empirical evidence of the relationship between PCK and teaching practice has remained ambiguous (Abell, 2008; Fischer, Borowkski, & Tepner, 2012; van Driel et al., 2014). Only a small number of studies investigate the relationship between PCK and responsiveness (Dreher & Kuntze, 2015; Falk, 2012; Meschede, Fiebranz, Kornelia, & Steffensky, 2017).

One difficulty in investigating the relationship between PCK and practice may come from different conceptualizations of PCK and corresponding methods for capturing PCK, making it difficult to compare findings across studies (Abell, 2007; 2008; Chan & Hume, 2019; Fischer et al., 2012; van Driel et al., 2014). Studies use different methods for capturing PCK (Chan & Hume, 2019) to investigate different *forms* of PCK—either *declarative PCK* (Schmelzing et al., 2013) or *dynamic PCK* (Alonzo & Kim, 2016). Furthermore, few studies make explicit which form(s) of PCK are addressed. Recently, the Refined Consensus Model (RCM: Carlson & Daehler, 2019) of PCK that incorporates consideration of different conceptualizations of and methodologies for capturing PCK has been proposed. The RCM describes three realms of PCK, which appear useful for understanding the relationship between PCK and teaching practice.

In this section, I first describe two different conceptualizations of PCK and corresponding methods for capturing PCK. I discuss how each conceptualization portrays the relationship between PCK and practice. Next, I discuss the three realms of PCK represented in the RCM. I argue that the constructs of *enacted PCK* and *personal PCK* seem promising for understanding the relationship between PCK and practice.

**Declarative PCK.** One way of conceptualizing PCK is to see PCK as a body of knowledge that is stored in one's mind, which may be applied to—but is separate from—teaching practice. Studies aim to capture *declarative* PCK (Schmelzing et al., 2013): "factual knowledge that can easily be expressed in sentences or indicative propositions" (p. 1371). This declarative PCK is articulable and explicit, such as when a teacher recalls common student ideas for a topic or an effective instructional representation for a topic. This form of PCK is often captured at a distance from the event of teaching, measured through performance on elicitation tasks such as written assessments or surveys (e.g., Hill, Rowan, & Ball, 2005; Baumert et al., 2010; Jüttner & Neuhaus, 2010; Schmelzing et al., 2013; Ergönenç, Neumann, & Fischer, 2014; Kirschner, Borowski, Fischer, Gess-Newsome, & Aufschnaiter, 2016; Park, Suh, & Seo, 2018). For example, studies of the relationship between PCK and responsiveness often compare PCK (measured through paper-pencil assessment) and teachers' noticing, as elicited by analysis of video clips (Meschede et al., 2017) or vignettes (Dreher & Kuntze, 2015).

While declarative PCK is an important intellectual resource that can be used in teaching practice, the mechanism through which declarative PCK impacts classroom practice is still a black box. In particular, it is not clear what aspects of declarative PCK are actually utilized in dynamic, interactive aspects of practice (e.g., attending and responding to student ideas in classroom interactions).

**Dynamic PCK.** Consistent with this view, another way of conceptualizing PCK is to focus on the aspects of PCK that are directly used in—not separate from—practice. Studies focus on capturing *dynamic* PCK (Alonzo & Kim, 2016) or *procedural* PCK (Schmelzing et al., 2013)—"the ability to do something" that entails "teachers' activities during a lesson, for example, if a teacher is able to react appropriately to students' questions and mistakes" (p. 1373). Rather than treating PCK as separate from teaching practice, studies consider teaching practice as itself evidence of PCK—e.g., how teachers use content representations in lesson (e.g., Janík, Najvar, Slavík, & Trna, 2009), how teachers use their content knowledge flexibly during classroom interactions (e.g., Alonzo, Kobarg, & Seidel, 2012), or how teachers react to unexpected classroom situations (e.g., Park & Oliver, 2008) or unexpected students' ideas in video-based interviews (e.g., Alonzo & Kim, 2016).

Compared to declarative PCK, dynamic forms of PCK are more closely related to spontaneous, interactive aspects of teaching practice, such as teachers' responsiveness to student ideas in classroom interactions. For example, in Alonzo et al. (2012), instances of "flexible use of content" (p. 1222) revealed the aspects of PCK that might contribute to teachers' responsiveness to student ideas in the moment. Instances of *recognizing*—"teachers recognized students' unconventionally worded contributions, either by rewording them at the time or by referring back to their ideas" (p. 1222)—and *rewording*—"teachers reworded their own questions to address student confusion" (p. 1222)—could be interpreted as teachers' responsiveness to student ideas. In contrast, instances of *missed opportunity*—"students raised legitimate content-related concerns that were not taken up by the teacher" (p. 1222)—could be interpreted as a lack of responsiveness to student ideas.

**Refined Consensus Model of PCK.** The RCM of PCK differentiates three "realms" of PCK: *collective PCK*, *personal PCK,* and *enacted PCK*. In the following sections, I describe each realm of PCK, with a focus on how the RCM describes the relationship between teachers' PCK and teaching practice.

***Collective PCK (cPCK).*** This realm of PCK represents the specialized professional knowledge held by multiple science educators. As knowledge accumulated and shared by a group of professionals, cPCK is public knowledge. cPCK is not limited to what is documented in the academic literature (contributed by researchers in research articles or conference presentations) but could also include teachers' own contributions (e.g., knowledge co-constructed in schools, districts, or professional learning communities). cPCK can be specific to discipline, topic, or concept, similar to how previous research has conceptualized PCK more generally (e.g., Magnusson et al., 1999; Veal & MaKinster, 1999). cPCK exists as declarative, explicit knowledge, given that it represents a shared, articulated knowledge base (Sorge, Stender, & Neumann, 2019).

The idea of cPCK resonates with what others have called *canonical PCK* (Smith & Banilower, 2015) or *indispensable PCK* (Park et al., 2018). While acknowledging the presence of personal PCK that is held by individual teachers and unique to contexts, Smith and Banilower (2015) emphasize the existence of canonical (or normative) PCK: "PCK that is widely agreed upon and formed through research and/or collective expert wisdom of practice" (p. 90). Similarly, Park et al. (2018) describe indispensable PCK as "the parts of PCK that can be applied to any teacher in any teaching context for teaching a given topic" (p. 554), which is distinguished from what they call *idiosyncratic PCK* that is specific to teachers and contexts.

When considering the connections between RCM and earlier research, efforts to develop standardized assessments of science teachers' PCK can be considered to measure the aspects of cPCK that individual teachers possess (e.g., Kirschner's vignettes, pp. 106-109 in Carlson et al., 2019). Studies that develop instruments such as paper-and-pencil science PCK tests for a particular topic and a particular grade-level (e.g., Ergönenç et al., 2014; Jüttner & Neuhaus, 2010; Kirschner et al., 2016; Park et al., 2018; Schmelzing et al., 2013) measure cPCK. Individual teachers' responses on these tests are read against the group or norm—i.e., cPCK—and evaluators decide "if it is in line with expert PCK or not (or is 'correct' or 'incorrect')" (Carlson et al., 2019, p. 108).

***Personal PCK (pPCK)*****.** This realm represents the personalized professional knowledge held by individual science teachers; thus, in contrast to cPCK, pPCK is private, personal knowledge. pPCK refers to the knowledge that a teacher has accumulated over time with respect to teaching specific subject matter. pPCK exist as both explicit and tacit knowledge (Alonzo, Berry, and Nilsson, 2019).

Most research that has investigated science teachers' PCK in classroom contexts could be considered to be studies of pPCK. Rather than determining whether teachers have normative PCK (cf., cPCK), this line of research honors the unique, personal nature of individual teachers' PCK (pPCK). Such studies typically ask teachers to articulate knowledge about teaching specific science subject matter in a given classroom context. Some of these studies explore how teachers' knowledge develops from their own practice or school practicum (Clermont, Borko, & Krajcik, 1994; Geddis et al., 1993; Mulholland & Wallace, 2005; van Driel et al., 2002). Other studies investigate how a teacher's personal traits (e.g., orientation to science teaching, knowledge), as well as contextual factors (e.g., classroom resources, testing, time constraints), may affect the teacher's knowledge about teaching a particular topic in a given context, or pPCK (Cohen & Yarden, 2009; Park & Oliver, 2008).

***Enacted PCK (ePCK).*** When a teacher is engaged in the act of instruction, it is impossible to draw on and use all the knowledge and skills that are stored in her/his mind (i.e., pPCK). Rather, a subset of the available knowledge and skills are accessed to generate ePCK that is unique to the particular instructional situation. In the RCM, ePCK is defined as knowledge and skills that are enacted in action. ePCK is present at each stage of the instructional cycle: planning a lesson, teaching the lesson, and reflecting on the taught lesson.

For an individual teacher, ePCK and pPCK are closely related. A teacher's pPCK provides the foundation for ePCK, and new perspectives and experiences gained from practice (i.e., ePCK) become part of the teacher's knowledge (i.e., pPCK). However, ePCK and pPCK are distinguished from each other in two ways (Alonzo et al., 2019). First, in contrast to pPCK that exists as both explicit and tacit knowledge, ePCK exists only in the moment of action as tacit (i.e., unarticulated) knowledge. Second, ePCK is more dynamic and flexible whereas pPCK is relatively static[2]. pPCK exists as a stored body of knowledge within an individual teacher, but ePCK is constantly changing and renewed every moment—even for the same topic—because each situation is unique to particular student, particular context, and particular time (Alonzo et al., 2019).

Compared to cPCK and pPCK, relatively little attention has been paid to the aspects of PCK that are enacted while teaching—i.e., ePCK (Alonzo et al., 2019). A small number of recent studies of dynamic PCK (e.g., Alonzo & Kim, 2016; Alonzo et al., 2012; Janík et al., 2009; Park & Oliver, 2008), which explore PCK "as it is" or "*in situ*" (Kind, 2009; van Driel et al., 2014), could be considered to investigate ePCK. After the RCM was proposed, some attempts have

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[2] I do not mean "static" in the sense of "unchanging" because teachers' PCK, either as pPCK or ePCK can be modified through interactions with students. However, while ePCK changes moment-to-moment depending on the situation, pPCK changes on a longer time scale.

been made to reconceptualize previous studies in terms of ePCK (e.g., Alonzo et al., 2019; Carlson et al., 2019; Park & Suh, 2019), and researchers began to use the constructs of ePCK in new studies (e.g., Carpendale & Hume, 2019). However, given its relatively recent introduction to the research literature, there are not yet enough empirical studies using the construct of ePCK and exploring the relationships between ePCK and pPCK.

Investigation of ePCK and its relationship to pPCK have potential to illuminate the relationship between PCK and practice. Teachers act for a variety of reasons, but ePCK focuses only on the aspects of the practice that have do to with PCK (i.e., knowledge of student ideas and knowledge of instructional strategies addressing those ideas). Moreover, the relationship between ePCK and pPCK helps us to identify what aspects of personal knowledge (pPCK) get translated into such practice (i.e., ePCK). According to RCM, no matter how much knowledge a teacher possesses (pPCK), only a portion of the personal knowledge that is available and relevant to the situation informs ePCK in a given moment. The relationship between ePCK and pPCK may help us to reveal parts of pPCK that are most closely related to ePCK and, thus, to teaching practice.

One challenge that researchers face when using the construct of ePCK in their research is that ePCK only exists in the moment of action as tacit knowledge (Alonzo et al., 2019). Not only would it be impractical to ask teachers to articulate the knowledge they are drawing on in the middle of instruction, but none of this knowledge is articulable due to its tacit nature. Moreover, even when asking teachers to articulate their ePCK with aid of classroom videos or artifacts, we capture pPCK rather than ePCK because ePCK is transformed into pPCK as teachers make their reasoning explicit; thus, “it is impossible to capture the true nature of ePCK” (Alonzo et al., 2019, p. 280).

An alternative approach is to infer ePCK from teachers' behaviors (Alonzo et al., 2019). I argue that interactive parts of teaching—such as responding to student ideas in classroom interactions—can be a potentially useful place for investigating evidence of ePCK. In this context, it is easier (and more obvious) to infer that knowledge of student ideas is likely to be involved; in contrast, when the teacher is giving a lecture, it would be harder (and less obvious) to infer whether teachers are drawing on specific knowledge of student ideas or instructional strategies. When teachers respond to student ideas in classroom interactions, it places significant demands on their ePCK, requiring teachers to draw on their knowledge of students' ideas and knowledge of instructional strategies to respond to those ideas. Moreover, this focus on interactive parts of instruction should help to uncover the aspects of ePCK that might be most closely related to student learning. Well-designed instructional plans and faithful enactment of those plans is still important for ensuring productive learning opportunities, but there is evidence that students benefit, in particular, from teachers' attention and responsiveness to their ideas during instruction (K. T. Anderson, Zuiker, Taasoobshirazi, & Hickey, 2007; Black & Wiliam, 1998; Pierson, 2008).

**Overview of the Study**

In this study, I address the challenge of connecting PCK and teaching practice by exploring the relationship between ePCK and pPCK. I focused on classroom discussions, an interactive part of instruction, as a suitable place for my research. Not only is inference of ePCK is clearer in discussions as compared to other types of instruction, but it provides the opportunity to investigate the relationship between ePCK and teachers' responsiveness to student ideas. I examined how teachers engage with student ideas elicited in classroom discussions and explored how ePCK is used to accomplish their engagement with student ideas. This investigation of one aspect of PCK and one aspect of teaching practice will inform the field about the relationship between PCK and teachers' responsiveness and, more broadly, the relationship between and PCK and teaching practice. In the following chapter, I discuss the methodology that I used to conduct this research.

# Chapter 3. Methods

In this chapter, I describe the study I conducted to answer my research questions. I first describe my research design. Next, I provide information about the research context, including descriptions of the larger research project, participants, and data sources. Then, I describe my data analysis in detail, specifying how I analyzed teachers' enacted PCK (ePCK), as inferred from teachers' response to student contributions in classroom discussions, and teachers' personal PCK (pPCK), as revealed in video-stimulated interviews, as well as how I explored the relationship between ePCK and pPCK.

## Research Design

I conducted a qualitative, multiple-case study to examine evidence of PCK as reflected in classroom discussions. The case study is an in-depth empirical inquiry of a contemporary phenomenon within a real life context that involves pursuing how and why questions (Yin, 2009). Multiple-case studies provide insight into a phenomenon of interest by illuminating similar and different patterns across cases as well as illustrating particular results within individual cases (Yin, 2009). I used a multiple-case study of five physics teachers' classroom discussions to examine various ways that PCK is used in real-time classroom discussions, both within and across teachers.

Specifically, I conducted an instrumental case study. The purpose of a case study can be either intrinsic or instrumental depending on how a case is chosen (Stake, 2005). In an intrinsic case study, a particular case is examined because the case itself is significant, and there is an inherent interest in the case. By contrast, an instrumental case study seeks to understand an issue or to build a theory by means of the case. Instead of there being an intrinsic interest in the population or the case, "(t)he case is of secondary interest, it plays a supportive role, and it facilitates our understanding of something else" (Stake, 2005, p. 445). In my study, five physics teachers are examined to understand issue of PCK as reflected in classroom discussions, rather than to understand the five teachers themselves.

**Research Context and Participants**

This study is part of a larger research project that aimed to support beginning teachers' PCK about force and motion concepts through video-based professional development. During the 2009-2010 academic year, the larger research project recruited seven experienced physics teachers in order to develop video cases that could be used for the professional development. Five of these teachers are the participants in my study. Complete data was not available for the other two teachers and, thus, they were excluded from my study.

The five participating teachers (Charlie, Denise, Frank, Jason, and Ryan[3]) taught physics or physical science/introductory physics in high schools in a Midwestern state (see Table 3.1). In these schools (four suburban or rural public schools and one urban private school), physics was typically an upper-level course taken by juniors and seniors ($11^{th}$ and $12^{th}$ graders) while physical science/introductory physics was typically a lower-level course taken by freshmen and sophomores ($9^{th}$ and $10^{th}$ graders). In some schools, students took one physical science course (which covered introductory chemistry and physics content); other schools offered separate introductory courses in chemistry and physics. In below, I describe each teacher's background, classroom context, and overall instructional practice.

[3] Pseudonyms are used for all teachers in this study.

Table 3.1 Background Information about Participating Teachers

| Teacher | Class Observed | School Type | Community Context | Teaching Experience | Subject Background (Minor) |
|---|---|---|---|---|---|
| Charlie | Physics | Public | Suburban | 25 years | Physics |
| Denise | Physics | Private | Urban | 5 years | Physics |
| Frank | Physical science | Public | Suburban | 12 years | Chemistry (Math) |
| Jason | Intro physics | Public | Rural | 9 years | Biology (Physical science) |
| Ryan | Physics | Public | Rural | 9 years | Physics |

**Charlie.** Charlie was the most experienced of the participating teachers (Table 3.1). After completing bachelor's and master's degrees in physical geography, he obtained certification to teach physics by completing a teacher preparation program. At the time of this study, he was teaching physics in a suburban high school where he had spent his entire career, teaching physics most of the time. He described that most students in the physics class we observed are college-bound juniors and seniors (11th and 12th graders), who are generally "motivated kids." He had been to national and regional conferences of science and physics teachers and participated in a local group of physics teachers to discuss their instruction.

Charlie's teaching was entertaining and energetic. He had lots of gadgets and other materials for attention-getting physics demonstrations. He often showed a series of demonstrations to illustrate a single concept. For example, he used a series of four demonstrations to illustrate Newton's First Law of Motion. He often brought the complexity of the real world into his instruction, addressing friction and air resistance, rather than only discussing the idealized physics world. He tended to pursue accurate and complete explanations of content, resulting in explanations that sometimes seemed overly complicated, highlighting advanced concepts, rather than those that the students were to be learning. For example, when discussing a balloon rocket demonstration, he went beyond the common identification of the action-reaction forces (i.e., the balloon pushes against the air and the air pushes against the balloon), challenging students to further specify whether the air inside or outside of the balloon is involved in the pushing.

**Denise.** Denise had a background in physics and five years of teaching experience. Although she was less experienced than the other teachers in the study, she benefited from a five-year fellowship that provided extensive professional development support. During the fellowship, she had participated in an intensive course about Modeling Instruction[4] for kinematics and forces. The fellowship also offered an opportunity for Denise to research teacher questioning, such as the ideas of wait time and questions that elicit higher levels of Bloom's taxonomy[5]. At the time of the data collection, Denise was teaching physics to juniors and seniors ($11^{th}$ and $12^{th}$ graders) at a private high school in an urban area. She described the students in this class as "generally C and B students" but "good students that ask great questions."

Rather than the traditional "rows of desks," Denise arranged students' desks in a multi-layered semicircle facing toward her. This allowed students to see other students seated across the room from them. She had a smartboard in the classroom and skillfully used the various functions of the device, from writing/drawing to projecting from her computer.

[4] Modeling Instruction, a research-based teaching philosophy developed through Arizona State University, emphasizes helping students construct and apply conceptual models to account for physical phenomena (Jackson, Dukerich, & Hestenes, 2008). Models are constructed through representation tools (e.g., graphs and diagrams) and validated and refined throughout the class (Brewe, 2008).

[5] Bloom's revised taxonomy (L. W. Anderson & Krathwohl, 2001) presents six categories of learning objectives in the cognitive domain. These categories are ordered from simple to complex: *remember*, *understand*, *apply*, *analyze*, *evaluate*, and *create*.

There was a somewhat light, informal atmosphere in Denise's class. Students casually conversed and freely jumped in to express ideas during classroom discussions, which made the class sometimes noisy and seemingly chaotic. Denise engaged with student ideas by asking conceptual questions to probe and push students' thinking (e.g., "How do you know it's equal?", "Why does there have to be [another force]?"). During the observed lessons, Denise actively involved students in her instruction. She often asked students to volunteer for a classroom activity, and students seemed eager to volunteer, with multiple students vying for the opportunity to participate. On one occasion, Denise encouraged students to test answer to questions about questions about Newton's Laws[6] by using her demonstration materials: a cart on a "frictionless" air track at the front of the room. She emphasized that "Anyone can do this," and a few students came to the front to manipulate the equipment.

**Frank.** Frank was primarily certified to teach chemistry, but he taught mathematics—his minor subject area—for the first seven years of his career. Five years before the study, he had come back to teaching science. At the time of data collection, he was teaching physical science at a suburban public high school. Students in his physical science class were primarily freshmen (9th grade students) whose "ability ranges are fairly wide."  This class was also "an inclusion classroom," so there were some special education students, who were occasionally supported by an aide.

Frank taught the class in a loud and vibrant voice. During the observed lessons, he used an overhead projector to display PowerPoint slides containing information about the content and

[6] The three questions were: 1) If you continually push on something with a constant force and there is virtually no friction pushing back, what will happen?; 2) If you initially push on something and there is virtually no friction pushing back, what will happen?; and 3) If you push on a wall, describe the force that you feel from the wall? For the third question, Denise said that "You can push the wall if you want."

activities covered in his instruction. His lessons followed a fairly common structure: lecture, followed by independent work time. He revealed bullet points on the slides (e.g., definition of balanced/unbalanced forces) as he lectured, and students copied information from the slides into their notebooks. He consistently asked for students' answers to his mostly factual questions (e.g., "What's gravity?" "Where does gravity come from?"); students rarely asked questions about content in the whole class. During independent work time, which typically took up almost half of class, Frank walked among the students and provided one-on-one support. The level of content discussed in Frank's class seemed simpler as compared to what was discussed in other teachers' classrooms, consistent with the lower level of his class as compared to those of the other teachers (except Jason, who also taught physical science).

**Jason.** At the time of the study, Jason had nine years of teaching experience and was teaching introductory physics at a rural public high school. Although he was primarily certified to teach biology, he sometimes also teaches regular (i.e., more advanced) physics classes. He reported learning about teaching physics from regional and national science teaching conferences, as well as through sharing ideas with a network of science teacher friends who work in other districts. Students in Jason's intro physics class were mostly freshmen (9th graders) who have "varying skill sets." Similar to Frank, Jason's class included some special education students.

Students in Jason's classroom sat in groups of four, although no small group activities were observed. Similar to Frank, Jason's instruction consisted of lecture and independent student work time. During his lectures, Jason primarily provided verbal explanations and rarely conducted demonstrations. He talked relatively fast, often long in fairly long monologues. He wrote important information on the blackboard, and students copied this information onto a handout. He also spent time supporting students with basic math needed to solve problems. For example, he devoted almost an entire class period to numerical calculation problems involving Newton's Second Law of Motion, supporting students in manipulating the equation F=ma to solve for different variables.

**Ryan.** At the time of the study, Ryan had been teaching mostly physics at a rural public high school for nine years. When he came to the school, with a background in physics, he redesigned the physics course since to resemble the content of a first-year college course. He reported that his physics class is usually made up of juniors and seniors (11th and $12^{th}$ graders) who are "good students, academic-wise."

Ryan's school used a block schedule, so his lessons were longer (1 hour, 30 minutes) than other teachers' lessons (approximately 50-60 minutes). His classroom had calm and quiet atmosphere. Ryan provided opportunities for individual students to speak one at a time, asking students to explain or clarify their thinking (e.g., "Why does the ball go right back into your hand?", "What do you mean by the same?"), and students frequently contributed their ideas. In response, Ryan often asked students to "vote" their agreement/disagreement in order to see how the whole class was thinking (e.g., "How many say yes, [the golf club] affects the golf ball while it's in the air? … How many say no? … How many aren't sure?"). In his lessons, Ryan used a document camera to project handouts onto the white board. While he filled in blanks on the handouts, students copied the answers onto their handouts. During the lessons, he discussed questions and problems from these handouts and from students' homework. When needed, he showed the problem-solving process by writing on the board and sometimes asked students to volunteer to share their answers to the questions on the board. When conducting demonstrations, he often used a Predict-Observe-Explain (P-O-E) model (Gunstone, 1990). Before conducting a demonstration, Ryan asked students to write their predictions with explanations for those predictions. After the demonstration, students were instructed to write their observations and explanations.

**Data Collection**

In this section, I first describe the two primary data sources that I used for this study: classroom videos and post-unit video-stimulated interviews. I then describe additional data that provided contextual information for each teacher's instruction: pre-unit interview and classroom artifacts.

**Classroom Videos.** As part of the larger research project, teachers' instruction on force and motion was observed and video recorded. Approximately three force and motion lessons were video recorded for each teacher, with a range from two (Frank) to four (Denise and Ryan). The purpose of the classroom video recordings was to 1) develop a set of video clips that could be used in the video-based professional development for beginning teachers and 2) explore teachers' PCK as enacted in teaching practices. Lessons when students' ideas would be most explicitly expressed were targeted to be video recorded; lab or test days were excluded. Two cameras were used for video recording: one angled at the teacher (typically from the back of the classroom) and the other angled at the students (typically from the front of the classroom). The average duration of a lesson was 1 hour 3 minutes (SD=16 minutes).

**Post-Unit Video-Stimulated Interview.** At the end of the force and motion unit, each teacher participated in a post-unit video-stimulated interview. The purpose of these interviews was to explore the PCK underlying teachers' instructional decisions using videos from the teachers' own instruction. In contrast to typical interviews that mainly rely on verbal prompts, video-stimulated recall interviews use video segments from classroom instruction to support teachers' reflection. Videos preserve authentic features of classroom practice and, thus, do not reduce the complexity of the work of teaching (Sherin, Linsenmeier, & van Es, 2009; Hewitt, Pedretti, Bencze, Vaillancourt, & Yoon, 2003). Video clips from teachers' own classrooms allow the teachers to revisit particular instructional events with rich information about the context and help them to recollect their reasoning and the knowledge that they were drawing upon for instructional decisions (Calderhead, 1981; Yinger, 1986).

For each teacher's interview, a set of video clips was created to probe the teacher's reasoning about student ideas and/or instructional strategies, i.e., the two components of PCK. The clips highlighted specific classroom events that might involve teachers' instructional decisions: "e.g., the expression of a student idea, a teacher's response to a student idea, a teacher's use of a particular instructional representation, a teacher's emphasis on a particular idea during instruction" (Alonzo & Kim, 2016, p. 1266). Since each teacher had a unique classroom environment and instructional practices, the number and average length of video clips that were used for the interviews differed by teacher (see Table 3.2). The number of video clips ranged from 11 (in Charlie's interview) to 19 (in Ryan's interview), with an average of 14.6 (SD=3.7) video clips per interview. Video clips ranged in length from 7 seconds (a student's question about normal force in Denise's classroom) to 6 minutes, 42 seconds (Charlie's whole class discussion about a Newton's third law demonstration), with an average length of 1 minute, 7 seconds (SD=27 seconds).

Table 3.2 Video Clips Used in Post-Unit Video-Stimulated Interviews

| Teacher | Number of Video Clips | Average Duration of Video Clips (M:SS) |
|---|---|---|
| Charlie | 11 | 1:50 |
| Denise | 18 | 0:41 |
| Frank | 13 | 1:13 |
| Jason | 12 | 0:49 |
| Ryan | 19 | 1:04 |
| M (SD) | 14.6 (3.7) | 1.07 (0:27)* |

* These numbers were calculated when averaging the length of video clip across all of the clips.

Interview questions were developed for each video clip to elicit the teacher's PCK. The questions asked for teachers' interpretations of student ideas, explanations for instructional strategies, and connections between student ideas and/or instructional strategies (Alonzo & Kim, 2016)—for example, "Can you talk a little bit about how you interpret that student's comment?" (Ryan, Clip 11; interpretation of student ideas), "Could you talk about why you chose that as an example of action-reaction?" (Jason, Clip 11; explanations for instructional strategies), and "Do you find that [instructional strategy] helps [students] get over this misconception that the bigger object has to be exerting a bigger force?" (Charlie, Clip 10; connections between student ideas and instructional strategies). Interviews lasted on average 1 hour 3 minutes (SD=17 minutes) and were all video recorded and transcribed prior to analysis.

**Pre-Unit Interview and Classroom Artifacts.** At the beginning of the force and motion unit, the teachers were interviewed about their backgrounds, their students, and their goals and plans for the unit. Interviews lasted on average 38 minutes (SD=14 minutes) and were video recorded. In addition, artifacts and documents related to instruction (power point slides, student worksheets, and/or copy of textbooks), were collected as part of classroom observations.

## Data Analysis

To answer my research questions, I analyzed teachers' ePCK, pPCK, and engagement with student ideas, independently and then explored how ePCK relates to a) teachers' engagement with student ideas and b) pPCK, respectively. Below, I describe how I conducted each analysis.

**Teachers' ePCK and Engagement with Student Ideas.** To answer Research Question 1 (What aspects of ePCK are evident from physics teachers' classroom discussions about force and motion? How is ePCK related to teachers' engagement with student ideas?), I analyzed video recordings of classroom discussions to investigate teachers' ePCK and engagement with student ideas.

***Step 1: Identifying Classroom Discussions*.** The first step of my analysis was to identify classroom discussions from video recordings of classroom observations. I used four criteria, modified from the ones in Carpenter, Irish, Nilsen, and Bianchini (2016). First, discussions involved the teacher and at least one student in a whole class conversation. All teachers engaged in these sorts of whole class teacher-student conversations. Teachers also interacted with individual students on problem-solving or with a few students working in groups, but these were not included in my study. Second, a discussion could be initiated by either the teacher or a student. For example, the teacher could elicit student ideas by posing a question to the class, or a student could bring up an interesting idea by asking a question. Third, discussions involved at least three talk turns. This captured how the teacher and student(s) responded to or built on expressed ideas. Finally, the discussion had to be substantive, focused on a physics concept/topic, a phenomenon, or a student idea. When the class moved on to a different concept/topic, phenomenon, or student idea, I considered the discussion to have ended. Conversations about procedures, guidelines, or other logistics issues were excluded.

Once classroom discussions were identified, I characterized the overall profile of classroom discussions for each teacher. I characterized overall patterns of interactions during discussions and calculated the average number of discussions per observation and the overall percentage of time devoted to classroom discussions. As described in the next section (Step 2), not all classroom discussions identified at this stage were used for further analysis. However, this holistic characterization of teachers' classroom discussions provided insight into the broader context of the classroom discussions analyzed in this study.

***Step 2: Identifying Classroom Discussions That Were Used in the Video-Stimulated Interview.*** Of all of the classroom discussions identified in Step 1, only those used in video-stimulated interviews were selected for further analysis. One goal of my study was to compare teacher's ePCK, as inferred from classroom discussions, and associated pPCK, as revealed in video-stimulated interviews (Research Question 3). This comparison could only be made for ePCK and pPCK associated with the same classroom discussion. Thus, I focused only on classroom discussions that were used in the video-stimulated interviews.

Sometimes, classroom discussions identified from the classroom videos fit exactly the clips used in the interviews. In some cases, however, discussions were longer than what was included in the interview. This is at least partly because the video clips of discussions used in the video-stimulated interviews highlighted student ideas, and thus the clip often stopped before teachers' follow up responses or extended talk after an initial student idea. If part of a discussion was used in the interview, I included the entire discussion in my ePCK analysis, even though part was not included in the interview (and, thus, my pPCK analysis). All classroom discussions identified in this way were transcribed for further analysis.

***Step 3: Analyzing ePCK in Classroom Discussions.*** After identifying and transcribing the classroom discussions used in video-stimulated interviews (Step 2), I zoomed in on the teacher's instructional moves in each discussion to find evidence of ePCK. In particular, I examined teachers' responses to student idea(s) expressed in the discussion, identifying some as indicative of presence of ePCK (i.e., if the response indicated knowledge about a student idea and/or instructional strategy addressing the student idea) and others as evidence of a gap in ePCK (i.e., if the response indicated a gap in knowledge of a student idea and/or instructional strategy addressing the student idea). I constructed a set of codes to capture these responses, relying upon both deductive and inductive processes.

Deductively, I began with three kinds of a priori codes drawn from previous research. First, I identified codes related to teachers' flexible use of content from Alonzo et al.'s (2012) list of evidence of PCK reflected in classroom interactions. These forms of evidence reflect ways that teachers used content in dialog with students. Second, I identified codes related to selective discourse moves that teachers use when responding to students' ideas during classroom discussions (e.g., Lau, 2010; Pierson, 2008; Richards, 2013; van Zee & Minstrell,1997). For this purpose, I selected discourse moves that have a potential to draw on knowledge of student ideas and/or instructional strategies addressing the student ideas. For example, *reflective toss* (van Zee & Minstrell, 1997)—a discourse strategy that "'catch[es]' the meaning of the student's prior utterance (p. 229)" and presses the student to reflect on a specific aspect of his/her idea—requires teachers to recognize the content-related significance of a student's idea and to identify the aspect(s) of that idea that could be productively challenged to support student learning. Third, I included a code related to errors or mistakes that researchers observe in lessons by teachers with weak content knowledge (e.g., L. R. Sanders, Borko, Lockard, 1993; M. Sanders, 1993). In these instances, constraints in teachers' own knowledge, including knowledge of the content and knowledge of student ideas about the content, lead to instruction that may reinforce common student misconceptions.

Inductively, I derived additional codes for teachers' responses to student idea(s) from the data themselves (Corbin & Strauss, 2008). Table 4.2 in Chapter 4 shows the final set of codes. The codes reflect nine ways that teachers' responses to student ideas indicated presence of or gaps in ePCK. Once the coding scheme was finalized, I coded at the level of teacher speech turn for each transcript.

***Step 4: Exploring the Relationship Between ePCK and Teachers' Engagement With Student Ideas.*** After coding the teacher's responses for ePCK (in Step 3), I zoomed out to examine how ePCK indicators were used to support teacher's engagement with student ideas in the discussion. I first coded the quality of the teacher's engagement with student ideas: the extent to which the teacher attempted to engage and work with elicited student ideas during the discussion. As shown in Table 4.3, I identified three levels of teachers' engagement with student ideas (low, moderate, and high) based on three criteria: (1) the teacher's attempts to engage with student ideas, (2) what ideas were elicited from students, and (3) what the teacher appeared to focus on during the discussion. A discussion was rated as low engagement if the teacher made few attempts to work with student ideas, mostly elicited short answers, and focused on conveying content. A discussion was rated as medium engagement if the teacher made some attempts to work with student ideas, occasionally elicited evidence of student thinking and sense-making, and focused on addressing a student's question, confusion, or misunderstanding. A discussion was rated as high engagement if the teacher made persistent attempts to work with student ideas, consistently probe and clarify the logic of student ideas, and focused on eliciting and supporting multiple students' ideas. After assigning a rating to each discussion, I examined the ePCK indicators found in discussions with each level of engagement to look for patterns in the indicators associated with each level.

As part of this analysis, I noticed that classroom discussions tended to include not only ePCK indicators but also more general discourse moves that appeared to support teachers' engagement with student ideas. I further explored this relationship by coding the transcripts of classroom discussions for different types of discourse moves. Initial coding started with discourse moves drawn from prior research (Lineback, 2015; Michaels & O'Connor, 1993; 2012; Pierson, 2008; van Zee & Minstrell, 1997), but I also constructed additional coding categories that emerged from the data. The final coding scheme (see Table 4.11) was applied to teacher utterances in the transcript.

***Step 5: Memo Writing.*** After coding the transcripts (Steps 3 and 4), I engaged in memo-writing (Charmaz, 2004) for each teacher to summarize and synthesize the codes applied to classroom data. Each memo included a description of a) the ePCK evident in each discussion, b) engagement with student ideas in the discussion, and b) the relationship between ePCK and engagement in the discussion. Each memo also included an overall summary of the classroom analysis for the teacher. I looked across analysis of individual classroom discussions to characterize an overall picture of the teacher's ePCK, engagement with student ideas, and the relationship between ePCK and engagement.

**Teachers' pPCK.** To answer Research Question 2 (What aspects of pPCK are evident from physics teachers' explanation of their classroom discussions about force and motion?), I analyzed the post-unit video-stimulated interviews. All interviews were transcribed prior to analysis.

***Step 1: Identifying Interview Segments Focused on Video Clips Containing Classroom Discussions.*** Of each teacher's interview, only parts focused on video clips containing discussions were selected for further analysis. This was to facilitate comparison of teacher's ePCK, as inferred from classroom discussions, and teachers' pPCK, as revealed from video-stimulated interviews. I examined each video clip to determine whether it contained one (or more) of the classroom discussions that I had used to analyze the teacher' ePCK.

***Step 2: Analyzing pPCK in Video-Stimulated Interviews.*** After identifying interview segments (Step 1), I analyzed the segments for pPCK. I examined which element of PCK (knowledge of student ideas and/or knowledge of instructional strategies) was exhibited in the teacher's reasoning about the video clip and how the exhibited element of PCK was explained/justified by the teacher. To do this, I developed three layers of coding to capture evidence of pPCK revealed in teachers' reasoning in the video-stimulated interviews (Table 3.3).

Table 3.3 Coding Scheme for Teachers' pPCK Elicited by Video-Stimulated Interviews

| Type of Codes | Description of Codes |
|---|---|
| Focus of reasoning | **ST**: Student ideas<br>**IR**: Instructional representations and strategies<br>• **IRp**: Proposing (an) instructional representation(s)<br>• **IRe**: Evaluating (an) instructional representation(s)<br>• **IRr**: Reflecting on (an) instructional representation(s), i.e., identifying a change to one's practice in future instruction<br>**PC**: Physics content<br>**Context**<br>• **Context: Instruction** (e.g., considering instructional representations in light of the level of the class)<br>• **Context: Student** (e.g., commenting on a student's level of confidence) |
| Nature of reasoning | **None**: No attempt to interpret or explain ST and/or IR<br>**Lack**: Demonstrating lack of awareness of ST and/or IR<br>**Tacit**: Expressing difficulty articulating the reasoning behind an IR<br>**Connect**: Noting similarities between videos in terms of ST or PC<br>**Interpret**: Interpreting ST (i.e., interpreting what a student has said in terms of what this means about his/her thinking)<br>**Explain**: Explaining ST or IR (i.e., explaining why students might think in particular ways or justifying an instructional strategy) |

Table 3.3 (cont'd)

| | |
|---|---|
| Basis of reasoning<br>(applied to "Explain" codes) | Applied to Explain codes for ST:<br>• **Curriculum** (e.g., textbook, students' experience in lower level courses, district expectation)<br>• **Student Experience** (students' real word experience)<br>• **IR** (i.e., how instructional strategies influence student ideas)<br>Applied to Explain codes for IR:<br>• **Curriculum** (e.g., textbook, students' experience in lower level courses, district expectation)<br>• **Student Experience** (students' real word experience)<br>• **ST** (i.e., how student ideas influence instructional strategies)<br>• **Motivation** (students' interest, motivation, or attention)<br>• **Own Experience** (teachers' own experience as a learner)<br>• **PC** (physics content)<br>• **Level** (e.g., physical science vs. physics)<br>• **Convenience** (practical and convenient aspect of instructional demonstrations)<br>• **Preference** (teachers' personal preference)<br>• **Time** (time constraints) |

*Note*: Parentheses were used to indicate vagueness with respect to student ideas (ST) and instructional representations and strategies (IR) in the codes for the focus of reasoning and the basis of reasoning. An asterisk (*) was used to flag a segment for any of following reasons: problematic physics content was present, interpretations of student thinking seem problematic, or the proposed instructional representation seems unrelated to the targeted student thinking.

The first layer of coding indicated the focus of the teacher's reasoning (*focus of reasoning*), capturing what a teacher focused on when explaining instruction in the video. These codes capture the two elements of PCK, student ideas (*ST*) and instructional representations and strategies (*IR*), as well as the teacher's focus on physics content (*PC*) and contextual factors (*Context*) related to the video. Most of the time, teachers' discussion of instructional strategies involved justifications of the instruction shown in the videos (*IR*). However, additional codes were developed to indicate when the teacher proposed an alternative instructional strategy (*IRp*), evaluated an instructional strategy in the video (*IRe*), or reflected to inform their future instruction (*IRr*).

The second layer of codes indicated the nature of the teacher's reasoning (*nature of reasoning*) to capture how the teacher reasoned about student ideas and instructional strategies. In some cases, there was little reasoning offered (*None*), the reasoning demonstrated a lack of awareness of student ideas or instructional strategies (*Lack*), or the teacher expressed difficulty articulating the reasoning behind his/her instructional strategies (*Tacit*). In other cases, teachers made connections across videos (*Connect*), interpreted student thinking (*Interpret*), and/or explained student ideas or instructional strategies (*Explain*).

Finally, the third layer of codes, the basis of teacher's reasoning *(basis of reasoning),* was applied to segments coded as *Explain* in order to capture what the teacher drew upon when explaining student ideas or instruction in the video. For example, a teacher might explain student ideas by considering students' everyday experience (*Student Experience*) or might explain an instructional strategy by referring to a targeted student idea *(ST*).

An asterisk (*) was used sparingly to flag segments for the following reasons: problematic physics content was present, interpretations of student ideas seemed problematic, or the proposed instructional strategy seemed unrelated to the targeted student idea.

***Step 3: Memo Writing.*** After coding the transcripts, as with the classroom observations, I engaged in memo-writing for each teacher in order to summarize the interview analysis (Charmaz, 2004). Each memo included a description of the teacher's pPCK elicited by each video clip, as well as an overall picture of the teacher's pPCK across the video clips.

**Relationship Between ePCK and pPCK.** To answer Research Question 3 (How is physics teachers' ePCK and pPCK related for the topic of force and motion?), I compared ePCK, as evidenced in classroom observations (Research Question 1) and pPCK, as evidenced in video-stimulated interviews (Research Question 2) for the same discussion. For each discussion, I first looked at the coded transcript of and the memo written about the discussion to see how the teacher responded to a student idea in the discussion (ePCK). I then moved to the coded transcript of and the memo written about the teacher's video-stimulated interview about the same discussion to see how the teacher explained the expressed student ideas and/or instructional strategies responding to those ideas (pPCK). As described in Chapter 6, I identified relationships between ePCK and pPCK in video clips of classroom discussions. I considered relationships at the video clip, rather than the classroom discussion, level because more than one video clip could come from the same classroom discussion, and these did not necessarily represent the same relationship between ePCK and pPCK.

After comparing ePCK and pPCK for individual classroom discussions, I engaged in memo-writing for each teacher in order to characterize the overall relationship between ePCK and pPCK for the teacher. I looked across classroom discussions to explore how ePCK indicators may be related to pPCK for the teacher.

## Summary

In this chapter, I described my research design and research context. I also described how I analyzed evidence of teachers' ePCK, pPCK, and engagement with student ideas, as well as how I explored the relationships between ePCK and pPCK and between ePCK and teachers' engagement with student ideas.

The next three chapters present findings: teachers' ePCK and engagement with student ideas, as evidenced in their classroom discussions (Chapter 4); teachers' pPCK, as evidenced in video-stimulated interviews (Chapter 5); and the relationship between ePCK and pPCK (Chapter 6).

## Chapter 4. Findings I: Teachers' ePCK and Engagement with Student Ideas

This chapter provides evidence of ePCK in classroom discussions and describes how ePCK seemed to be related to teachers' engagement with student ideas. As described in Chapter 3, I identified classroom discussions from videos of classroom instruction and analyzed the discussions for evidence of teachers' ePCK and for teachers' engagement with student ideas. From the analysis, I was able to identify a set of ePCK indicators and to categorize classroom discussions using three levels of quality (low, moderate, and high) according to teachers' engagement with student ideas. I found that ePCK indicators varied with the level of teachers' engagement with student ideas during discussions.

I begin the chapter by providing overall information about and characteristics of each teacher's classroom discussions. This provides a broader context of the classroom discussions used for analyses of ePCK and teachers' engagement in this chapter. Next, I describe the set of ePCK indicators that were inferred from teachers' responses to student ideas in classroom discussions. Then, I describe teachers' engagement with student ideas. I provide a rubric that characterizes teachers' engagement with student ideas in terms of three levels of quality and describe how the teachers' discussions were distributed among these levels. Finally, I describe how ePCK seemed to have been used to enact each level of engagement with student ideas.

### Classroom Discussions

Using the four criteria for classroom discussions (see Chapter 3), I identified a total of 78 classroom discussions, representing an average of 15.6 (SD = 5.4) classroom discussions per teacher (see Table 4.1). Teachers facilitated an average of 5.2 (SD = 1.1) classroom discussions per observation, ranging from 4.0 (Denise) to 6.5 (Frank). On average, 24.5% (SD = 8.6%) of teachers' class sessions were identified as discussions, ranging from 16.0% (Frank) to 35.8% (Charlie).

A total of 37 discussions overlapped with the video-stimulated interviews and were included in further analyses. This represents an average of 7.4 (SD = 0.9) discussions per teacher, an average of 50.6% (SD = 13.8%) of each teacher's total number of classroom discussions.

Table 4.1 Information about Classroom Discussions Identified in Videos of Classroom Observations

| Teacher | Number Discussions Across Observations | Number of Discussions per Observation | Percentage of Time Devoted to Discussions (%) | Number of Discussions Overlapping with Interview | Percentage of Discussions Overlapping with Interview (%) |
|---|---|---|---|---|---|
| Charlie | 15 | 5.0 | 35.8 | 7 | 46.7 |
| Denise | 12 | 4.0 | 24.8 | 8 | 66.7 |
| Frank | 13 | 6.5 | 16.0 | 8 | 61.5 |
| Jason | 13 | 4.3 | 16.2 | 6 | 46.2 |
| Ryan | 25 | 6.3 | 29.6 | 8 | 32.0 |
| Total | 78 | - | - | 37 | - |
| M (SD) | 15.6 (5.4) | 5.2 (1.1) | 24.5 (8.6) | 7.4 (0.9) | 50.6 (13.8) |

**Characteristics of Each Teacher's Classroom Discussions.**

***Charlie.*** As shown in Table 4.1, Charlie facilitated 5.0 discussions per lesson, similar to the average number of per lesson across teachers; however, in contrast to other teachers, he devoted a greater percentage of time to discussions. His discussions were often dominated by teacher monologue focused on content delivery. Many of these discussions were conducted in an

Initiation-Response-Evaluation (I-R-E) manner (Mehan, 1979), in which Charlie posed a question (initiation), student(s) provided a short answer (response), and he evaluated the answer, or provided content when needed, and moved on (evaluation). The few more dialogic instances occurred when students expressed a question, confusion, or a novel idea, resulting in a more back-and-forth conversation. These discussions sometimes contained spontaneous expressions of student ideas not elicited by Charlie.

***Denise.*** Denise facilitated 4.0 discussions per lesson, slightly less than the average of 5.2 (Table 4.1). However, she devoted 24.8 % of her lesson time to discussions, almost exactly the average percentage across teachers. This means that her discussions were typically longer than other teachers' discussions. Denise's discussions were characterized by multiple, continuous back-and-forth exchanges regarding a single idea or topic. Students contributed their ideas frequently, and Denise facilitated discussions using ideas from multiple students. In her classroom, on occasion, students not only offered their own ideas but also responded to other students' ideas. Sometimes Denise's discussions appeared chaotic because multiple students made comments simultaneously.

***Frank.*** Frank facilitated 6.5 classroom discussions per lesson, slightly more than the average of 5.2 (Table 4.1). However, he devoted a relatively low percentage of time (16.0%) to these discussions, meaning that his discussions were all relatively short. Frank's discussions were usually straightforward, conducted in a I-R-E manner. His discussions often focused on short demonstrations, occurring in a structured way. He conducted a demonstration and then asked students for their observations of (e.g., "What happened to the cart? What did you see?") and reasoning about the demonstration (e.g., "It didn't move, right? Why didn't it move?").

***Jason*.** In Jason's class, discussions occurred infrequently. As shown in Tables 4.1, he facilitated 4.3 discussion per lesson, slightly less than the average, and spent relatively little time on discussion (16.2%). Unlike other teachers, Jason rarely conducted demonstrations during the lessons we observed, so discussions did not focus on demonstrations. Jason's discussions appeared similar to Charlie's. Many of Jason's discussions were conducted in an I-R-E manner, dominated by teacher monologue focused on presenting content. A few discussions included more back-and-forth exchanges, but this type of discussion usually came from students' contributions (e.g., expression of a question, a learning difficulty, a novel idea), rather than initiated by Jason.

***Ryan*.** Ryan's discussions were similar to Denise' discussions in several respects. Many of Ryan's discussions consisted of multiple, continuous back-and-forth exchanges regarding a single idea or topic. Students frequently contributed their ideas, and Ryan facilitated discussions using multiple student ideas. However, Ryan's discussions were much more structured than Denise's. Rather than having multiple students speak freely at the same time, Ryan consistently provided the opportunity for individual students to speak one at a time.

**Indicators of ePCK**

After selecting classroom discussions for analysis (Table 4.1), I examined how teachers responded to student ideas in the discussions and identified nine ways that teachers' responses to student ideas indicated presence of or gaps in ePCK. The nine indicators of ePCK are shown in Table 4.2.

In addition to the seven indicators of ePCK that resonate with those identified in the literature, I identified two additional ePCK indicators: *foregrounding common student ideas* and *guiding student understanding.* During classroom discussions, teachers often gathered information to see if students had a learning difficulty or common idea (*foregrounding common ideas*) and provided immediate, relevant instructional responses in order to meet students' learning needs (*guiding student understanding*).

Table 4.2 Indicators of Presence of and Gaps in ePCK in Classroom Discussions

| Codes | Descriptions of Code | Examples |
|---|---|---|
| Presence of ePCK | | |
| *Challenging student ideas* | The teacher pressed students to reason further with, reflect on, or clarify their own ideas, instead of providing a direct answer (*Reflective toss*, van Zee & Minstrell, 1997) | Student: But there is something pushing with a force!<br>…<br>Teacher: *If something was pushing on them, what would be happening to those objects?* (Denise-Class01-D5) |
| *Comparing student ideas* | The teacher put student ideas side by side to highlight similarities/differences (Lau, 2010; Richards, 2013) | Teacher: *Some of you think that the forces exerted on each other are not equal, but that the accelerations are. And some of you think that the forces are equal and the accelerations are different.* (Denise-Class2-D4) |
| *Elaborating student ideas* | The teacher restated a student's contribution in a more standard or scientific form (*Revoicing*, Michaels & O'Connor, 1993) | Student: Because it says that an object like that's in motion will stay in motion, and like since it has more mass, it would stay in motion? Unless there's like a bigger force moving it back?<br>Teacher: *Right. This one has more inertia than this one so it will continue in motion more likely than this one, right?* (Denise-Class2-D4) |

Table 4.2 (cont'd)

| | | |
|---|---|---|
| *Foregrounding common student ideas** | The teacher stated or identified what students usually find confusing, or the teacher posed a question to elicit a common student idea | Teacher: *I think there are subtle of aspects that I think we need to make sure we pay attention to. The object that is at rest stays at rest unless it is acted upon by an outside force. I think people tend to think this. That, "Oh, it's not moving, there are no forces acting on it." Is that a true statement or not?* (Charlie-Class1-D1) |
| *Guiding student understanding** | The teacher provided relevant content, examples, or demonstrations to resolve a student's question, confusion, or misunderstanding | Student: Why is the net force going up? … I don't get like how the net force is up and she's falling downward.<br>Teacher: … *So, we want to slow her down, that means we want a net force up to slow her down. She's moving down and we want the force in the opposite direction. So, acceleration is in the opposite direction, so she slows* (Charlie-Class3-D1) |
| *Modifying questions* | The teacher modified his/her question in a different (or more specific) form (*Rewording*, Alonzo, Kobarg, & Seidel, 2012) | Teacher: What happens to the net force that's acting on her?<br>Class: (Silent)<br>Teacher: *Will that increase, decrease, or stay the same?* (Charlie-Class3-D1) |
| *Questioning to develop student ideas* | The teacher asked a question based on student ideas, in order to help students develop understanding of the target concept (*Building on students' ideas*, Lau, 2010) | Student: There was a force that's exerted on the tires of the truck.<br>Teacher: … *What's exerting that force? What object is exerting that force on the tires of the truck?* (Frank-Class1-D4) |

Table 4.2 (cont'd)

| Gaps in ePCK | | |
|---|---|---|
| *Dismissing a student idea* | The teacher rejected or did not recognize a student idea that seemed promising for development toward conceptual understanding of the target concept (*Missed opportunities*, Alonzo et al., 2012) | Student: Isn't it like gravity pushing down on it at the same time so it can't like move in a different direction? Like you're pushing on one, but gravity's pushing down on the top one? … They're like stuck together.<br>Teacher: *Well, they're not stuck together. They are all loose. Stuck is a funny word.*<br>*Student: Yes, (they're not stuck, but…)*<br>*Teacher: Yeah. Because some people could say well, wait, maybe they are stuck together. No, in order for this to move, there has to be a horizontal force acting on that bottle.* (Charlie-Class1-D2) |
| *Reinforcing a misconception* | The teacher made errors or mistakes that may have reinforced a misconception (L. R. Sanders, Borko, Lockard, 1993; M. Sanders, 1993) | Teacher: *My textbook is laying on the table … Gravity is pulling down on the textbook. What's the reaction force that keeps it in place? … Right, the table pushes back … So, action forces, reaction forces.* (Frank-Class2-D3)† |

* These codes were inductively derived from data.

† When a book is at rest on a table, a Newton's Third Law pair is the gravitational force of the Earth on the book and the gravitational force of the book on the Earth. However, students often treat the weight of the book and the normal force as a Newton's Third Law pair (Bryce & MacMillan, 2005).

**Teachers' Engagement with Student Ideas**

Classroom discussions that were selected for analysis varied in the quality of teachers' engagement with student ideas, i.e., the extent to which teachers attempted to engage and work with elicited student ideas. Through my analysis, I identified three levels of teachers' engagement with student ideas: low, moderate, and high (Table 4.3). Each level is comprised of three criteria: (1) teachers' overall attempts to engage with student ideas, (2) what ideas were elicited from students, and 3) what the teacher appeared to focus on during the discussion.

Table 4.3 Quality of Teacher's Engagement with Student Ideas

| Level | Descriptions |
|---|---|
| High | • The teacher made persistent attempts to work with student ideas.<br>• The teacher consistently asked questions to reveal and clarify the meaning and logic that student ideas convey.<br>• The teacher focused on eliciting and supporting multiple students' ideas. |
| Moderate | • The teacher made some attempts to work with the student ideas.<br>• The teachers occasionally elicited evidence of student thinking and sense-making.<br>• The teacher focused on addressing a question, confusion, or misunderstanding implied by a student's contribution. |
| Low | • The teacher elicited student ideas but made few attempts to work with the elicited ideas.<br>• The teacher mostly elicited short responses that did not show students' thinking or sense-making.<br>• The teacher mainly focused on conveying content, rather than revealing or developing student ideas. |

Based on the criteria (Table 4.3), each classroom discussion was assigned a level to indicate the teacher's engagement with student ideas. For each teacher, the number and percentage of discussions at each level of engagement are shown in Table 4.4.

Table 4.4 Number and Percentage of Classroom Discussions at Each Level of Engagement

| Level of Engagement | Teacher | | | | | Total |
|---|---|---|---|---|---|---|
| | Charlie | Denise | Frank | Jason | Ryan | |
| High | 1 (14.3 %) | 3 (37.5 %) | 0 (0.0 %) | 0 (0.0 %) | 2 (25.0 %) | 6 (16.2 %) |
| Moderate | 3 (42.9 %) | 5 (62.5 %) | 2 (25.0 %) | 3 (50.0 %) | 5 (62.5 %) | 18 (48.6 %) |
| Low | 3 (42.9 %) | 0 (0.0 %) | 6 (75.0 %) | 3 (50.0 %) | 1 (12.5 %) | 13 (35.1 %) |
| Total | 7 (100.0 %) | 8 (100.0 %) | 8 (100.0 %) | 6 (100.0 %) | 8 (100 %) | 37 (100 %) |

**Relationship Between ePCK and Teachers' Engagement with Student Ideas**

In this section, I illustrate how ePCK played out in discussions according to the level of teachers' engagement with student ideas. For each level of engagement, I begin by describing how teachers elicited and worked with student ideas in discussions. Then, I describe what ePCK indicators were typically found with that level of engagement and how ePCK was used to accomplish teachers' engagement with student ideas.

**Low Engagement.** As shown in Table 4.4, 35.1 % of the analyzed discussions (across teachers) fall into the low engagement category. All teachers except Denise had at least one discussion rated as low engagement. Compared to other teachers, a relatively large percentage (75.0%) of Frank's discussions were characterized as low engagement, but many of Charlie's and Jason's discussions were also characterized in this way (42.9 % and 50.0 %, respectively). I found two ways that ePCK appeared related to low teacher engagement, described in the following sub-sections.

***ePCK for Content Delivery.*** Classroom discussions rated as low engagement often included the ePCK indicators *questioning to develop student ideas* and/or *elaborating student ideas*. These indicators appeared to play a role in highlighting and expanding the correct/relevant aspect of student ideas for the purpose of conveying the target concept. One example comes from Frank's discussion of a demonstration of friction. This discussion occurred as part of a lecture in which Frank was defining friction for his students. As the discussion proceeded, he uncovered bullet points on his slides, such that each part of the discussion ended with a pre-determined piece of the definition of friction, and students copied each point from the slide into their notebooks. In this demonstration, Frank put a small toy car on top of a ramp. Once he released the car, it rolled down the ramp. At the end of the ramp, the car rolled a little and finally came to a stop. An excerpt of this discussion is shown in Table 4.5.

Table 4.5 Transcript Excerpt from Frank's Discussion (Class1-D4)

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Frank: Okay, eventually what happens to the F-150 [truck]? | |
| 2 | Class: It stops. | |
| 3 | Frank: It stops, right? The car rolls, the pickup truck in this case, and it stops. Why does it stop? Student 1? | |
| 4 | Student 1: Friction | |
| 5 | Frank: Friction. What does that mean? | *Challenging student ideas* |
| 6 | Student 1: There was a force that's exerted on the tires of the truck. | |
| 7 | Frank: Okay, there's a force exerted on the tires of the truck. What's exerting that force? What object is exerting that force on the tires of the truck? | *Questioning to develop student ideas* |
| 8 | Student 2: Track? | |

Table 4.5 (cont'd)

| | | |
|---|---|---|
| 9 | Frank: The ground or in this case specifically, we have the track, right? So, the track is exerting a force in the opposite direction of the movement of the truck and eventually it slows it down and it stops it, and that force is the force of friction. (Frank revealed bullet points about definition of friction on the slide and students started to copy the information from the slide into their notebooks). | *Elaborating student ideas* |
| 10 | Frank: So, friction is the force between two objects that are in contact and it opposes the direction of motion. So, from your perspective here, the truck's motion was to the right, and the force of friction if it's opposing it must be which way? | |
| 11 | Student: To the left. | |
| 12 | Frank: To the left. It's opposing the movement of that object. And that's the friction that is between the tires and the track, in that case. | *Elaborating student ideas* |

In this excerpt, Frank appeared to mainly focus on delivering content and getting to the correct answer (friction). Although Frank consistently asked for students' observations of and reasoning about the demonstration and posed follow-up questions based on students' contributions, in response to students' contributions, he mainly highlighted and expanded aspects of student ideas that connected to the academic content he wanted to convey (i.e., the specific bullet point from his slides that he intended to uncover next). For example, Lines 9-12 show how Frank used a student idea simply to fill in a word in his explanation. Because both his questions and responses were focused on this pre-determined content, his discussions consisted primarily of *questioning to develop student ideas* and *elaborating student ideas*.

***Gaps in ePCK.*** Classroom discussions rated as low engagement sometimes included teachers' responses indicating gaps in ePCK: *reinforcing a misconception* and *dismissing a student idea* (Table 4.2). The few instances of a teachers' discussion of content appearing to *reinforce a misconception* occurred primarily in Frank's classroom. This can be seen in a discussion as Frank conducted a demonstration about unbalanced forces. Frank and a student pushed a cart from opposite sides with unequal forces. An excerpt of the subsequent discussion is shown in Table 4.6.

Table 4.6 Transcript Excerpt from Frank's Classroom Discussion (Class1-D3)

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Frank: Okay, so, question for you guys here. What happened that time? What happened there? Student 4? | |
| 2 | Student 4: It moved back. | |
| 3 | Frank: Right, it, it moved back. Keep going. | *Challenging student ideas* |
| 4 | Student 4: It went toward you and pushed you back. | |
| 5 | Frank: Okay, why did it go toward me? Why didn't the cart go toward Student 3? | *Questioning to develop student ideas* |
| 6 | Student 4: 'Cause she [inaudible] more than you? | |
| 7 | Frank: Yeah, was I pushing it? | *Questioning to develop student ideas* |
| 8 | Class: No, yes. | |
| 9 | Frank: Student 3, was I pushing the cart? | |
| 10 | Student 3: Yeah. | |
| 11 | Frank: There was resistance, right? I was exerting a force on the cart, but Student 3's force was? | *Elaborating student idea & Questioning to develop student ideas* |
| 12 | Class: Greater? | |
| 13 | Frank: Greater, okay? So, the two forces were not the same, and so as a result, the cart moved towards me, right? The cart moved towards me 'cause the force exerted by Student 3 was greater, and those are what we refer to as unbalanced forces. | *Reinforcing a misconception* |

Frank explicitly stated that unbalanced forces result in motion, rather than <u>change</u> in motion (Line 13). This is a violation of Newton's Second Law (F = ma) and a common misconception (Champagne, Klopfer, & J. H. Anderson, 1980; Gilbert & Watts, 1983; Halloun & Hestenes, 1985).

In addition, there were a few instances in which teachers *dismissed a student idea* that could be used as a "stepping stone" (Duncan & Rivet, 2013; Foster & Wiser, 2012; Wiser, Smith, & Doubler, 2012) towards new understanding of a target concept. In these instances, the teachers identified the idea as incorrect and ensured that the correct answer was provided. One such example occurred when Charlie was conducting a demonstration using the set-up in Figure 4.1: a stack of wooden blocks with a jar of water on top. He slowly pushed the bottom block with a meter stick to make the whole stack (wooden blocks and jar) slide around the table. An excerpt of the discussion about the demonstration is shown in Table 4.7.

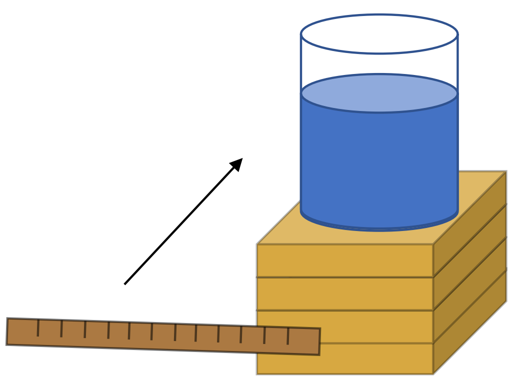

Figure 4.1 Charlie's Demonstration with Blocks and a Water Bottle

Table 4.7 Transcript Excerpt from Charlie's Classroom Discussion (Class1-D2)

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Charlie: So, here is what I'm going to do. Take this meter stick and I'm only going to exert a force on the bottom block. Okay. And I'm just going to do that slowly. | |
| | (Charlie pushes the bottom block with the meter stick.) | |
| 2 | Charlie: (I'm) Exerting a force on just the bottom block and all of them move, right … I'm not touching the three blocks that are on top and I'm not touching the wood or the water. How is that they're all moving? | |
| 3 | Class: (Silence) | |
| 4 | Charlie: Ah… | |
| 5 | Student 1: Gravity is acting on them while they're stacked up. | |
| 6 | Charlie: It's-, It's true, they're stacked up and gravity is acting on them. As we said before with the puck just sitting here, gravity pulls down, and the table pushes up. You'd be able to say that about each of these individual pieces as well. The bottom block has the force of weight pushing down on it. It pushes back on that. Gravity's pulling down on it, and the table pushes it up. It's true. Those are all true statements. But what is the direction of those forces? Those are up and down, right? | *Elaborating student idea & Guiding student understanding* |
| 7 | Student: Yes. | |
| 8 | Charlie: And this is not moving up or down. This is moving to the – | (*Continued: Guiding student understanding)* |
| 9 | Student 2: Isn't it like gravity pushing down on it at the same time so it can't like move in a different direction? Like you're pushing on one, but gravity's pushing down on the top one? | |
| 10 | Charlie: It's true that gravity's pushing down, but what a direction is that? Down. | *Guiding student understanding* |
| 11 | Student 2: Down, but they're like stuck together. | |

Table 4.7 (cont'd)

| | | |
|---|---|---|
| 12 | Charlie: Well, they're not stuck together. They are all loose. Stuck is a funny word. | *Dismissing a student idea* |
| 13 | Student 2: Yes, (they're not stuck, but…) | |
| 14 | Charlie: Yeah. Because some people could say well, wait, maybe they are stuck together. No, in order for this to move, there has to be a horizontal force acting on that bottle. | *(Continued: Dismissing a student idea)*<br>*Guiding student understanding* |

The answer that Charlie was looking for was friction, "a horizontal force," but two students repeatedly expressed the idea that gravity pushes down on the blocks, making the blocks stick together and move as a whole. The students' idea appeared to have potential to be developed into the idea of friction in that friction is directly proportional to the normal force, which—on a horizonal plane—is equal to weight due to gravity. However, rather than using the students' idea as a stepping stone, Charlie *dismissed the idea* and focused on the correct answer: there must be a horizontal force acting on the blocks. When that student idea first appeared (Line 5), Charlie acknowledged the correct aspect of the student's idea by stating that both gravity and the normal force act on the blocks. However, he pointed out that these forces are vertical forces, implying that there must be a horizontal force in order for the blocks to move on the table. When another student expressed the same idea as the first student, that gravity was responsible for the motion of the blocks (Lines 9 and 12), Charlie eventually *dismissed the idea*. He evaluated the idea as incorrect and stated that there must be a horizontal force acting on the blocks.

**Moderate Engagement.** As shown in Table 4.4, 48.6 % of the analyzed discussions (across teachers) were coded as moderate engagement. All teachers enacted discussions with this type of engagement. For all of the teachers except Frank, this was the most common (or tied for the most common) type of discussion.

In classroom discussions rated as moderate engagement, there was some evidence of ePCK indicators used in discussions with low engagement, but ePCK indicators of *foregrounding a common student idea* and/or *guiding student understanding* were more prevalent. These ePCK indicators were used to elicit common student ideas and/or address questions, confusion, or learning difficulties that arose in classroom interactions. One example is in Charlie's discussion of a question about Newton's third law: "When you kick a football, do you exert a force on the ball, or does it exert a force on your foot?" An excerpt of this discussion is shown in Table 4.8.

Table 4.8 Transcript Excerpt from Charlie's Classroom Discussion (Class3-D3)

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Charlie: Number two, it says when you kick a football, do you exert a force on the ball, or does it exert a force on your foot? | |
| 2 | Class: Both. | |
| 3 | Charlie: Right. I mean we just, we've kind of gone over that a lot, right? So, in this case, everybody knows that both of those things happen, right? When you exert-, when you kick a football, you're exerting a force on the football, and the football is, is exerting a force back on your foot. Everybody is okay with that. Right? | *Elaborating student ideas* |
| 4 | Now the twenty-five-thousand-dollar-question though is which one is bigger? | *Foregrounding a common student idea* |
| 5 | Student 1: Your force. | |
| 6 | Student 2: The force you put on. | |
| 7 | Charlie: The force of your foot on the ball or the force of the ball on your foot? | *(Continued: Foregrounding a common student idea)*<br>*Modifying the question* |
| 8 | Class: They are the same. Equal and opposite. | |

Table 4.8 (cont'd)

| | | |
|---|---|---|
| 9 | Charlie: Yeah. They have to be the same. That's the third law, right? They have to be equal to each other. Does that make sense? The force that you exert on the ball must be equal to the force that the ball that exerts back on your foot. | *Elaborating student ideas* |
| 10 | Student 1: Then why does that your foot, why don't we like (gestures both fists bounce in opposite direction) | |
| 11 | Charlie: Yeah, why don't we do this? (follows Student 1's gesture) Well, um, I think that's a good thing to look at. In fact, let's just expand this out a little bit. What is a force equal to? | *Guiding student understanding* |
| 12 | Class: Mass times acceleration. | |
| 13 | Charlie: Mass times acceleration, right? (Charlie begins to explain by writing the equations on the board. See the first equation in Figure 4.2. Charlie shows that the force exerted by the foot on the ball, "$F_{12}$," equal and opposite to the force exerted by the ball on the foot, "$F_{21}$"). | *(Continued: Guiding student understanding)* |

$$F_{12} = - F_{21}$$
$$m\text{a} = \text{m}a$$

F: force

m: mass

a: acceleration

Figure 4.2 Charlie's Equation to Explain Kicking a Ball

Although the discussion rarely deviated from the I-R-E pattern, Charlie did do some work with student ideas to probe and advance student thinking about Newton's Third Law. ePCK indicators of *foregrounding a common idea* and *guiding student understanding* appeared to play a crucial role in Charlie's engagement with student ideas in this discussion. A common idea that students have about Newton's Third Law is that if two objects collide, the heavier object exerts a bigger force (Brown, 1989). Since the lighter object has a greater change in its motion after the collision, students often think that a bigger force must be applied. Charlie *foregrounded this idea* by asking students to compare the relative magnitude of the two forces (Line 4, "Which one is bigger?"). When students responded with the common idea (Lines 5 and 6), the class could then examine it. In addition, when one student continued to express the misconception, wondering why the foot does not fly back like the ball if the forces acting on the two objects are the same (Line 10), Charlie attempted to address the student's confusion by *guiding student understanding*. He provided a set of equations (Figure 4.2), showing that the forces acting on the foot and the ball are equal to each other, but the acceleration of the foot is much less than that of the ball because the mass of the foot is much greater than that of the ball. In particular, he wrote the second equation with different symbol sizes, visually showing students that the acceleration of the ball is large relative to the foot.

**High Engagement.** As shown in Table 4.4, 16.2 % of the discussions (across teachers) featured high levels of teacher engagement with student ideas. This type engagement occurred in 14.3% of Charlie's discussions, 37.5% of Denise's discussions, and 25.0% of Ryan's discussions.

In classroom discussions rated as high engagement, we can see that different indicators of ePCK occurred in coordination with one another. These ePCK indicators were used to facilitate discussions using ideas from multiple students, probe the meaning and logic that student ideas convey, and help students to advance their own thinking. One example comes from Ryan's discussion of the forces acting on a golf ball while it is in the air. Prior to the discussion, Ryan introduced the definition of a contact force, a force that exists only when objects come in contact, and emphasized that contact forces no longer exist when contact is broken. He then engaged students in the discussion shown in Table 4.9.

Table 4.9 Transcript Excerpt from Ryan's Classroom Discussion (Class1-D3): Part 1

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Ryan: So, you swing a golf club, you hit the golf ball … Does the golf club affect the ball while it's in the air? Okay so it's kind of yes or no answer, right? How many say yes, it affects the golf ball while it's in the air, the club still affects it? | *Foregrounding a common student idea* |
| 2 | Class: (Few students raise their hand) | |
| 3 | Ryan: How many say no? | |
| 4 | Class: (Most of students raise their hand) | |
| 5 | Ryan: How many aren't sure? | |
| 6 | Class: (A couple of students raise their hands) | |
| 7 | Ryan: Okay, all right. Ah, how many say, who said no again? Someone give me a reason why you said no. [Student 1], why no? | |
| 8 | Student 1: Because the ball is like a projectile when the club hits it, it goes up. | |
| | (A few seconds later) | |
| 9 | Ryan: What else? Why d-, so who else said no, it doesn't affect it? | |
| 10 | Student 5: Uh, the golf club and the ball are no longer in contact. | |
| 11 | Ryan: Okay, so the golf, so uh we are using just a straightforward definition here. | |
| 12 | Student 5: Sure. | |
| 13 | Ryan: Sure, makes sense. So, we're told that it no longer. But then why does the golf ball move in the air? If that force no longer exists on the golf ball, then how come the golf ball can still be moving in the air? | *Challenging a student idea & Foregrounding a common idea* |
| 14 | Student 6: Well, it's still existing. | |
| 15 | Ryan: What's that? | |

Table 4.9 (cont'd)

| | | |
|---|---|---|
| 16 | Student 6: I feel like when you hit it, the force still exists on the s-, uh, on the ball, but it's not... the golf ball isn't actually touching it, or the golf club isn't actually touching the ball. You know what I mean? | |
| 17 | Ryan: Like after - | |
| 18 | Student 6: Like the force is still acting on it while it's in the air that's, the whole reason it's moving. | |
| 19 | Ryan: Okay, so, let's, so the golf ball applies a force at contact, right? Makes it turn into a projectile. But you're saying even though they're no, no longer in contact, that that force is still applied to the ball. It's still making it move. Am I understanding what she's saying there? | |
| 20 | How many agree with that statement? That the ball is, applies a force to it, hits it, and it continues to move but that force is still a-, that force is still there. | *Foregrounding a common idea* |
| 21 | Class: (Many students raise their hands) | |

In the discussion, Ryan eventually elicited the "impetus" conception (Buridan as cited in Halloun & Hestenes, 1985, p. 1057), the idea that moving objects carry a force along with them, accounting for their motion. While this conception is very common, the majority of Ryan's students initially gave the correct answer ("no"—Line 4). Ryan easily could have moved on at that point, but instead he directly *challenged* students' correct answer (Line 13), specifically *foregrounding* the impetus conception. His question prompted students to think more deeply about their initial responses, eliciting a clear statement of the impetus idea from Student 6 (Lines 14-18). Ryan then *compared student ideas*, highlighting how Student 6's idea (impetus conception) is different from Student 1's ("projectile") and Student 5's ("no longer in contact").

Once the impetus conception had been elicited (Table 4.9), Ryan tried to address it by facilitating a discussion about a demonstration in which he threw a ball back and forth with a student. An excerpt of this discussion with ePCK indicators is shown in Table 4.10.

Table 4.10 Transcript Excerpt from Ryan's Classroom Discussion (Class1-D3): Part 2

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Ryan: All right. So, I throw the ball. As I throw the ball, I change its velocity 'cause right now what would you say about the velocity? | |
| 2 | Student: It's zero. | |
| 3 | Ryan: Zero. Good. I may give it a velocity, now it's moving. Once I release it, the question now is does that force, my hand, still act on it while it's in the air? Does that force still exist? | *Foregrounding a common student idea* |
| 4 | Class: Yeah, no. | |
| 5 | Student 6: No, well. The force you put on it, but not the force directly from your hand. I don't know if that makes any sense at all. | |
| 6 | Ryan: Okay. | |
| 7 | Student 6: Kind of - | |
| 8 | Ryan: Here's, here's the question we're getting to. Does an object need to have a force on it to make it move? | *Modifying questions & Guiding student understanding* |
| 9 | Student: Yeah. | |
| 10 | Ryan: That's basically the question and I want, and, let's actually get a show of hands. Does a force need to act on an object to make it move? | (Continued: *Guiding student understanding)* |
| 11 | Class: No, yes | |
| 12 | Ryan: Or how about this, to keep it moving? 'Cause that's what we're talking about here. Does an ob-, does a force need to act on an object to keep it moving? Who says yes, a force must be present on this ball to keep it moving while it's in the air? Raise your hand. | (Continued: *Guiding student understanding)* |

Table 4.10 (cont'd)

| | | |
|---|---|---|
| 13 | Student 6: Well, I'm confused because when you say force though, you mean like your hand or just the force from your hand? That's the confusing part. | |
| 14 | Ryan: My hand, all it does is it applies a force. It makes the ball move, right? Okay, so my hand is the means of applying the force. Okay, just like kicking a ball. My foot applies the force. The force is the interaction, the actual force we're talking about is the interaction that my hand applies to the ball. Okay. | *Guiding student understanding* |
| 15 | So, let's say in order to make this ball move, and we'll get a number. I have to apply 2 Newtons of force to throw the ball, okay? My hand applies that number. Does that 2 Newtons of force still act on that ball while it's in the air? Does that kind of help make it seem a little more numerical? So, is there 2 Newtons of force still acting on this ball to keep it moving? How many say yes, 2 Newtons of force is still acting on that ball while it's in the air. Raise them high 'cause we want to make sure we, and if you do one of these, just you have to, to say yes or no. Have confidence in your vote. | *Modifying a question* |
| 16 | Class: (Most of students raise their hands) | |
| 17 | Ryan: Okay, how many say no, that that force, 2 Newtons, is no longer acting on it? | |
| 18 | Class: (A couple of students raise their hands) | |

In this excerpt, Ryan engaged in a series of attempts to address the impetus conception. After the demonstration, Ryan *foregrounded* the impetus conception by asking if the force from the hand is still acting on the ball to make it move in the air. Student 6 continued to express the impetus conception by arguing that "the force you put on (the ball)" still acts on the ball to make it move (Line 5). Ryan responded by pushing students to consider whether "a force need[s] to act on an object to keep it moving" (i.e., *modifying questions* and *guiding student understanding*—

see Lines 8-12). However, Student 6 expressed confusion about the question, wondering whether Ryan meant the force to be “[his] hand or just the force from [the] hand” (Line 13). Ryan responded to her continued expression of the impetus conception by explaining how the hand and the force from the hand are distinguished (i.e., *guiding student understanding*—see Line 14). He further *modified his question* in a numerical form to make the distinction clear (Line 15).

Across the two excerpts, Ryan coordinated different indicators of ePCK—*challenging student ideas, foregrounding a common idea, guiding student understanding, and modifying questions*—as he persistently elicited, probed, and worked with student ideas throughout the discussion. However, these discussions did not occur solely through these indicators of ePCK; rather, less content-specific teacher moves also seemed to contribute to Ryan’s high engagement with student ideas. I explore the use of discourse moves in high engagement discussions in the next sub-section.

***General Discourse Moves.*** When facilitating classroom discussions, teachers utilized a set of discourse moves that promoted students’ participation and contributions (Table 4.11). Although these discourse moves were sometimes present in discussions rated as low and medium engagement, they were more prevalent in discussions rated as high engagement. In high engagement discussions, the teachers frequently utilized these discourse moves, regardless of whether student ideas were correct or not. These discourse moves appeared to support teachers to elicit a variety of student ideas and respond to those ideas by carefully listening to what students said, clarifying the meaning of student ideas, and further probing student reasoning. In classroom discussions with high engagement, student ideas were welcomed and occupied a central role in the discussion.

Table 4.11 Discourse Moves in Classroom Discussions Rated as High Engagement

| Discourse Moves | Descriptions | Examples |
|---|---|---|
| *Soliciting multiple responses* | The teacher solicited other ideas (in addition to the one expressed)* | "Other thoughts or ideas you guys had?" (Ryan-Class2-D2) |
| *Eliciting agreement/disagreement* | The teacher asked students whether they agree or disagree with the idea | "How many say yes, it affects the golf ball while it's in the air, the club still affects it? … How many say no? … How many aren't sure?" (Ryan-Class1-D3) |
| *Probing reasoning* | The teacher asked the student to explain the reasoning behind an expressed idea | "Why is it? What's the reason?" (Denise-Class2-D3) |
| *Clarifying a student idea* | When a student expressed an idea, the teacher asked the student to clarify his/her thinking | "What do you mean by the same?" (Ryan-Class4-D4-A) |
| *Summarizing student ideas* | The teacher summarized the range of the ideas that students express | "Some of you think that the forces exerted on each other are not equal, but that the accelerations are. And some of you think that the forces are equal and the accelerations are different." (Denise-Class2-D4) |

* While teachers sometimes use this to signal that a student is incorrect, the teachers responded this way to both correct and incorrect responses.

Ryan used these discourse moves in a discussion about the motion of a ball that is thrown straight up by a person on a plane moving at a constant speed. The correct answer is that the ball goes straight back into the person's hand because both the ball and the person continue moving at the same speed as the plane. I present two excerpts from this discussion. The first coded except is shown in Table 4.12.

Table 4.12 Transcript Excerpt from Ryan's Classroom Discussion (Class4-D4): Part 1

| | Transcript Lines | Discourse Moves |
|---|---|---|
| 1 | Ryan: You are flying on a plane at a constant speed … You throw a ball straight up in the air. What happens? | |
| 2 | Student 1: Um, the ball goes right back into your hand. | |
| 3 | Ryan: Okay. Why does the ball go right back into your hand? | *Probing reasoning* |
| 4 | Student 1: Because both have the same velocity in the x direction, so it's traveling at the same speed as you. | |
| 5 | Ryan: Okay. How many have that the ball is gonna land back in your hand? Raise your hand. I'm just curious to see where we're at with that response. | *Eliciting agreement /disagreement* |
| 6 | Class: [Several students raise their hand] | |

In this excerpt, Ryan expressed interest in the reasoning behind a student's answer and wondered if other students have the same idea. When a student gave the correct answer right away, Ryan asked him to explain the answer (*probing reasoning*). The student provided the accompanying reasoning—which was correct—and he asked for the rest of class to indicate whether they agreed by raising their hand (*eliciting agreement/disagreement*). This allowed Ryan to see not only which students thought the ball would fall back into their hands (correct answer), but also which students did <u>not</u> have this idea. In the following excerpt (Table 4.13), we see how Ryan continued the discussion with a focus on other ideas.

Table 4.13 Transcript Excerpt from Ryan’s Classroom Discussion (Class4-D4): Part 2

| | Transcript Lines | Discourse Moves |
|---|---|---|
| 1 | Ryan: Okay. So, there’s a couple [of students who did not raise their hand to indicate agreement with the idea that the ball would land back in your hand]. You didn’t have that response [correct answer] or? | *Soliciting multiple responses* |
| 2 | Student 2: No, but I don’t think that’s right. | |
| 3 | Ryan: But tell me what you have please. | |
| 4 | Student 2: I said that it will land in a different spot because the plane is moving in and you don’t throw it like forward with the plane really, you’re throwing it straight up. I don’t think that's right. | |
| 5 | Ryan: … We have one idea that it’s gonna land straight in because he's saying that both you and the ball have the same velocity in the x direction … What you’re saying is that as you throw the ball up in the air, it will land in a different spot. | *Summarizing student ideas* |
| 6 | Do you have an idea about where you think it would land if it didn’t land straight down? Will it land in front of you or behind you? | *Clarifying a student idea* |
| 7 | Student 2: It’d land behind you? | |
| 8 | Ryan: Behind you? How many have that idea behind? | *Eliciting agreement /disagreement* |
| 9 | Class: (A few students raise their hands) | |
| 10 | Ryan: Thank you. Okay. Very good. Thanks for raising your hand. So, it’s gonna be behind. Well ... hold on one second. | |

In this excerpt, the idea that the ball will land behind the person was eventually elicited and became the main idea that Ryan addressed through discussion. After taking a poll of students’ responses (Table 4.12, Line 6), Ryan specifically asked the students who did not raise their hands—i.e., those who did not have the correct answer—for their ideas (*soliciting multiple responses*). This question elicited the idea from Student 2 that the ball will go straight up (i.e., maintain its horizontal position) while the plane and the person move forward (Line 4). Ryan clarified whether Student 2 thinks the ball "[will] land in front of you or behind you" and further asked the rest of class to indicate their agreement with "that idea behind" (*eliciting agreement/disagreement*).

As shown in these two excerpts, discourse moves allowed Ryan to get student ideas out in the open. For him and for other teachers with high engagement discussions, eliciting student ideas like this provided opportunities to engage and work with student ideas.

**Summary**

This chapter described ePCK and engagement with student ideas, as inferred from the five teachers' classroom discussions, and explored how ePCK was related to the teachers' engagement with student ideas. I identified a set of ePCK indicators—nine ways that teachers' responses to student ideas indicated presence of or gaps in ePCK—and found that ePCK indicators varied with the level of teachers' engagement with student ideas in classroom discussions. In classroom discussions rated as low engagement, teachers mainly *questioned to develop student ideas* and/or *elaborated student ideas* in order to deliver content. In addition, there were a few instances in which the teachers' responses to student ideas indicated gaps in ePCK (e.g., *reinforcing a misconception*, *dismissing a student idea*). In classroom discussions rated as moderate engagement, there was some evidence of ePCK indicators used in discussions with low engagement, but ePCK indicators of *foregrounding a common student idea* and/or *guiding student understanding* were more prevalent. In classroom discussions rated as high engagement, a range of ePCK indicators occurred in coordination with one another. The high levels of teacher engagement with student ideas also appeared to be supported by less content-specific teacher moves.

In this chapter, I characterized teachers' ePCK inferred from their classroom practices. In the next chapter, I characterize teachers' pPCK as reported by teachers in video-based interviews, through their explanations of video clips containing classroom discussion.

## Chapter 5. Findings II: Teachers’ pPCK Associated with ePCK

This chapter examines evidence of personal PCK (pPCK) from video-stimulated interviews in which teachers explained video clips of their classroom discussions. As described in Chapter 3, I examined evidence of pPCK as the teachers reasoned about both student ideas highlighted in the videos and instructional strategies to respond to those ideas. This method captured pPCK underlying teachers’ ePCK, since they watched a segment of their actual instruction (evidence of ePCK) and were asked to explain the segment using explicit knowledge of student ideas and instructional strategies (pPCK). I identified three levels of pPCK across the five teachers.

This chapter begins with information about the video clips that I used to analyze teachers’ pPCK from the video-stimulated interviews. Then, I describe the three levels of pPCK as exhibited in the teachers’ reasoning about classroom discussions shown in the videos.

### Video-Stimulated Interviews

As described in Chapter 3, I examined each video clip used in the interviews to determine whether it contained one (or more) of the classroom discussions that I had identified and used to analyze teachers’ ePCK (Table 4.1). An average of 8.2 (SD = 1.6) video clips per teacher contained classroom discussions (Table 5.1). For all teachers except Ryan, this represented approximately 60% of the video clips used in the interview. Across teachers, a total of 41 video clips were used to analyze teachers’ pPCK.

Table 5.1 Video Clips from the Video-Stimulated Post-Unit Interview Used for pPCK Analysis

| Teacher | Number of Video Clips Containing Classroom Discussions | Percentage of Video Clips Containing Classroom Discussions (%) |
|---|---|---|
| Charlie | 7 | 63.6 |
| Denise | 11 | 61.1 |
| Frank | 8 | 61.5 |
| Jason | 7 | 58.3 |
| Ryan | 8 | 42.1 |
| Total | 41 | - |
| M (SD) | 8.2 (1.6) | 57.3 (8.7) |

**Evidence of pPCK**

In order to find evidence of pPCK underlying ePCK, I analyzed how teachers articulated their knowledge of student ideas and instructional strategies when explaining their classroom discussions. Using the coding scheme described in Chapter 3 (Table 3.3.), I examined whether the teacher focused on explaining a student idea or instructional strategy (*focus of explanation*) and how the student idea or instructional strategy was explained/justified by the teacher (*nature & basis of explanation*).

The teachers demonstrated a range of pPCK in terms of 1) specificity and quality of their interpretations of student ideas and 2) connections between instructional strategies and student ideas. Based on these criteria, I identified three levels of pPCK (Table 5.2): weak (Charlie and Frank), intermediate (Ryan), and elaborate (Denise and Jason). In the following sections, I discuss each level of pPCK, describing how teachers interpreted student ideas and how they explained instructional strategies in terms of student ideas.

Table 5.2 Quality of Teacher's pPCK as Evidenced in Video-Stimulated Interviews

| Level | Teacher | Descriptions |
|---|---|---|
| Elaborated | Denise, Jason | • The teacher provided specific explanations of student ideas, often considering students' prior knowledge and experience.<br>• The teacher described instructional strategies with clear connections to student ideas. |
| Intermediate | Ryan | • The teacher recognized common student ideas and provided simple explanations.<br>• The teacher described instructional strategies with unclear connections to student ideas. |
| Weak | Charlie, Frank | • The teacher expressed little specific consideration of student ideas.<br>• The teacher exhibited weak content knowledge (found only in Frank's interview) |

**Weak pPCK: Charlie and Frank.** Evidence of weak pPCK was apparent in Charlie's and Frank's reasoning about classroom discussions during their video-stimulated interviews. This level of pPCK was exhibited in two ways: expressing little specific consideration of student ideas and demonstrating weak content knowledge.

***Expressing Little Specific Consideration of Student Ideas.*** Charlie and Frank explained their instructional decisions primarily in terms of physics content, with little specific consideration of student ideas. In their interviews, they tended to describe what they wanted students to get from the instruction (i.e., content knowledge) rather than how students might interact with that content (i.e., PCK). For example, Charlie explained his discussion of the block demonstration (Figure 4.1) in terms of content, seemingly at the expense of student understanding of the targeted content. The original purpose of the demonstration was to explain the concept of inertia: if Charlie hit the bottom block fast, the blocks above dropped down. However, as shown in Table 4.7, he also asked students to explain what happened when he pushed on the bottom block slowly and the blocks and water moved together. He discussed the decision to complicate the demonstration in his interview:

> **Excerpt 5.1** (Charlie-Interview-Clip2)
> I think it [friction]'s a force that they should be conscious of and aware of … And maybe we just touch on it a little bit, the idea that the force of friction is parallel to the surface of contact. So, in order for that demo to make sense, I think you have to mention that that there are forces between the blocks that are gunna get knocked out from underneath that … So, if you just push slowly on the bottom you can make everything move because you know the frictional force is applied to the blocks above and everything else that's up above it because you're not exceeding that maximum possible frictional force … I don't know if it helps them understand that last concept [inertia] or not … But to me, I feel like it's just a more complete description of what's going on to mention that there's friction involved in here.

While focusing on an accurate and complete portrayal of the phenomenon, he appeared to prioritize what made the most sense to him over what would best support students' understanding of inertia.

When reasoning about student ideas shown in the videos, Frank's and Charlie's interviews sometimes suggested a lack of awareness of student ideas. These two teachers often offered general or superficial interpretations of student ideas, such as "Those are fairly typical" (Frank-Interview-Clip1) and "To them, that's a challenging idea" (Charlie-Interview-Clip3), rather than providing specific interpretations. Frank's and Charlie's interviews sometimes indicated unfamiliarity with common student ideas about force and motion. This can be seen when Frank was directly asked about students' difficulty in understanding the concepts of unbalanced forces—the topic discussed in the classroom discussion represented in Table 4.6:

> **Excerpt 5.2** (Frank-Interview-Clip2)
> Interviewer: I was wondering if you sort of had the experience that students have trouble with the idea that forces cause changes in motion, as opposed to just motion itself?
> Frank: Um, yeah, because I think that that sometimes is the case ... (but) I would say that's one of the concepts that students, again, probably understand pretty well.

It is possible that Frank's students really do not experience the learning difficulty identified by the interviewer. However, its widespread prevalence, even among advanced physics students (e.g., Champagne, Klopfer, & J. H. Anderson, 1980; Gilbert & Watts, 1983; Halloun & Hestenes, 1985), along with instruction (such as in Table 4.6) that could reinforce such learning difficulty, suggests that at least some of his students did not have the full understanding that he assumed.

***Demonstrating Weak Content Knowledge*.** Frank was the only teacher who exhibited weak pPCK in this way. In his focus on physics content, in a few instances, Frank exhibited common misconceptions and described instruction that may reinforce those misconceptions. One such instance occurred during Frank's explanation for his use of a cart demonstration (Table 4.6):

> **Excerpt 5.3** (Frank-Interview-Clip2)
> There's a reason why it's squirting out left or right, there must be an unbalanced force in the direction that's making it move in that direction … I would say that's one of the concepts that students again probably understand pretty well. That if

the forces are on an object pushing are equal, then the object probably won't move whereas if they're unequal, they'll move proportional to the force itself.

Here, Frank made the incorrect statement that "they'll move proportional to the force itself" and explicitly said that students understand this incorrect statement pretty well. Seemingly constrained by own content knowledge, he did not recognize a common student misconception: that motion is proportional to unbalanced force. Instead, he treated the idea as something students should understand (i.e., as a correct description of the relationship between force and motion).

**Intermediate pPCK: Ryan.** Ryan's video-stimulated interviews illustrate the intermediate level of pPCK, which is characterized by isolated expressions of knowledge about common student ideas and instructional strategies to address those ideas.

***Knowledge of Student Ideas.*** Ryan often recognized common student ideas about force and motion and provided simple explanations of student ideas. This could be seen, for example, when Ryan explained his classroom discussion of hitting a golf ball with a golf club. In the discussion (Table 4.9), students expressed the idea that the force from the golf club is still acting on the ball while it is in the air (impetus conception). In the interview, Ryan explained why students might have the impetus idea:

**Excerpt 5.4** (Ryan-Interview-Clip 4)
Because they go "Well, it is moving, so something has got to make it move in that direction" … I think that is the idea. If something is moving, how it is moving, constant speed or not, a force has to be making it move in that direction.

Ryan recognized that students often associate force with motion (rather than <u>change</u> in motion) and explained that this relates to why students have the impetus idea (moving objects carry a force along with them).

***Knowledge about Instructional Strategies.*** Ryan sometimes attempted to explain how he responds to a student idea, but the connections between his instruction and the student idea were not always clear. Although he provided examples of instructional strategies commonly used in physics classes, Ryan did not necessarily articulate how his instruction would address a student learning difficulty or support students' understanding. For example, he explained how he responds to the impetus conception (moving objects carrying forces): "Newton's First Law [of Motion]. Once you let go continues what it's doing. So, I think that's something that I try to stress more so right there at that point (Ryan-Interview-Clip3). Although Newton's First Law is a common and adequate way to show that objects do not need a force to "continue what it's doing," it was not articulated enough how Ryan used this instruction to address the impetus conception.

**Elaborated pPCK: Denise and Jason.** Denise and Jason displayed elaborated pPCK in their reasoning throughout the interviews. This level of pPCK was characterized by deep insight into student ideas and tight connections between student ideas and instructional strategies.

***Knowledge of Student Ideas.*** Denise and Jason demonstrated rich knowledge of student ideas during their video-stimulated interviews. They recognized many force and motion concepts that were difficult for students, often providing nuanced considerations of why these concepts might be challenging. They attempted to understand what students think and why, providing specific, insightful interpretations. For example, Jason explained why students might hold the impetus conception as follow:

**Excerpt 5.5** (Jason-Interview-Clip3)
In the real world, when we look at it, if something's moving, a lot of times, if we're going to keep it moving, we got [to] put force on it because of friction. So, kids have a hard time like ignoring the fact that friction really exists. So, when you talk about things like, "Well hey, if it wasn't for friction, then this would," they don't quite get that. Everything in their real world concept is, "Well, if I want it to go, I've got to push it. So, if there's an unbalanced force, then it moves," instead of "It could already be moving and we could just be changing it."

Jason attempted to explain student ideas by considering students' everyday experience. He identified the difficulty of ignoring friction (due to its existence in real word) and explained how students' experience in a friction-filled world is related to the impetus idea.

Another example occurred when Denise explained a classroom discussion of forces acting on a puck sitting on a table. In the classroom discussion, multiple students expressed the idea that "the table's just in the way," not recognizing the (normal) force from the table:

**Excerpt 5.6** (Denise-Class01-D1)

Denise: I have a puck … and I'm going to sit it here. And I want you to tell me what forces are acting on it right now.
Class: Gravity.
Denise: Okay.
Student: That's it.
(a few seconds later)
Student 2: What about the table force? The force of that table.
Student: I think the table's just in the way.
(A few seconds later)
Student: The table has its own- exerting?

Student: The table has its own force?

(A few minutes later)

Denise: Let me ask you this, guys. Let me ask you this … [Student 3], if you were running down the hallway and forgot to make a turn and ran into a wall … You put a force on that wall, didn't you? Did that wall put a force on you?

Student 3: I'd say yes.

In the video-stimulated interview, Denise explained the students' idea as follows:

**Excerpt 5.7** (Denise-Interview-Clip2)
They're confused about that because they sit in their desks all day, they walk around on stairs all day, they don't realize that anything is pushing up on them to keep them where they are … They would think of it as pushing you up? They don't think of that because they don't think of themselves as exerting a force either. I don't think … They think about forces happening when they push on something or when they pull on something those are things that they can exert.

Like Jason, Denise provided an explanation of the student idea, considering students' everyday experience and typical conceptions of "force."

***Knowledge of Instructional Strategies***. Denise and Jason provided specific examples of instructional strategies with clear connections to student ideas. In particular, the teachers described how their instruction could support students' understanding, articulating students' prior knowledge and experience or specific aspects of student ideas that the instruction would build on. One such example occurred in Ryan's interview as he explained his use of outer space scenarios. He viewed these friction-free scenarios as helping students understand Newton's First Law: an object that is in motion stays in its motion unless acted upon by an outside force.

**Excerpt 5.8** (Jason-Interview-Clip4)
I think kids have gotten it driven into them that space is a vacuum. And they kind of get the air resistance thing because we've usually done some examples where we talk about

air resistance and friction … So, when we start talking about space, they really do believe that there's not air in space, luckily. And so they can get that idea that that's the one place that there's nothing really slowing it down. So, we can translate that to their understanding of friction-free.

In the excerpt, Jason explained his use of space scenarios by considering students' prior knowledge and instructional experiences: students understand space as "a vacuum" and have learned about "air resistance and friction." Building on those aspects of student ideas, Ryan explained that space scenarios could serve as friction-free scenarios to support students' understanding of Newton's First Law.

Denise's explanation of the discussion involving the idea that "the table's just in the way" (See Excerpt 5.6 above) provides another example of knowledge of instructional strategies:

**Excerpt 5.9** (Denise-Interview-Clip2)
I think that them saying being in the way is their idea of a force. And I don't think that's necessarily wrong thinking on their way. They just have to start thinking of well if it's in the way, what is it doing to you? If you are running down the hallway and someone gets in your way, they're going to exert a force on you. So, I don't think that that's necessarily incorrect thinking. They just have to start thinking of how the vocabulary would match what they're saying.

Denise identified correspondence between the students' idea of "being in the way" and the scientific concept of force. She described an example of "running down the hallway"—the one used in her classroom discussion (See Excerpt 5.6)—as a means of building on the promising aspect of students' idea to advance their understanding of the normal force.

**Summary**

In this chapter, I describe pPCK as explicit knowledge of student ideas and instructional strategies expressed in teachers' explanations of their classroom discussions. Three groups of teachers were identified according to levels of pPCK. Charlie and Frank demonstrated weak pPCK. They explained their instruction mainly in terms of physics content, without clearly considering student ideas, and sometimes seemed to display gaps in knowledge of student ideas. Ryan exhibited intermediate pPCK. He provided some simple explanations of student ideas and explained his instruction with unclear connections to student ideas. Denise and Jason demonstrated elaborated pPCK. They attempted to make sense of what students think and to explain why, considering the everyday experiences that might contribute to students' ideas. Denise and Jason also explained their instructional decisions with clear connections to student ideas.

In Chapters 4 and 5, I have characterized teachers' ePCK and pPCK, respectively; however, the question remains as to how ePCK (exhibited in classroom discussions) relates to the pPCK that teachers articulated in their interviews. In the next chapter, I consider the relationship between ePCK and pPCK.

# Chapter 6. Findings III: Relationship Between ePCK and pPCK

This chapter explores how ePCK is related to pPCK in classroom discussions. As described in Chapter 3, I compared ePCK, as evidenced by teachers' classroom discussions, to pPCK, as evidenced by teachers' explanations of those discussions in video-stimulated interviews. From the analysis, I was able to identify three potential relationships between ePCK and pPCK in classroom discussions; two of the relationships were further divided into sub relationships. Across the five teachers, there were different patterns in the frequency of clips exhibiting each type of primary relationship and sub-relationship.

I begin the chapter by describing the three relationships between ePCK and pPCK as exhibited in the teachers' classroom discussions. I describe primary relationships and sub-relationships and provide information about the frequency of each. Next, I discuss each relationship, describing how the relationship (and sub-relationship) appeared in teachers' classroom discussions.

## Three Relationships Between ePCK and pPCK

As shown in Table 6.1, the analysis revealed three potential relationships between ePCK and pPCK in classroom discussions: 1) congruence between ePCK and pPCK; 2) incongruence between ePCK and pPCK; and 3) through reflection, generation of pPCK that is then available to inform ePCK in future classroom discussions. For each teacher, I assigned one (or no[7]) relationship for each video clip used in the video-stimulated interviews; I also assigned one sub

[7] There were a couple of reasons that not all video clips were categorized using one of the relationships identified in this analysis. First, some video clips elicited pPCK related to planned aspects of instruction (e.g., "Why did you choose to do the investigation using rubber bands?"), rather than interactive aspects of instruction and, thus, did not relate to ePCK as evidenced in the teacher's in-the-moment response to student idea(s). Second, some video clips did not have enough evidence of pPCK and/or ePCK for comparison. This occurred when teachers responded to a video clip in a brief and superficial way.

relationship for each video clip classified as Relationship 1 or 2. I then tallied the frequency (i.e., number of video clips) assigned to each relationship (and sub-relationship). These frequencies are shown in Table 6.2.

Table 6.1 Relationships Between ePCK and pPCK

| Relationships | Description | Sub-relationships |
|---|---|---|
| Relationship 1 | Congruence between ePCK and pPCK | 1.1 Consistent Evidence of Both ePCK and pPCK |
| | | 1.2 Apparent Gaps in Both ePCK and pPCK |
| Relationship 2 | Incongruence between ePCK and pPCK | 2.1 Evidence of ePCK Not as Sophisticated as Suggested by Evidence of pPCK |
| | | 2.2 Evidence of ePCK without Corresponding Evidence of pPCK |
| Relationship 3 | Reflection and generation of pPCK | - |

Table 6.2 Number and Percentage of Video Clips Demonstrating Relationships Between ePCK and pPCK

| Teacher | Clips Classified for Each Relationship | | | | | | | Clips Not Classified | Total Number of Clips |
|---|---|---|---|---|---|---|---|---|---|
| | Relationship 1 | | | Relationship 2 | | | Relationship 3 | | |
| | 1.1 | 1.2 | Total | 2.1 | 2.2 | Total | | | |
| Charlie | 3 (43 %) | 1 (14 %) | 4 (57 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 3 (43 %) | 7 (100 %) |
| Denise | 6 (55 %) | 0 (0 %) | 6 (55 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 3 (27 %) | 2 (18 %) | 11 (100 %) |
| Frank | 2 (25 %) | 2 (25 %) | 4 (50 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 0 (0 %) | 4 (50 %) | 8 (100 %) |
| Jason | 3 (43 %) | 0 (0 %) | 3 (43 %) | 3 (43 %) | 0 (0 %) | 3 (43 %) | 0 (0 %) | 1 (14 %) | 7 (100 %) |
| Ryan | 2 (25 %) | 1 (13 %) | 3 (38 %) | 0 (0 %) | 2 (25 %) | 2 (25 %) | 2 (25 %) | 1 (13 %) | 8 (100 %) |
| Total | 16 (39 %) | 4 (10 %) | 20 (49 %) | 3 (7 %) | 2 (5 %) | 5 (12 %) | 5 (12 %) | 11 (27 %) | 41 (100 %) |

As shown in Table 6.2, congruence between ePCK and pPCK (Relationship 1) was more common than incongruence between ePCK and pPCK (Relationship 2). Reflection and generation of pPCK (Relationship 3) was similarly infrequent. In the following sections, I elaborate on each of these relationships.

**Relationship 1: Congruence Between ePCK and pPCK.** In most cases, teachers' ePCK as evident in classroom discussions resembled their pPCK articulated in video-stimulated interviews. Teachers' in-the-moment responses to student ideas (ePCK) appeared to be influenced by teachers' existing knowledge of common student ideas and instructional strategies to address those ideas (pPCK). As shown in Table 6.2, 49 % of the analyzed video clips (across teachers) demonstrated congruence between ePCK and pPCK. Below, I describe two ways that this occurred.

***Sub-Relationship 1.1: Consistent Evidence of Both ePCK and pPCK.*** Teachers whose classroom discussions included evidence of ePCK often described an existing repertoire of knowledge about student ideas on the topic of the discussion and instructional strategies to address those ideas (pPCK) in video-stimulated interviews. As shown in Table 6.3, across teachers, this consistency between ePCK and pPCK was demonstrated in 80% of the video clips with evidence of congruence between ePCK and pPCK. This represents 39% of the total number of video clips analyzed (See Table 6.2).

Table 6.3 Number and Percentage of Video Clips Demonstrating Relationship 1

| Teacher | Sub-Relationship 1.1 | Sub-Relationship 1.2 | Total |
|---|---|---|---|
| Charlie | 3 (75 %) | 1 (25 %) | 4 (100 %) |
| Denise | 6 (100 %) | 0 (0 %) | 6 (100 %) |
| Frank | 2 (50 %) | 2 (50 %) | 4 (100 %) |
| Jason | 3 (100 %) | 0 (0 %) | 3 (100 %) |
| Ryan | 2 (67 %) | 1 (33 %) | 3 (100 %) |
| Total | 16 (80 %) | 4 (20 %) | 20 (100 %) |

Charlie demonstrated this sort of consistency with respect to his classroom discussion of kicking a football as an example of Newton's Third Law (Table 4.8). As described in Chapter 4, Charlie *foregrounded a common idea* about forces exerted by heavy and light objects and used a set of equations (Figure 4.2) to *guide student understanding* of how heavy and a light object move with the same applied force. In the video-stimulated interview, Charlie explained his use of the equations as follows:

**Excerpt 6.1** (Charlie-Interview-Clip10)
Charlie: I almost always do that [use of the equations] … because again "if the forces are equal then why does anything happen?" that's sort of the next question that students ask so I always do that … I would think that there would still be a couple kids in there that would say "Oh, your foot exerts a bigger force on the ball than the ball does on your foot because the ball is the thing that moves there must be a greater force acting on it … That sort of semi-quantitative cartoon assessment of acceleration and mass, I mean it's right out of Hewitt [a common textbook]. He does that same kind of thing when he's showing those comparisons. He uses a little "a" for the little acceleration and big "m" [for the big mass]. I'm just again swiping that from him.

Charlie demonstrated awareness of the common student idea that he had *foregrounded* in the classroom discussion, not only recognizing that it occurs frequently but also expressing a sense for why students might hold this idea. In addition, he displayed existing knowledge of an instructional strategy, the "semi-quantitative" equation, that he had used to *guide student understanding*.

Another example occurred during Denise's classroom discussion of forces acting on a puck sitting on a table (Excerpt 5.6). During the discussion, multiple students expressed the common idea that "the table's just in the way," and Denise responded by providing an example of "running into a wall" to *guide student understanding* of the normal force. When explaining this classroom discussion in the video-stimulated interview (Excerpts 5.7 and 5.9), Denise demonstrated existing knowledge of the student idea (pPCK) that she had responded to in the classroom discussion (ePCK). She explained why students often hold the idea of "being in the way" and identified a correspondence between the student idea and the scientific concept of force. Denise also indicated that her existing repertoire of instructional strategies included the "running down the hallway" example that she had used to *guide student understanding,* and she connected this instructional strategy to her interpretation of the promising nature of the student idea.

***Sub-Relationship 1.2: Apparent Gaps in Both ePCK and pPCK.*** Teachers whose classroom discussions suggested gaps in ePCK sometimes exhibited corresponding gaps in pPCK in the video-stimulated interviews. This suggests that unfamiliarity with common student ideas and common student expressions of conceptual understanding (pPCK) may constrain teachers' in-the-moment responses to student ideas (ePCK). As shown in Table 6.3, across teachers, this consistency between ePCK and pPCK was demonstrated in 20% of the video clips with evidence of congruence between ePCK and pPCK. This represents 10 % of the total number of video clips analyzed (see Table 6.2). This type of consistency was found in 14 % of Charlie's video clips, 25 % of Frank's video clips, and 13 % of Ryan's video clips; it was not observed for any of Denise's or Jason's video clips (see Table 6.2). As shown in Table 6.3, such gaps in both ePCK and pPCK (Relationship 1.2) were as frequent for Frank as was consistent evidence of both ePCK and pPCK (Relationship 1.1).

As seen in Table 4.2, two indicators suggest gaps in ePCK: *reinforcing a misconception* and *dismissing a student idea*. In my analysis, both appeared related to pPCK. First, teachers who had *reinforced a misconception* in classroom discussions appeared to hold—or at least not to recognize the problem with—the common misconception that their instruction may have reinforced. One example can be seen in Frank's classroom discussion of unbalanced forces (Table 4.6), in which Frank's treatment of the content could inadvertently *reinforce the common misconception*. When explaining this classroom discussion in the video-stimulated interview (Excerpt 5.3), he did not recognize the problem with the common misconception that his instruction might have *reinforced*.

Second, teachers who had *dismissed a common student idea* in classroom discussions seemed, in their interviews, to be unaware of ways students might express their understanding of the target concept, including the way the idea was expressed in the classroom discussion. For example, Charlie *dismissed a common student idea* as incorrect in his discussion of the wooden block demonstration (Table 4.7). When explaining the classroom discussion in his video-stimulated interview (Excerpt 5.1), Charlie mostly focused on correctly describing the content of demonstration, without considering how students might think about it—i.e., he did not consider the idea that he had *dismissed* in the classroom discussion.

**Relationship 2: Incongruence Between ePCK and pPCK.** Sometimes teachers' ePCK as evident in classroom discussions did not necessarily match their pPCK articulated in video-stimulated interviews. As shown in Table 6.2, 12 % of the analyzed video clips (across teachers) demonstrated this incongruence between ePCK and pPCK (Relationship 2). This relationship was only exhibited in Jason's and Ryan's video clips (see Table 6.4). For Jason, this was exhibited as Relationship 2.1, while for Ryan, this was exhibited as Relationship 2.2. In the following, I illustrate how the two types of incongruence occurred.

Table 6.4 Number and Percentage of Video Clips Demonstrating Relationship 2

| Teacher | Sub-Relationship 2.1 | Sub-Relationship 2.2 | Total |
|---|---|---|---|
| Charlie | 0<br>(0 %) | 0<br>(0 %) | 0<br>(0 %) |
| Denise | 0<br>(0 %) | 0<br>(0 %) | 0<br>(0 %) |
| Frank | 0<br>(0 %) | 0<br>(0 %) | 0<br>(0 %) |
| Jason | 3<br>(100 %) | 0<br>(0 %) | 3<br>(100 %) |
| Ryan | 0<br>(0 %) | 2<br>(100 %) | 2<br>(100 %) |
| Total | 3<br>(60 %) | 2<br>(40 %) | 5<br>(100 %) |

***Sub-Relationship 2.1: Evidence of ePCK Not as Sophisticated as Suggested by Evidence of pPCK.*** Jason sometimes demonstrated elaborated pPCK that was not apparent as ePCK in his classroom discussions. In these cases, pPCK did not appear to have been fully translated into classroom practice (as ePCK). Given the wide range of factors, both internal and external, affecting a teacher's instruction (Fang, 1996; Kennedy, 2010; Nespor, 1987), it is perhaps not surprising that classroom discussions (ePCK) might be impacted by more than just the teacher's existing knowledge (pPCK). As shown in Table 6.2, this relationship was exhibited in 43% of Jason's video clips (exactly half of those that were categorized in terms of a relationship between ePCK and pPCK); this relationship appeared as frequently as Relationship 1.1 (consistent evidence of both ePCK and pPCK).

As described in Chapter 5, Jason exhibited elaborated understanding of student ideas and instructional strategies to address those ideas (pPCK). This knowledge, however, was not always reflected as ePCK in his classroom discussions, such as one about the forces acting on a tennis ball thrown in the air (Table 6.5).

Table 6.5 Transcript Excerpt from Jason's Classroom Discussion (Class1-D4)

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Jason: There used to be a classic question that they used to say that "Hey, well if this law [Newton's First Law] is so true, when you shoot a cannonball, why does it keep going? You need something to keep it moving, right?" So, what people used to do was to justify it. So, they used to say actually the cannon would fire it out and then when it was going through the air, the air would squeeze it … And that's what (they thought) made the cannonball keep going. | *Foregrounding a common idea* |
| | (A few seconds later. Jason brings out a tennis ball) | |
| 2 | Jason: When I let that tennis ball go if I threw it to the back of the room, "whooh," as hard as I could, right. All right. Okay. I threw it as hard as I could, alright. Once it leaves my hand, is anything making it go forward anymore? | *(Continued: Foregrounding a common idea)* |
| 3 | Student: No. | |
| 4 | Student 2: No, just the nothing. | |

Table 6.5 (cont'd)

| | | |
|---|---|---|
| 5 | Jason: Just the nothing. Alright. I put a force on it when I threw it, but as soon as it left my hand and it was in the air, the only thing there is air resistance slowing it down. Okay. There's nothing that's actually making it go forward anymore … If air wasn't around, it would keep going. | *Elaborating student response* |

Jason *foregrounded* the impetus conception by explaining that people often think that moving objects require something to keep moving (Line 1) and directly asking students about whether there is a force acting on the tennis ball to make it move (Line 2). While the impetus concept is extremely common, the students who responded gave the correct answer (Lines 3 and 4), and Jason *elaborated* these responses to highlight that no forces are acting on the ball to make it move. In the video-stimulated interview, Jason described his classroom discussion as follows:

> **Excerpt 6.2** (Jason-Interview-Clip5)
> [Students], in their real world, they think that everything has to keep pushing it along, so we kind of talk about the fact that there doesn't have to be something pushing the ball once it goes in the air … I think a lot of it is that whole idea that they think it's going forward with some kind of energy and they equate that to force. So, if they think, like "Well, it's going to hit, if the ball hit me, it would hurt, so it must have some force behind it" whereas, there we've got to link back to momentum and energy and all those kinds of concepts … At that point I could link back to momentum, that you know, if you get hit with the ball, it hurts, because it does have momentum. It's got to transfer that somewhere. It's got to go somewhere. It's got to cause a change to you somehow. So, you could link it back to that idea.

Jason offered deep insight into the impetus conception and instructional strategies to address this idea (pPCK), which was not fully apparent as ePCK in classroom discussion. In the interview, he identified a correspondence between students' impetus conception and scientific concepts of energy and momentum, explaining how he could tailor instruction to the nature of student ideas by "link[ing] back to momentum and energy." In his classroom discussion, Jason did not help students to see their ideas as connected to energy and momentum. Instead, while he seemed to target the impetus conception in his classroom discussion, Jason did not fully demonstrate understanding of why students might hold that idea or treat the impetus as a "stepping stone" (Duncan & Rivet, 2013; Foster & Wiser, 2012; Wiser, Smith, & Doubler, 2012) to canonical understandings.

***Sub-Relationship 2.2: Evidence of ePCK without Corresponding Evidence of pPCK.*** Ryan's classroom discussions appeared to indicate ePCK that was not necessarily articulated as pPCK in the video-stimulated interviews. As shown in Table 6.2, this relationship was exhibited in 25% of Ryan's video clips. For example, in Ryan's classroom discussion of whether a golf club still affects a golf ball while the ball is in the air (Table 4.9), Ryan *challenged his students' correct answer* by posing a question (Line 13) that elicited the impetus conception. In the video-stimulated interview, Ryan explained his question as follows:

> **Excerpt 6.3** (Ryan-Interview-Clip4)
> More hands just went up when I just asked it. I guess I am not sure why that would be … I wonder if the way I asked it maybe gave kids some reassurance that "Well, that makes sense, but then yeah, of course it is still acting on it." I am not sure. The way, maybe the tone was of the question, maybe had kids more kind of wishy washy. Pushed them to the one side.

Ryan explained his question (which I had regarded as evidence of the ePCK indicator *challenging student idea*) without a clear connection to the impetus concept. Although I had interpreted his question as specifically designed to target the impetus conception, Ryan appeared to have difficulty explaining why students changed their initial responses; his explanation of this classroom discussion in the interview lacked evidence of pPCK regarding the impetus concept.

**Relationship 3: pPCK Generated with Potential to Inform Future ePCK.** Teachers' reflections on their own classroom discussions appeared to generate pPCK that might inform future ePCK. During the video-stimulated interviews, teachers mostly articulated existing knowledge of student ideas and instructional strategies (pPCK) that appeared to have been the basis for the ePCK used in classroom discussions. In some instances, however, videos of classroom discussions prompted teachers to reflect on their response(s) to a student idea, offering new insights about the student idea(s) and alternative instructional response(s). In the future, teachers may draw on this understanding of student ideas and instructional strategies (pPCK) to respond to similar situations in a different way (ePCK). As shown in Table 6.2, this type of reflection was found in 27 % of Denise's video clips and 25 % of Ryan's video clips; none of the other teachers exhibited this type of reflection. Below, I focus on Denise to illustrate how pPCK was generated through reflection.

While watching videos of her classroom discussions during the interview, Denise appeared to engage in in-depth analysis of student ideas and sometimes recognized aspects of student ideas that she had not noticed during her teaching. A potential explanation for the frequency with which Denise noticed new aspects of student ideas after instruction could be the nature of discussions in her classroom. Often, many students spoke at the same time, which could have made it difficult for Denise to hear all of the ideas being expressed. However, Denise made new observations even about the student ideas that she had responded to in classroom discussions, considering the ideas from a different perspective and rethinking her responses. One example of this occurred when Denise watched a video of her classroom discussion of a hockey puck being pushed on a frozen ocean. An excerpt of this discussion is shown in Table 6.6.

Table 6.6 Transcript Excerpt from Denise's Classroom Discussion (Class01-D3)

| | Transcript Lines | ePCK |
|---|---|---|
| 1 | Denise: If you were the person on the puck on the [frozen] ocean and it's frictionless and I pushed you, and you would just keep going and going forever, right? Just like in space. | |
| | (A few seconds later) | |
| 2 | Student 2: What about um, so, it, it wouldn't stop. | |
| 3 | Denise: Ever. | |
| 4 | Student 2: Why wouldn't gravity be able to like pull it down onto the ice? Wouldn't gravity, would slow it down, at all? | |
| 5 | Denise: No, 'cause gravity is just pulling it down so that it doesn't go up. Gravity prevents it from going this way [pointing up]. What would slow it down is something that would prevent it? [Rubbing hands side to side] What is this? | *Guiding student understanding* |
| 6 | Class: Friction. | |
| 7 | Denise: Friction. But if it's frictionless, there is none of that. You guys see that? | (Continued: *Guiding student understanding*) |

In the excerpt, a student expressed the common idea that gravity slows an object moving horizontally. (This is similar to the student idea as expressed in Charlie's classroom discussion—see Table 4.7). Denise responded by *guiding students to the idea* that gravity (a force acting vertically) cannot slow down the puck that is moving horizontally; friction slows it down. After watching the video of this classroom discussion, Denise reflected on her response to the student's idea as follows:

**Excerpt 6.4** (Denise-Interview-Clip6)

Oh, I did a bad job of answering his question … I answered it in a very like "Well duh, gravity is acting down." … Gravity does influence friction in which then it does influence the normal force and he's thinking like if you pull hard enough down something's not gunna move which is true. And I just said "Well it's gravity" because I was trying to concentrate more on these forces acting in and what directions they're acting on. But I totally glossed over his question from watching this … They're thinking that heavier things are harder to get moving and that totally aids in your discussion about friction and why friction works the way it does … Gravity slows things down in the way that it's related to the other forces not by itself … I'm like "How can [gravity slow things down] because it's acting up and down?", but to them gravity means mass and I can see that now … When he asked that question, [I] thought "Duh, why aren't you seeing this?"

While watching the video of classroom discussion, Denise recognized a new aspect of the student's idea that she had "glossed over" during her teaching: a potential connection to the concept of friction. Denise identified that the student' idea of gravity is actually related to friction because gravity is related to normal force that is one of the factors in friction. In the future, Denise may draw on this understanding of the student idea (pPCK) to respond differently (ePCK).

**Summary**

This chapter described how ePCK appeared to be related to pPCK. I found three potential relationships between ePCK and pPCK. First, in most cases, ePCK resembled pPCK. In these cases, teachers who displayed evidence of ePCK in classroom discussions demonstrated pre-existing knowledge about common student ideas and instructional strategies to address those ideas (pPCK). In contrast, teachers with gaps in ePCK appeared, in the interviews, to be unfamiliar with common student ideas and expressions of conceptual understanding (pPCK). Second, sometimes ePCK did not necessarily match ePCK. Sometimes teachers articulated sophisticated understanding of common student ideas and instructional strategies to address those ideas (pPCK) that was not apparent as ePCK in classroom discussions. In addition, occasionally ePCK indicators in classroom discussions were not reflected in pPCK as articulated in the video-stimulated interviews. Third, teachers' reflections on their own classroom discussions sometimes appeared to generate pPCK that might then be available to inform future ePCK. On these occasions, teachers noticed a new aspect of a student idea and/or reconsidered how they had responded during the classroom discussion. Their understanding of student ideas and instructional strategies (pPCK), developed through reflection in video-based interviews, may inform teachers' ePCK when they respond to similar student ideas in their future classrooms.

The three previous chapters described five physics teachers' ePCK, pPCK, and relationships between ePCK and pPCK and between ePCK and teachers' engagement with student ideas. These findings present my efforts to explore the relationship between PCK and teachers' responsiveness to student ideas in classroom interactions, and more broadly, the relationship between PCK and teaching practice. In the final chapter, I will discuss limitations and contributions of my study.

# Chapter 7. Discussion

This study aimed to understand the aspects of PCK that contribute to teachers' responsiveness to student ideas in classroom discussions and, more broadly, the relationship between PCK and practice. In particular, I examined ePCK, pPCK, and the relationships between ePCK and associated pPCK and between ePCK and teachers' engagement with student ideas. In Chapter 4, I identified a set of ePCK indicators from teachers' responses to student ideas in classroom discussions and illustrated how these indicators played out differently as teachers engaged with student ideas at low, moderate, and high levels. In Chapter 5, I examined teachers' pPCK, as evident in reasoning about their classroom discussions during post-unit video-stimulated interviews, and identified three levels of pPCK. In Chapter 6, I explored how ePCK appears to be related to pPCK, identifying three potential relationships between ePCK and pPCK in classroom discussions.

This concluding chapter starts with consideration of how the findings contribute to the literature. In particular, I discuss three areas of literature that this study contributes to: 1) research on the relationship between PCK and teachers' responsiveness, 2) the constructs of ePCK and pPCK, and 3) support for teachers' engagement with student ideas in classroom discussions. Then, I discuss implications of this study for teacher education. I close this chapter with a discussion of the limitations of this study and directions for future research.

## Capturing Aspects of PCK Contributing to Teachers' Responsiveness

This study provides preliminary evidence about the aspects of PCK that might contribute to teachers' responsiveness to student ideas. In this study, I identified a set of nine ePCK indicators from teachers' responses to student ideas in classroom discussions (Table 4.2). In contrast to previous studies that capture PCK at a distance from the event of teaching, as measured through paper-pencil assessment (e.g., Hill, Rowan, & Ball, 2005; Baumert et al., 2010; Jüttner & Neuhaus, 2010; Schmelzing et al., 2013; Ergönenç, Neumann, & Fischer, 2014; Kirschner, Borowski, Fischer, Gess-Newsome, & Aufschnaiter, 2016; Park, Suh, & Seo, 2018), this study captured the aspects of PCK that are directly used in practice (*dynamic* PCK; Alonzo & Kim, 2016). As shown in Table 4.2, seven of the nine ePCK indicators resonate with those identified by other researchers as either responsive discourse moves or (positive/negative) evidence of PCK reflected in classroom interactions. In addition to indicators already reflected in the literature, my study identified two additional ePCK indicators: *foregrounding common student ideas* and *guiding student understanding*. In this study, when teachers *foregrounded common student ideas* and *guided student understanding,* they appeared to engage in interactive formative assessment practices (Cowie & Bell, 1999; Furtak, 2006; Shavelson et al., 2008). These instances provide additional evidence of the role of PCK in formative assessment (Bennett, 2011; Black, Harrison, Lee, Marshall, & Wiliam, 2004; Falk, 2012; Heritage, 2007; Heritage, Kim, Vendlinski, & Herman, 2009).

### Constructs of ePCK and pPCK

This study provides one of the first attempts to apply the constructs of ePCK and pPCK in empirical research. In the following, I describe challenges and affordances of using these constructs to explore the relationship between PCK and teaching practice.

**Challenges.** This study presents two methodological challenges to be considered when capturing ePCK and pPCK. First, inference of ePCK involves uncertainty. In this study, I inferred ePCK from teachers' in-the-moment responses to student ideas, assuming that knowledge of student ideas and of instructional strategies to address those ideas were likely to be involved. This was an attempt to capture ePCK, which exists only in action as tacit knowledge (Alonzo, Berry, & Nilsson, 2019). Compared to other parts of instruction, such as lecturing, where inferences about use of knowledge of student ideas are less clear, the focus on discussions, as interactive parts of instruction, appeared to permit ePCK inferences. However, inferring knowledge from teachers' behavior still involves uncertainty and is subject to attribution error (Kennedy, 2010). Teachers' ePCK is manifested in teachers' behaviors, but the ePCK itself is never visible to researchers (Alonzo et al., 2019), nor are many of internal and external factors that influence teachers' behaviors. Since teachers' intentions are not accessible during classroom observations, I could not accurately distinguish instructional moves that were informed by ePCK from those that were not. It is possible that some instructional moves I did not regard as ePCK should have been considered as such. Conversely, I could have assumed ePCK was involved when it was not. Thus, where teachers' pPCK articulated in the interviews did not seem to match ePCK in classroom discussions, this could be because I failed to accurately identify ePCK in the classroom discussions.

Second, pPCK elicited with video-based interviews may not fully capture pPCK that provided the basis for ePCK. In this study, video-based interviews were used to capture pPCK that provided the basis for ePCK. Video clips serve as a memory aid, helping teachers to revisit particular instructional events with rich information about the context and to recollect the knowledge and reasoning that they were drawing upon to make instructional decisions (Calderhead, 1981; Yinger, 1986). However, interviews are still conducted after teachers finish teaching, and the time gap between teaching and the interview limits the extent to which teachers provide accurate recollections of their in-the-moment reasoning about classroom events

(Ericsson & Simon, 1984; Kagan, 1990). Even when interviews are conducted very shortly after teaching, teachers cannot accurately represent what they were thinking in the moment of teaching and, thus, they may be recreating, rather than recalling, their reasoning (Ericsson & Simon, 1984). In this study, the video-stimulated interviews were conducted about six weeks after teachers finished teaching the unit of force and motion. Although the interviews appeared to capture a range of teachers' knowledge about student ideas and instructional strategies, teachers' reasoning elicited during the interview might have been different from the actual reasoning that happened in the moment of instruction. Where pPCK articulated in the interviews did not seem to correspond to the ePCK inferred from classroom discussions, it could be because the teachers were articulating different pPCK from what they actually drew upon in-the-moment of instruction. In addition, the nature of pPCK itself impacted what could be captured in this study. pPCK includes both articulable and tacit forms of knowledge (Alonzo et al., 2019). Some aspects of teachers' knowledge cannot be expressed verbally since teachers' knowledge is strongly tied to action (Kind, 2009; Baxter & Lederman, 1999). Tacit aspects of teachers' pPCK cannot be fully articulable even in a video-stimulated interview. Thus, for teachers like Ryan whose ePCK seemed more sophisticated than the pPCK he articulated in the interview, it is possible that some of the pPCK that provided the basis for ePCK in classroom discussions may have not been fully articulated/articulable.

**Affordances.** Despite these limitations in capturing ePCK and pPCK, the constructs of ePCK and pPCK allowed me to see detailed linkages between PCK and practice. For a given classroom discussion, these constructs helped to not only focus on aspects of teaching practice that are informed by PCK (i.e., knowledge of student ideas about a topic and knowledge of instructional strategies to respond to those ideas), but also identify the aspects of the teacher's stored knowledge (pPCK) that actually get translated into practice.

As part of this exploration of the relationship between PCK and practice, this study also tests conceptualizations of the relationship between ePCK and pPCK described in RCM. In this study, I explored the relationship between ePCK and pPCK in the context of classroom discussions. I found that teachers' responses to student ideas in classroom discussions (ePCK) appeared to depend on teachers' existing knowledge about student ideas and instructional strategies (pPCK), but pPCK did not fully prescribe ePCK used in classroom discussions. These findings confirm the relationships among ePCK and pPCK described in the RCM (Carlson & Daehler, 2019). According to RCM, a teacher's pPCK provides the basis for the teacher's ePCK, serving as an available pool of knowledge for the teacher to draw on, but at the same time, we would not expect ePCK and pPCK to be congruent because ePCK is constantly changing and renewed every moment—even for the same topic—because each situation is unique to particular student, particular context, and particular time (Alonzo et al., 2019).

### Supporting Teachers' Engagement with Student Ideas

This study can contribute to our knowledge of the competencies that contribute to teachers' engagement with student ideas in classroom discussions. First, the findings point to the importance of teachers' pPCK. In this study, knowledge of student ideas and instructional strategies (pPCK) provided a foundation for teachers' in-the-moment responses to student ideas (ePCK) that, in turn, supported their engagement with student ideas during classroom discussions. In contrast, weak pPCK appeared to limit teachers' ePCK and, consequently, teachers' engagement with student ideas. In particular, unfamiliarity with common student ideas appeared linked to in-the-moment responses to student ideas that *dismissed student ideas* or *reinforced misconceptions.* These ePCK indicators were typically found in classroom discussions with low levels of teacher engagement with student ideas. Thus, pPCK seems crucial for teachers' engagement with student ideas during classroom discussions.

Second and relatedly, weak content knowledge seemed to limit teachers' pPCK. Teachers who appeared to hold the same misconceptions as their students often did not notice common misconceptions during the video-stimulated interviews (pPCK). This is consistent with previous studies showing that content knowledge is a prerequisite for teachers' PCK (Davidowitz & Potgieter, 2016; Käpylä, Heikkinen, & Asunta, 2009; Kirschner et al., 2016; Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008). Weak pPCK, specifically due to weak content knowledge, was sometimes reflected in teachers seeming to *reinforce student misconceptions* (ePCK); these responses were often found in classroom discussions rated as low teacher engagement with student ideas. Thus, content knowledge seems important as the basis for pPCK and, ultimately, ePCK and teachers' engagement with student ideas in classroom discussions.

Finally, teachers need to create a classroom culture in which students can actively express their ideas. In this study, engagement with student ideas appeared to be supported not only by teachers' ePCK (and, in turn, pPCK), but also by teachers' discourse moves. In classroom discussions with high level of teacher engagement with student ideas, the teacher consistently invited and carefully listened to students' contributions by utilizing a variety of content-general discourse moves (Table 4.12). Many of these discourse moves overlap with ones that others have identified as being responsive to student ideas (Lineback, 2015; Michaels & O'Connor, 1993; 2012; Pierson, 2008; van Zee & Minstrell, 1997). For teachers like Jason, with elaborated pPCK yet classroom discussions with only low or moderate engagement with student ideas, supporting skills for (and propensity to enact) these discourse moves might be important. If discourse moves encourage students to express their ideas, there might be more opportunities for the teacher to draw on pPCK to exhibit ePCK, and, thus, responsiveness to student ideas.

## Implications for Teacher Education

In the previous section, I pointed to the importance of teachers' pPCK, content knowledge, and content-general discourse moves for engagement with student ideas in classroom discussions. Despite recognizing the importance of teachers' knowledge, concerns have been raised about knowledge-based teacher education. In response, scholars have argued for opportunities for preservice teachers to practice the actual tasks and activities involved in teaching (Ball & Forzani, 2009; Grossman, Hammerness, & McDonald, 2009; McDonald, Kazemi, Kavanagh, 2013). This new vision of teacher education centers curriculum around a set of core practices—often called *high leverage practices*—"that are essential to the work of teaching, and which novices can learn to enact in their early years" (McDonald et al., 2013, p. 379). Below, I use studies of teacher learning to suggest potential ways that practice-based teacher education might support teachers' pPCK, content knowledge, and discourse moves.

First, research points to the benefits of teachers analyzing student ideas in terms of developing knowledge of student ideas and content knowledge. For example, research has shown that teachers enhance their familiarity with student ideas and deepen their content knowledge as they analyze examples of common misconceptions (e.g., Geddis, 1993) and classroom videos that highlight evidence of student ideas (e.g., Harlow, Swanson, & Otero, 2014; Kanter & Konstantopoulos, 2010; Roth et al., 2011) or observe student questions and artifacts in their own classrooms (e.g., van Driel, de Jong, & Verloop, 2002). Therefore, a focus on high leverage practices of "diagnosing patterns of student ideas" and "interpreting student work"

(TeachingWorks, 2020) can be expected to support teachers in developing both pPCK and content knowledge.

My study identifies pPCK and content knowledge as needed for ePCK and, thus, teachers' engagement with student ideas in classroom discussions. Despite the focus on practices, practice-based teacher education does not mean that knowledge is no longer needed for practice, but rather than that "the knowledge that counts for practice is that entailed by the work" (Ball & Forzani, 2009, p. 503). However, little research is explicit about what knowledge is associated with practice and how that knowledge can be supported in a practice-based teacher education. This study provides some information about what knowledge teachers should develop as they engage in the practices of diagnosing patterns of student ideas and interpreting student work.

Second, engaging in the high-leverage practice of "leading a discussion" (TeachingWorks, 2020) could offer opportunities to develop skills for content-general discourse moves and to put into practice pPCK and content knowledge developed through diagnosing patterns of student ideas and interpreting student work. Teachers cannot learn to develop discourse moves that encourages expression of student ideas simply by reading about discourse moves. As teachers enact new routines for discourse moves to facilitate high quality classroom discussions, teacher educators can provide specific feedback and coaching that can help teachers "distinguish features of a complex practice that may be difficult to fully appreciate until one tries to enact the practice" (Grossman et al., 2009, p. 285). In addition, engaging in discussion about some content could offer opportunities for teachers to further strengthen their pPCK and content knowledge as specifically related to practice.

## Limitations and Future Work

There are several limitations of my study that must be noted to appropriately interpret my findings. First, the current study only involved five teachers. This sample does not represent a diversity of teachers. Although the participating teachers experienced different teacher preparation programs, had varying levels of teaching experience, and taught in different school contexts, I cannot make generalizable statements based on five teachers from the same geographic area. In order for the findings of this study to be generalizable to broader population, future study must be replicated with a larger number of teachers with diverse backgrounds teaching in varied contexts.

Second, and relatedly, this study only focused on the topic of force and motion. Since PCK is topic-specific (Magnusson, Krajcik, & Borko, 1999; Veal & MaKinster, 1999), evidence of ePCK and pPCK, as well as the relationship between ePCK and pPCK could look different for a different topic. Future studies might replicate the results with different topics.

Third, video-stimulated interviews were conducted about six weeks after teachers finished teaching. This time gap between teaching and the interview could have limited the extent to which teachers articulated the pPCK that they drew upon in-the-moment of instruction. This might have resulted in incongruence between ePCK and pPCK as exhibited by Jason and Ryan. Future research should conduct video-stimulated interviews more immediately to determine if the relationships between ePCK and pPCK identified in this study can be confirmed. Although even more immediate interviews would not completely resolve the fundamental issue of teachers' knowledge being tacit or that interviews necessarily capture reconstructions—rather than recollections—of reasoning, it may help teachers reconstruct their reasoning more accurately.

Fourth, this study examined the relationship between ePCK and pPCK only in the context of whole-class discussions. Teachers' ePCK is not only involved when teachers enact instruction in classroom situations with students but also when teachers are planning or reflecting on instruction (Carlson & Daehler, 2019). Further study is needed to test the relationship between ePCK and pPCK in different settings: in different types of instruction (demonstrations, lab sessions, lecturing etc.) as well as in different parts of the instructional cycle. This would help us discover evidence of ePCK that might look different (or similar) from that identified in this study and see if the RCM can be applied in other settings.

Despite these limitations, the current study offers evidence about the role of PCK in teachers' responsiveness to student ideas during classroom discussions. This finding fills a gap in the literature by connecting PCK and teachers' responsiveness, and more broadly, connecting PCK and teaching practice. In addition, the current study uncovers detailed linkages between PCK and practice by using the new constructs of ePCK and pPCK. Thus, this study not only contributes to our understanding of how we could use the new constructs of ePCK and pPCK in empirical studies, but also tests new conceptualizations of the relationship between ePCK and pPCK described in the RCM.

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