Chapter 3
Personal and Canonical PCK: A Synergistic Relationship?

P. Sean Smith, Courtney L. Plumley, Meredith L. Hayes, and R. Keith Esch

Abstract For 30 years, science education researchers and practitioners have waited for the promise of pedagogical content knowledge (PCK) to be fulfilled. PCK has the potential to shape instruction, teacher professional learning, and instructional materials. When the field speaks about PCK in terms of these benefits, a particular kind of PCK is envisioned. In our work, we refer to this kind of PCK as "canonical" to convey that it is widely accepted by the field and transcends context. Despite its promise, examples of canonical PCK are lacking in relation to the number of science topics in standards documents. In this chapter, we explore the possibility that the PCK held by teachers—"personal PCK"—can be compiled to grow the body of canonical PCK. We first describe a model of personal-canonical PCK synergy. We then explain how we have tested this synergy hypothesis, drawing on literature reviews and data collected directly from teachers. We find that, within the narrow range of topics we have focused on, personal PCK does not accumulate to fill gaps in the canon. We illustrate through several examples that instead, personal PCK appears largely as variations on PCK themes already apparent in the literature. We conclude the chapter by discussing implications for the field.

Keywords PCK · Personal PCK · Canonical PCK · Student thinking

3.1 Introduction

The construct of pedagogical content knowledge (PCK) is 30 years old and has an extensive literature on its many facets, including how it is defined, developed, elicited, assessed, and measured. Rather than review this literature comprehensively, we begin by using selected pieces to establish our orientation toward PCK.

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Shulman described PCK as “that special amalgam of content and pedagogy that is uniquely the province of teachers…” (Shulman 1987, p. 8). The word “amalgam” has important implications—among them, both content knowledge and pedagogical knowledge are necessary for PCK; neither is alone sufficient. Our particular orientation toward PCK aligns with that of others who argue that the content dimension is not just domain specific but topic specific as well (e.g., Gess-Newsome 2015; Veal and MaKinster 1999)—e.g., PCK exists for science, for chemistry, and for the topic of equilibrium within chemistry. Our work focuses exclusively on topic-specific PCK. Specifically, in this chapter, we use illustrations from our work on two fifth-grade topics (or disciplinary core ideas) in the Next Generation Science Standards ([NGSS] NGSS Lead States 2013): the Small Particle Model of Matter and Interdependent Relationships in Ecosystems.[1]

In attempts to parse the construct of PCK, several researchers have proposed categories. All researchers seem to agree on two broad categories of topic-specific PCK: knowledge of instructional strategies and knowledge of student thinking. The former may include laboratory activities, simulations, and ways to elicit student thinking, among others. The latter includes prominent misconceptions[2] and learning progressions. We have found these two broad categories particularly helpful in our own work, as have others (e.g., Alonzo and Kim 2016).

Shulman’s original conception of PCK clearly describes knowledge that resides in teachers, what some researchers refer to as “personal PCK” (e.g., Gess-Newsome 2015). A critical feature of our orientation is the assertion that PCK can exist external to teachers, available to all in the same way that science knowledge is available to all in books and other forms. We characterize this form of PCK as “canonical” to suggest that it is, like canonical science knowledge, widely accepted by the field. Shulman described a construct similar to canonical PCK when he wrote about the collected and codified “wisdom of practice among both inexperienced and experienced teachers” (Shulman 1987, p. 11). Examples of synthesized canonical PCK are limited, but they do exist and tend to focus on student thinking, in particular the well-known works of Rosalind Driver and colleagues (e.g., Driver 1994; Driver and Easley 1978; Driver et al. 1985). For example, several studies have found that young students often believe liquid substances not only disappear when they evaporate but the matter itself ceases to exist (Lee et al. 1993; Osborne and Cosgrove 1983; Russell et al. 1989; Tytler and Peterson 2000). However, relative to the number of science topics in K–12 standards documents, examples of widely accepted patterns in student thinking are sparse, and examples of widely accepted instructional PCK are even more elusive. We hypothesize that personal and canonical PCK can have a synergistic relationship, which we elaborate on below.

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[1] Using NGSS notation, these topics correspond to DCIs 5-PS1.A and 5-LS2.A, respectively. We selected these topics because of our focus on upper elementary science instruction and because of the contrast they offer between physical and life science.

[2] We define misconceptions as student ideas that (1) are in conflict with accepted scientific ideas and (2) form through interaction with the natural world. Misconceptions are neither good nor bad, but they do tend to be deeply ingrained in students’ thinking. Some are part of a learning progression for a topic, suggesting that many students will have them at some point as they develop full understanding. Examples include (1) air does not have mass, and (2) plants get their food from soil.

3.2 A Model of Personal-Canonical PCK Synergy

A robust PCK canon could benefit the field in important ways. For example, it could form the basis for curriculum materials design, for professional development design, and for PCK assessments. Figure 3.1 shows a model that suggests a synergistic relationship between canonical and personal PCK. The model was first formalized in preparation for an international meeting on science PCK in 2012 (Carlson et al. 2015), in which the lead author of this chapter participated.

The model asserts that canonical PCK exists and that it traditionally emerges from research on student thinking and instructional strategies. However, with the exception of Driver's work on student thinking referenced above, efforts to synthesize such research have been infrequent. Personal PCK, as described in the model, forms through teaching (or teaching-related) experience. For example, PCK may develop as a teacher plans for instruction or enacts a lesson and monitors its effect on students. We have found personal PCK particularly difficult to elicit from teachers, as we describe later in this chapter.

The model suggests that it is possible, but not inevitable (as represented by the dashed lines), for a synergistic relationship to exist between canonical and personal PCK; however, neither is dependent on the other. The first aspect of synergy is evident in the assertion that personal PCK, through consensus among many teachers, may ultimately become canonical PCK. We have been testing this hypothesis in our work and summarize our findings later in this chapter. Efforts to collect and make public the consensus of many teachers' personal PCK are not widespread, but there are notable precedents. Researchers at Monash University in Australia pioneered such work on a local scale through their CoRe instrument (Loughran et al. 2004).

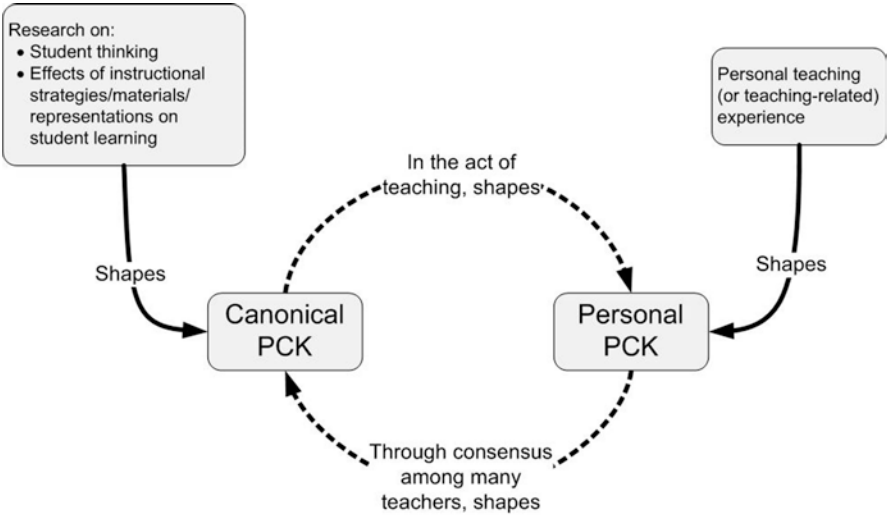

Fig. 3.1 Personal-canonical PCK synergy model

We have tried to combine personal PCK from many teachers in many parts of the USA, looking for aspects that transcend context.

It is important to note, however, that canonical PCK is *not* dependent on personal PCK. It can accumulate entirely from the types of research listed in the model. Unfortunately, the canon has large gaps—that is, some topics lack widely accepted PCK, and even those that do often focus more on student thinking than effective instructional strategies. For example, canonical PCK about students' thinking related to force and motion is abundant (e.g., Gunstone and Watts (1985) synthesized several studies more than 30 years ago), but our literature search (Smith and Plumley 2016) suggests that knowledge of effective ways to teach elementary students about the particle model of matter is scarce.

A second aspect of synergy is represented in the assertion that personal PCK can be shaped by canonical PCK. That is, a teacher may read about a particular aspect of student thinking or about a particularly effective instructional strategy. Then, in the act of teaching (or preparing to teach), that knowledge may be transformed by a teacher's experience. Personal PCK is not, however, dependent on canonical PCK. This phenomenon is particularly evident at the university level, where professors have abundant disciplinary *content* knowledge (e.g., physics or biology knowledge) but, historically, have had little or no exposure to canonical PCK. However, they still have personal PCK by virtue of their teaching experience. Through their teaching alone, they form ideas about effective instructional strategies and patterns in student thinking—that is, they form personal PCK.

The 2012 PCK Summit (Carlson et al. 2015) generated a consensus model of teacher professional knowledge that reflects the notion of synergy. Although canonical PCK is not included by name, a component named "topic-specific professional knowledge" (or TSPK) is the same construct. Describing the model, Gess-Newsome wrote:

> TSPK is clearly recognized as codified by experts and is available for study and use by teachers…. TSPK is canonical, generated by research or best practice and can have a normative function in terms of what we want teachers to know about topic- and context-specific instruction. It can be identified and described to construct measures, tests, or rubrics to determine what teachers know, might act as the basis for creating a learning progression for teachers, and should be used as a framework for the design of professional development. (Gess-Newsome 2015, p. 33)

Like our model, the consensus model of teacher professional knowledge includes a synergistic relationship between TSPK (i.e., canonical PCK) and personal PCK and elaborates on the relationships. Teacher's beliefs, orientations, prior knowledge, and context, along with classroom practice, are active in transforming TSPK to personal PCK. Gess-Newsome (2015) also acknowledges that personal PCK can become TSPK through consensus among many teachers.

As we described above, canonical PCK for some topics is sparse at best, and even where it is abundant, it tends to focus more on student-thinking aspects and less on effective instructional strategies (Hayes et al. 2017; Smith and Plumley 2016). Certainly there is research on effective teaching strategies, but not topic-specific teaching strategies. If one imagines a matrix with NGSS disciplinary core ideas as rows and research on student thinking and instructional strategies as columns, we suspect the majority of cells would be empty or lightly populated.

We hypothesized that personal PCK, collected and codified from many teachers, could fill gaps in canonical PCK. Over 3 years, we tested that hypothesis in the context of the two NGSS disciplinary core ideas mentioned in the Introduction. First, we reviewed empirical research studies and practitioner-oriented literature and then synthesized information on student-thinking and topic-specific instructional strategies, generating canonical PCK (e.g., Smith et al. 2017). Next, we surveyed and interviewed teachers to collect their PCK, exploring whether common elements in their knowledge might rise to the level of canonical PCK as we have defined it and whether it would fill gaps in a topic-specific canon. We were not looking for evidence of canonical PCK in teachers' responses, but rather testing whether we could generate canonical PCK from their combined responses. The work has yielded important insights. Before discussing these, it is necessary to briefly describe the methods used to elicit personal PCK from teachers.

3.3 Eliciting Personal PCK from Teachers

Attempts to elicit PCK from teachers, which are almost as old as the construct itself, face a common obstacle. Shulman wrote in one of his earliest papers conceptualizing PCK: "Practitioners simply know a great deal that they have never even tried to articulate" (Shulman 1987, p. 12). His statement is true 30 years later. Teachers seldom need to articulate their PCK for themselves, and they are rarely, if ever, asked to articulate it for others. Consequently, their PCK tends to be tacit (Cohen and Yarden 2009; Henze and Van Driel 2015; Loughran et al. 2004, 2008). Despite this formidable obstacle, testing our synergy hypothesis required eliciting and characterizing teachers' personal PCK. Like other PCK researchers, we found affordances and limitations in a survey approach. Survey questions were based on the CoRe methodology (Loughran et al. 2004) used widely in studies of teacher knowledge (e.g., Alvarado et al. 2015; Williams and Lockley 2012).

We administered a web-based survey to grades 4–6 teachers from several states about their topic-specific PCK related to the small particle model of matter and interdependent relationships in ecosystems. Some questions asked about teachers' knowledge of student thinking, for example, "Please describe the ideas or misconceptions your students have that make it difficult for them to learn about **the particle model of matter**."[3] Others asked about their instructional strategies, for example, "Please describe a question or activity you use to find out what ideas students already have about the interdependent relationships in ecosystems **before** you

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[3] Teachers were presented with this question only if they had already responded that students do have misconceptions that make it difficult for them to learn about the small particle model or interdependent relationships in ecosystems.

begin teaching about it."[4] The survey allowed respondents to upload documents they used in their teaching, including laboratory activities and worksheets. Respondents were also encouraged to share other resources, for example, online simulations and videos.

The survey forced teachers to compartmentalize their knowledge (e.g., they responded to separate survey questions about student-thinking patterns and instructional activities). From an analysis standpoint, this feature was an affordance. However, survey responses did not represent how different types of personal PCK related to each other. As illustrated by the examples above, the survey asked respondents to describe misconceptions and instructional activities separately, rather than explain which activities they use to address their students' misconceptions. In addition, responses tended to be vague, lacking detail needed to characterize a teacher's PCK adequately.

We ultimately found a combined survey-and-interview approach most effective. Teachers first completed the web-based survey. We then conducted a follow-up telephone interviews with survey respondents, during which we probed on each of their survey responses.[5] Before the interview, each interviewee received his or her survey responses by email and was encouraged to have them on hand during the interview. The interview followed essentially the same structure as the survey, but researchers probed for elaboration of survey responses that were unclear and for connections among compartmentalized responses. For example, a survey respondent may have written "I ask questions" when describing a particular activity. During the interview, a researcher prompted the respondent to name the specific questions and asked for typical student responses. Similarly, a survey respondent who provided only a sentence or two about an activity was asked to expand upon their description during the interview. Interviewers also asked respondents how they used the resources that they had uploaded in their survey responses (e.g., lesson plans, student handouts). Table 3.1 shows an example of survey and follow-up interview responses from one teacher.

Researchers merged the survey responses and interview transcripts into a single document for each individual, with the response for each survey question arranged next to relevant parts of the interview transcript. Researchers coded the documents using a two-dimensional framework: (1) PCK type (e.g., student thinking, instructional activity) and science content (i.e., the discrete science ideas in each concept[6]). Together, researchers first coded several documents to establish common understanding of the framework and then divided and coded the rest of the documents as individuals using qualitative analysis software (Dedoose). After all documents were coded, two researchers—one for each topic—analyzed the documents for

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[4] Teachers were presented with this question only if they had already responded that they try to elicit student thinking before instruction begins.

[5] The findings in this chapter are based on 42 combined survey-interviews, about equally split between the two topics (small particle model of matter and interdependent relationships in ecosystems).

[6] The science ideas are described in Smith and Plumley (2016) and Hayes et al. (2017).

Table 3.1 Survey and follow-up interview responses

Survey	Interview
Please describe a question or activity you use to find out what ideas students already have about the particle model of matter before you begin teaching about it I just ask them what a gas is, a solid is, and a liquid is, and we brainstorm properties that each have	*Interviewer (I)*: You said you do a bit of a brainstorming about the different states and properties. What kinds of things in that brainstorming session do you hope to accomplish? *Teacher (T)*: Well, we put something on the whiteboard, and we talk about, "Okay, give me examples of solids. Give me examples of liquids. Give me examples of gases." Then we put all those down. Then we discuss how they are similar, how they are different, and we kind of then come up with the fact that—I'll say to them, "But did you know that all of these have something in common because they're all made up of matter that is composed of these particles." We kind of just go through that thing. I'm not really teaching it to them at this point, just letting them know that they all do have something in common *I*: When the students are giving you examples, what are some of the typical responses that they come up with? What kinds of things do they say about the properties? *T*: Well, they'll say, for example, with the solids, "Well, solids are things that you can touch." Then they'll break it down into things like, "Well, things that are wood or things that are metal and that sort of thing." Liquids, they'll break those down into just common household things—soda, water, milk, all of those. They're really not getting to the actual properties themselves, but they're listing everything that they can that has to do with the solids and the liquids—household items that they know of.

frequency of PCK and summarized the findings. The research team reviewed the summaries to confirm that findings aligned with their own experience interviewing teachers and coding the combined survey-interview response documents.

3.4 Unrealized Synergy Potential

As evidenced by the preceding discussion, some aspects of our work have been challenging. However, we began investigating the synergy hypothesis optimistically. We had already identified large gaps in canonical PCK before we surveyed and interviewed teachers, and the potential to fill those gaps with personal PCK from many teachers—that is, the path in our model from personal PCK to canonical PCK—was appealing. However, our work thus far does not support the hypothesis. When responding to survey and interview questions, teachers tend to report instructional approaches similar to those in the literature—variations rather than new, effective ways of teaching concepts. Regarding PCK about student thinking, teachers tend not to describe student misconceptions reported in literature, and they generally do not identify new misconceptions. In short, we claim that the hypothesized potential for synergy between canonical and personal PCK is not being realized. In the discussion that follows, we support this claim with evidence from our studies. We address PCK in two broad categories—instructional PCK first, followed by knowledge about student thinking.

3.4.1 Instructional PCK

Before the NGSS, the small particle model of matter (SPM) and the phenomena it explains were taught mainly in middle grades and higher (American Association for the Advancement of Science 1993; National Research Council 1996). Not surprisingly, the literature on instructional activities for SPM in the elementary grades is very limited. In contrast, an abundance of instructional activities exists for interdependent relationships in ecosystems. Looking across many of these activities in the empirical and practitioner literature, broader instructional approaches emerged, including engaging students with a scenario of an ecological disturbance, constructing and analyzing foods webs, and examining a particular ecosystem. Generally, instructional activities reported by teachers appeared to be variations on one of those broader approaches, rather than novel ones. We illustrate this pattern with several examples below.

The scenario approach appeared in numerous forms in the literature, including roleplay simulations, thought experiments, online simulations, and videos. Roleplay simulations, in which students take on organism roles and act out a scenario, were particularly prevalent. However, when describing seemingly similar activities, authors and teachers differed in their procedures and intended student learning outcomes. Table 3.2 includes examples of how the widely used “Oh Deer!” roleplay activity was referred to in the practitioner literature and by a teacher. In the example from the literature, predation is not introduced in the activity itself, whereas the teacher described this addition, with some students playing the part of wolves. Acknowledging the prevalence of the activity, but not the differences among versions, another teacher said:

> I know [“Oh Deer!”] shows up in a lot of different curriculums under different names. I just attached the one that I could find online to make it easier.

Interestingly, the version that the teacher attached to her survey response differed from the implementation she described, in that the attached version did not introduce predation (see Table 3.2). The larger point is that teachers reported minor variations of the “Oh Deer!” scenario, for example, rather than wholly different activities.

Creating a food web, or in some cases a food chain, appears frequently in the literature as an instructional approach to represent and examine trophic relationships. Likewise, teachers often describe individual students drawing a web, arranging cards labeled with organisms, or using an online interactive simulation. One oft-cited whole class activity uses string, or yarn, to trace connections among organisms (typically with individual students playing the role of a population of organisms—e.g., rabbits) and simulate the effects of disturbances to an ecosystem (Appel et al. 1982; Camp 1995; Clement et al. 1997; Kuhn 1971). Table 3.3 includes two summaries of the string web activity from the practitioner literature, as well as two teachers’ accounts of how the activity takes shape in their classroom. Again, the teacher accounts include variations but not new approaches.

Table 3.2 Example uses of the "Oh Deer!" instructional activity

Source	"Oh Deer!" implementation description
Rockow (2007, p. 19)	*Students play "Oh Deer!" (Dalton, 1992), an interactive game that demonstrates what happens to a population of animals when there are more animals than the ecosystem can support…. Students sometimes have the misconception that if the population of a species declines, extinction will follow. This activity shows students that populations can decline and then rebound, without leading to extinction. At the end of this period I talk about the limitations of this activity as a model for an ecosystem…*
Teacher A	*Briefly, it's basically, a fourth of your students become "deer," and the other three-fourths become the "resources." You can be "food," "water," and "shelter." There's an accompanying gesture that you make for the deer to know what you are. The deer can't see what's out there until they turn around after you say, "Oh Deer." Then they run across the field. They're holding whatever sign it is, and trying to find a matching sign on the other side…. What we'll do to create some interesting years in our data chart will be, this year there's a "drought," and no one can be "water." This year there's a fire, so no one can be "shelter." Any deer looking for those things would perish, and we would be able to be like, "Oh, that's the year of the fire!"…. Just have 'em thinking about some other factors that might influence the population. Eventually, to make a little more game out of it, we'll introduce a predator. We usually call it a "wolf." … It's trying to find one deer per year to bring back to its den. Its population begins to shift as well…. Usually, what happens, is the wolf, somehow, they're able to draw the resources, or whatever; but, usually, the game ends by the wolf population just dominating the deer population. The deer die out. The following year, the wolves die out. We talk about, "How would that look in nature? Would that really happen if we have 20 wolves and two deer, and the deer was the only food source?" I think that's one of the problems with the whole activity is that most organisms have many different food sources…. In some form or another, I feel like I've done "ecosystems" for 8 or 9 years. I've always done "Oh Deer." It hits so many checkboxes where it's very focused on the learning objectives*

Examining a particular ecosystem—that is, observing, or researching an ecosystem and its components, and situating instructional activities in that ecosystem—emerged as another common instructional approach in the literature. One example is a comprehensive unit guide designed by the Long Island Pine Barrens Society (1998) to integrate classroom investigations with outdoor experiences related to the Long Island Pine Barrens. This guide includes the string food web simulation described previously, in which all organisms are native to this particular ecosystem (e.g., Pitch Pine, Tiger Beetle, Red Fox). Another example is the Smithsonian Institute's *Art to Zoo* publication (1996), which features instructional resources designed to contrast the coral reef of the Caribbean and the rocky coast of Maine. Within these activities, students examine trophic relationships and consider the impacts of both biotic and abiotic factors.

Similarly, teachers described concentrating a portion of their instruction on a particular, often local, ecosystem. Some teachers reported focusing on a local ecosystem as a starting point for instruction, because students have familiarity through prior experience, or the class could take a field trip to provide an experience upon which students can draw. One teacher described what influenced her decision

Table 3.3 Example uses of the string food web instructional activity

Source	String food web implementation description
Clement et al. (1997, p. 28)	*Using a large ball of yarn, start with water and sunlight and ask what members of the wetland use these things. Connect students with yarn as they demonstrate relationships. Cut the yarn whenever it becomes cumbersome. Eventually it should be clear that all members of the ecosystem are connected. Try tugging on one link of the web and seeing how many students can feel it. If each student who feels the tug pulls on the lines he or she is holding, the original tug will ripple through the whole community just as wetland disturbances affect many organisms*
Kuhn (1971, p. 832)	*As the data is analyzed, each student assumes the role of an organism of the community—one might be a green alga, another a water flea, another a catfish, another a snail,* etc. *As each relationship is established, a line is strung,* e.g., *between the "producer" organism and a primary consumer. Other relationships can be established in a similar manner. As the analysis continues, the existing relationships become evident; one primary consumer may feed upon several producers; a third-order consumer may feed upon several other animals. The complexity of the food web becomes strikingly evident, and the visual impact is substantial*
Teacher B	*Everybody, all the kids, all have a role. I pass out several different roles, or if I don't—like if I have a huge class, I pair them up… Everybody has a piece of the string. We pass it out, and I weave it through the kids, basically by saying, "Okay. You're a—," I'm just making up things right now—but, "You're a daisy." Okay. Well, a daisy is eaten by the rabbit. I'll throw the string across to the rabbit. The rabbit has to get it. Okay. Well, now the rabbit's gonna get eaten by a couple of different things* *By the time we're done, it's a web. It is truly. It looks like a web the way the string is passed around. The kids see the interconnection that way. Then what's also neat is you can see the web collapse when an animal misses, 'cause all of a sudden I'll say, "Okay. Somebody sprayed [herbicide] and all the plants died. If you are a plant or you are a producer, please drop." They'll physically drop the string. Well, then they see the whole thing go. A lot of times then I'll say, "Okay. What happens? How does this affect these animals? How does this affect these animals? Okay. How is this gonna affect an herbivore?" Well, they're not gonna have anything to eat. Okay. "Therefore?" "Well, they'll die." "Okay. Then when they die, what's gonna happen?" "Well, a decomposer will take over, but we won't have enough decomposers to take care of things."* *It's funny because when we really look at it—after they're done with the physical activity, we go back, and we answer some questions in our notebook about it. I'll make them think about if all the producers disappear, what's gonna happen to an herbivore? What's gonna happen to the land itself? What's gonna happen to—we take it apart as to each role and what happens*
Teacher C	*There's one, also, with food webs that we've tried, where you give them yarn, and they go from place to place. It ends up kind of a crazy web. Naturally, it doesn't really work perfectly. It's not a true food web, but they can see how complicated the food web can truly be. That's more the point of it is that those webs are pretty complicated.… You assign each child, "You're this kinda plant; you're this kinda bird," everybody has a role. Then the bird could fly from a plant, over to a different plant. Then the cat can come, and he has to stand with the bird, and then the bird is eaten, so the bird is still. It won't move anymore, and then something comes and gets the cat. As they move from place to place and you clear out the classroom, and they have a long piece of yarn—when the cat goes to the bird, the bird would hold on to the yarn, that part of the yarn, and then the cat could move on, but it took that to the bird. It's a three-dimensional kind of thing, and as I said, it doesn't work perfectly, but it does allow them to see the complexity*

to have students identify abiotic and biotic factors in a deciduous forest at the beginning of her ecosystems unit:

> It's mainly the fact that we live in Ohio … [Deciduous forests are] a very common ecosystem. We have this property that we visit that is a deciduous forest. They've all had that concrete experience of being there, which I find is really important for them to engage in the conversation.

3.4.2 Student-Thinking PCK

The vast majority of topic-specific PCK research literature focuses on student thinking. In these studies, researchers typically presented students with a phenomenon and asked them to explain it (e.g., Abraham et al. 1994; Helldén 1998; Leach et al. 1992). Some studies involved students responding to multiple-choice assessments, with common misconceptions as answer choices; others had students write (or draw) questionnaire responses or provide oral explanations in an interview. Whatever the format, in these studies, researchers presented students with something to explain, determined students' misconceptions, and described them in their reports. Excerpts from these types of studies, including the elicitation tasks and examples of resulting misconceptions, are in Table 3.4.

It appears that teachers rarely do these types of elicitation activities with students to find out what they think at the beginning of instruction. Instead, when teachers elicit student ideas, they tend to be about a broad topic (e.g., matter) using methods such as a KWL chart (What do I **K**now?, What do I **W**ant to know?, What did I **L**earn?). The box below includes an example of a teacher describing the use of a KWL.

KWL Description

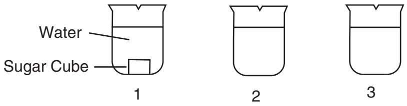
Interviewer: Going on to the next idea, could you lead me through how you set up this KWL chart for the concept of matter? You said it's pretty informal. Could you just give me a little better idea of how that looks in the class?

Teacher: Yeah. A lot of times, I will just make an anchor chart, so a piece of chart paper, and put a KWL on there, and we just divide it. We talk about, "Well, if I say 'matter,' what do you know about matter? What can you tell me about matter?" Sometimes—it depends if those teachers under us actually taught their science or not. Sometimes they have things that we already know.

Interviewer: Okay. What would you say your students do already know?

Teacher: This year, they didn't know a lot… It really varies from year to year. Sometimes they know that—sometimes they know, "Hey, I know that there's matter out there." I don't think I've ever had anybody come in being able to tell me that matter is particles that are too small to be seen, and sometimes really large, and it's everywhere, and it has mass, and it takes up space. No one's ever been able to really tell me the whole thing. There's always something to learn.

Table 3.4 Elicitation tasks and misconceptions from literature

Source	Elicitation task	Resulting problematic student thinking
Abraham et al. (1994)	A cube of sugar is added to a glass of water. The cube of sugar dissolves. Describe what happens to the sugar cube as it dissolves. Picture 1 shows how the glass looked after the sugar cube was added to the water. In glass 2 draw how the sugar cube and water would look after half of the sugar dissolved. In glass 3 draw how the glass of water would look after all the sugar dissolved. 	When sugar dissolves, the water in the glass absorbs the sugar. When the sugar dissolves, it undergoes a phase change, melts, or evaporates.
Helldén (1998)	What do you think will happen to the plant in the box if we plant it there and glue the lid on?	Students expected the plant to die immediately in the sealed, transparent box. Students viewed the plant as the "end station" for matter, describing how the necessary resources for growth and survival would be consumed but not attending to what plants produce.
Leach et al. (1992)	One summer there is a drought. A lot of the grass and crops die. What do you think might happen as result of this? Explain as carefully as you can.	Students often appeared to consider effects on individual organisms, rather than on a population. Students appeared more likely to trace effects up through the food web than down, demonstrating differences in their reasoning based on the trophic level being affected.

KWL charts can play an effective role in instruction, but as elicitations, they provide the teacher with little useful information about students' topic-specific misconceptions. The student thinking that typically arises in response to a KWL chart about a broad topic is something we refer to as a "missing conception"; that is, an idea that students are not familiar with rather than a *misconception* about the idea. Similarly, when asked about topic-specific student misconceptions, teachers instead typically respond that students "don't know about that," with "that" being either the concept itself or related vocabulary. Table 3.5 includes several examples of missing conceptions expressed by teachers.

Similarly, when attempting to describe misconceptions, teachers often report that their students have difficulty understanding the topics of SPM and interdependence because phenomena involve components and changes too small or too slow to see.

Table 3.5 Missing conceptions about interdependent relationships and SPM

Source	Missing conception
Teacher D	*Again, my students do not have knowledge of the natural world around them. They have the idea that animals eat what you feed them—basically a pet mentality.*
Teacher E	*They haven't been exposed to [decomposition] before. They haven't really thought about the roles of, say, the fungus with the mushrooms or the earthworms. They haven't really considered those roles before, and so they don't understand that they break things down.*
Teacher F	*Like I said, they might use it in a different terminology, where they have no idea that matter means everything that's around us, everything that we're seeing. There's different types of matter that make up the universe. They're using it in, "Well, I didn't do this, so why does it matter?" I 'm like, "No, that's not the type of matter I'm talking about." They're like, "What do you mean?" I'm like, "Matter—everything that makes up stuff."*

Table 3.6 Developmental challenges for interdependent relationships and SPM

Source	Developmental challenge
Teacher G	*Students often do not have any concrete experience with decomposition, other than molding food which is promptly thrown away. They can't see many of the microorganisms and often don't get to see the process from start to finish, which leads to misconceptions and just incorrect ideas.*
Teacher H	*I think it's hard for kids to understand anything that doesn't happen immediately. It's something that I also see, for example, with growing plants and things like that, things that take time. In their world, a long time is a week.*
Teacher I	*Sometimes if they can't see the particles, or anything for that matter, then it's difficult for some to grasp that there is actually stuff they can't see.*

We call this type of student thinking a "developmental challenge" rather than a misconception, because it relates to something that is difficult for students of this age to grasp, not an incorrect idea. Examples of developmental challenges shared by teachers are in Table 3.6.

In the work discussed in this chapter, we asked teachers about student thinking related to two specific topics. The teachers did sometimes provide misconceptions (in the sense that we use the term) that addressed concepts *prerequisite* to the topics. For example, in SPM we were interested in students' misconceptions about the particle model and about the phenomena that the particle model helps explain. However, teachers frequently described misconceptions related to states of matter instead, such as thinking that gases are not matter because they cannot be touched like liquids and solids. Similarly, for interdependent relationships in ecosystems, teachers spoke of students' misconceptions about components of the ecosystem, rather than how they interact. For example, many teachers described that their students think that they, themselves, are producers because they can make (i.e., cook) their own food. This finding—that teachers are more familiar with misconceptions at the boundaries of the key ideas about a topic—may be specific to the ideas we are investigating. More research is required in other topics. To repeat our general finding, however, teachers typically do not report topic-specific student misconceptions outside of those in the literature. Consequently, their potential to fill gaps in canonical PCK about student thinking appears limited.

3.5 Discussion

In concluding this chapter, we first acknowledge that canonical PCK is not universally accepted. We attribute the resistance in part to semantics; the term “canonical” evokes strong negative reactions in some. The idea that PCK exists outside of an individual is unacceptable to others. But we suspect that most would agree our field has identified prominent, enduring patterns in students’ topic-specific thinking. Young students tend to think that moving objects always stop, that dissolving solids cease to exist, and that decaying matter just “goes away” without any biochemical action. Similarly, the field has identified effective instructional strategies for helping students reconcile these ideas with accepted scientific concepts. When students slide a block across progressively smoother surfaces, the experience (if well facilitated by a knowledgeable teacher) can challenge their idea that moving objects always stop. Weighing the mass of a solid and liquid before and after dissolving suggests that the solid does not cease to exist. And careful observations of composting can open students’ minds to the possibility of invisible processes they had never considered. These are instances of what we call canonical PCK, but the term is not as important as what it represents—widely accepted knowledge about how students think and learn about a topic.

In exploring the synergy hypothesis, we focused on the potential for accumulated personal PCK to fill gaps in canonical PCK. We gave little attention to the other aspect of synergy—that canonical PCK can become personal as one takes it up and uses it in teaching. However, we see little evidence of this aspect of synergy either. Reports from teachers suggest minimal exposure to empirical literature on student thinking, which is not surprising. Apart from the Driver books mentioned earlier, attempts to synthesize the literature are infrequent, and attempts to make the knowledge accessible to teachers are even less frequent. Regarding instructional PCK, we described how teachers report using some of the same approaches we found in practitioner literature, but we saw little evidence that teachers got them *from* the literature. Rather, teachers tended to reference the results of Internet searches, citing sources such as BrainPOP, StudyJams, and Teachers Pay Teachers, among others.

We are unable to support either relationship in our synergy hypothesis, but a caveat is in order. We synthesized canonical PCK by collecting, reviewing, and summarizing empirical and practitioner literature. These tasks were straightforward, not substantially different from any other literature review. Eliciting personal PCK from teachers was far more challenging. We found the combined survey-and-interview approach promising, but we are uncertain that it adequately addresses the tacit nature of teachers’ PCK documented elsewhere (e.g., Cohen and Yarden 2009;

Henze and Van Driel 2015; Loughran et al. 2004, 2008). Other means of eliciting personal PCK may yield different findings, perhaps even evidence for the synergy hypothesis.

We did find complementarity between empirical and practitioner literature, at least for the interdependence topic.[7] Empirical literature focused heavily on student thinking, practitioner literature almost exclusively on instructional activities. Together, they form a richer knowledge base for teaching the topic than either does alone. What is lacking are efforts to (1) synthesize within and across these types of literature, and (2) make the product accessible to teachers in a form they are likely to use. Also lacking in either type of literature is knowledge about the affordances and limitations of an activity in terms of student thinking. Why is this activity important? What can it accomplish for students? What should come before and after it?

For all of these reasons, we are encouraged by the vision of educative curriculum materials—that is, curriculum materials that incorporate features designed to support teachers' purposeful enactment of the materials (Davis et al. 2014; Davis and Krajcik 2005). Educative features can make canonical PCK available to teachers when and where they need it. An example is narrative text for the teacher that explains how a unit sequence develops student understanding across activities. Within an activity, these features can highlight the activity's function in the broader unit, making it more likely a teacher will capitalize on the activity's affordances and compensate for its limitations. Another type of educative support can point teachers to patterns of student thinking the teachers can leverage and others the teacher should be prepared to challenge appropriately. In short, educative curriculum materials can do the work that teachers do not have time, and perhaps the background, to do themselves. In this way, educative features can catalyze the pathway from canonical PCK to personal PCK.

The work described in this chapter is ongoing, the findings tentative. Our goal was to put forth the synergy hypothesis and describe our findings to date in broad strokes. Given the large gaps in canonical PCK within and across topics, the synergy hypothesis is still appealing. An underdeveloped canon limits the work of teachers, teacher educators, and curriculum developers. For example, educative curriculum materials can make canonical PCK available to teachers only if it already exists. Topics with a weak canon require foundational research before educative curriculum materials can play their proper role. The question is whether such research can focus on accumulating topic-specific personal PCK, as we have attempted, or whether it must include student-level studies. The former is almost certainly more expedient and less costly, but our work suggests the latter may be necessary. The field needs more research on both fronts.

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[7] We discussed earlier in the chapter that the small particle model has not been taught widely in elementary grades prior to the NGSS. Consequently, practitioner literature for this topic in these grades is lacking.

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