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Eliciting Elementary Teachers' PCK for the Small Particle Model

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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.

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 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 & 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. In this paper, we describe our work on one fifth-grade topic (or disciplinary core idea) in the Next Generation Science Standards ([NGSS] NGSS Lead States, 2013): the Small Particle Model of Matter[1], which we refer to as SPM throughout this paper. It is important to point out that SPM has not been included in upper elementary grades historically. Predecessors to the NGSS—*Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) and the *National Science Education Standards* (National Research Council, 1996)—did not introduce the particle model until the middle grades or later.

In attempts to parse the construct of PCK, several researchers have proposed categories. Magnusson, Krajcik, and Borko (1999) proposed four categories, which have been widely used:

- Knowledge of science curricula;
- Knowledge of students' understanding of science;
- Knowledge of instructional strategies; and
- Knowledge of assessment of scientific literacy.

All researchers seem to agree on two broad categories of topic-specific PCK: knowledge of instructional strategies and knowledge of patterns of student thinking. The former may include laboratory activities, simulations, and ways to elicit student thinking, among others. The latter

[1] Using NGSS notation, the topic corresponds to DCI 5-PS1.A. It states: "Matter of any type can be subdivided into particles that are too small to see, but even then the matter still exists and can be detected by other means. A model that shows gases are made from matter particles that are too small to see and that are moving freely around in space can explain many observations, including the inflation and shape of a balloon and the effects of air on larger particles or objects."

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 & 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 call this form of PCK "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 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 & 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 & Cosgrove, 1983; Russell, Harlen, & Watt, 1989; Tytler & 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 rare. We believe personal and canonical PCK can have a synergistic relationship, which we elaborate on below, as it is important for understanding our efforts to elicit PCK from teachers.

Finally, we agree with others (e.g., Abell, 2008) who argue that PCK has a quality dimension—that is, individuals' PCK varies with regard to accuracy, complexity, and depth. As Abell wrote, "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" (Abell, 2008, p. 1410). We believe PCK can be fundamentally incorrect, the most obvious example of which is PCK that incorporates incorrect science content knowledge (Smith & Banilower, 2015).

A Model of Personal-Canonical PCK Synergy

We originally came to PCK from a measurement perspective, as part of a project attempting to trace the impacts of professional development on student learning. In contrast to attempts to measure teachers' disciplinary content knowledge (e.g., knowledge of ideas in force and motion), our attempts to measure PCK encountered a persistent obstacle: a lack of topic-specific canonical PCK. Through our unsuccessful efforts to develop measures of PCK, a model began to emerge for how a body of canonical PCK might grow. Shown in Figure 1, the model suggests that a

[2] In this paper, "misconception" is used to denote any idea that conflicts with accepted scientific ideas about a phenomenon, acknowledging that such ideas may represent a productive step in a student's learning progression.

synergistic relationship between canonical and personal PCK might exist. The model was first formalized in preparation for an international meeting on science PCK in 2012 (Carlson, Stokes, Helms, Gess-Newsome, & Garder, 2015), in which the lead author of this paper participated.

First, the model asserts that canonical PCK exists and that it traditionally emerges from research on student thinking and instructional strategies (including instructional materials and assessment strategies). However, with the exception of Driver's work on student thinking referenced above, efforts to synthesize such research have been lacking. 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 pin down, as we describe later in this paper.

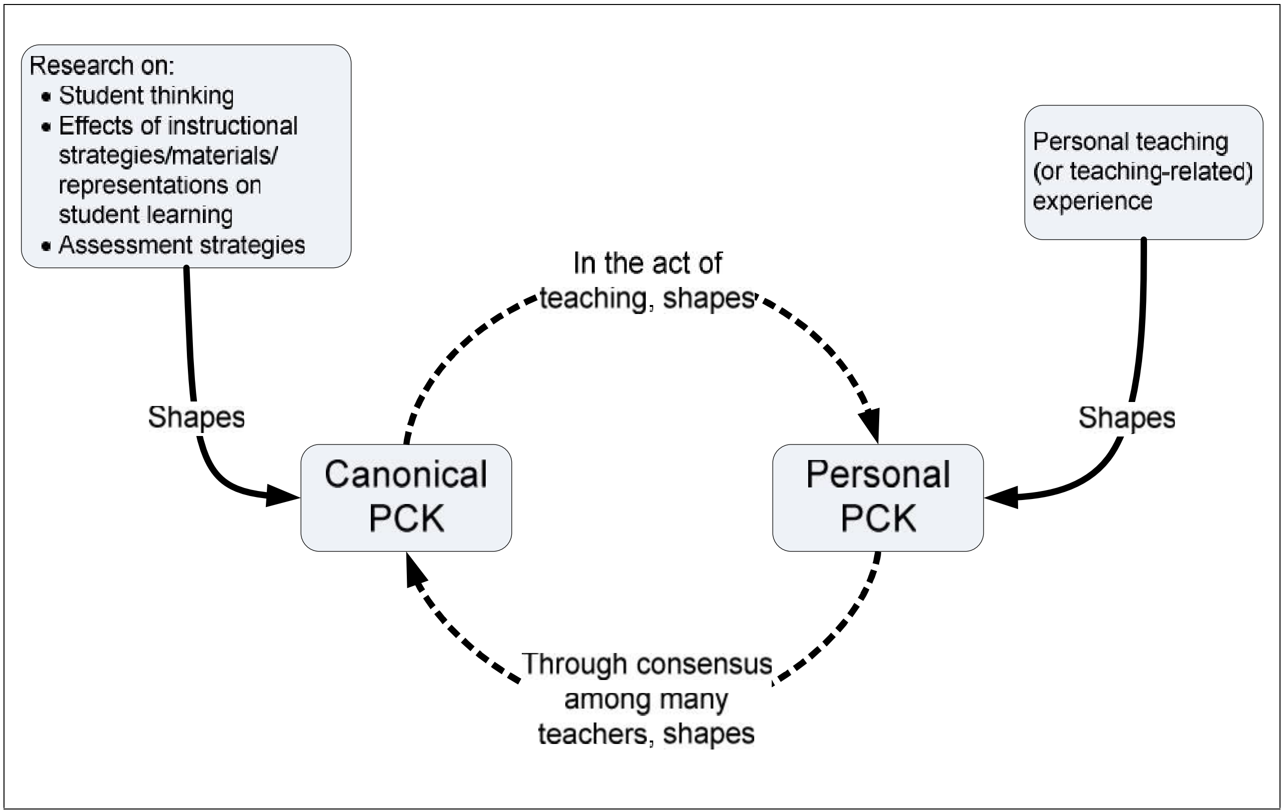

Figure 1

The model suggests that it is possible, but not inevitable (as represented by the dashed lines), for there to be a synergistic relationship between canonical and personal PCK. 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 report our findings later in this paper. Although efforts to collect and make public the consensus of personal PCK across many teachers are not widespread, there are notable precedents. Researchers at Monash University in Australia pioneered such work on a local scale through their CoRe instrument (Loughran, Mulhall, & Berry, 2004). We are attempting to combine personal PCK from many teachers in many parts of the US, 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 described above. Unfortunately, canonical PCK, with few exceptions, has not accumulated, or at least it has not accumulated systematically, which has resulted in large gaps. For example, although canonical PCK about students' thinking related to force and motion is abundant, canonical PCK about effective ways to teach elementary students about the particle model of matter is scarce at best.

The 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 canonical 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 have formed ideas about effective instructional strategies and patterns in student thinking.

At the 2012 PCK Summit (Carlson et al., 2015), attendees developed a consensus model of teacher professional knowledge, shown in Figure 2. Although canonical PCK is not included by name, the component labeled "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)

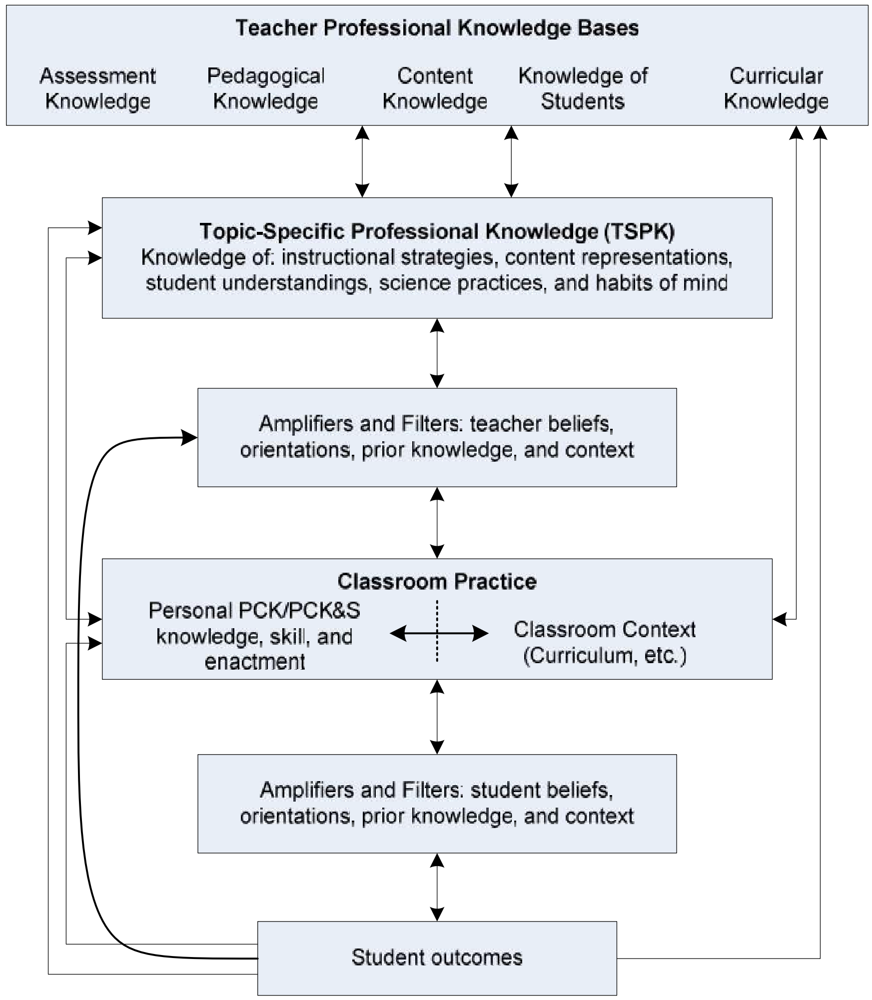

Figure 2

Like our model, the consensus model of teacher professional knowledge includes a synergistic relationship between TSPK and personal PCK and elaborates on the relationships. Teacher 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. 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, the majority of cells would likely be empty or lightly populated.

We hypothesized that personal PCK, collected and codified from many teachers, can fill gaps in canonical PCK. For the past three years, we have been testing that hypothesis in the context of the two NGSS disciplinary core ideas, one of them being SPM. First, we reviewed empirical research studies and synthesized information on student thinking and topic-specific instructional strategies, generating canonical PCK (Smith, Plumley, & Hayes, 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. The work is ongoing but has already yielded important insights related to eliciting personal PCK and the kinds of PCK that teachers express.

Eliciting Personal PCK from Teachers about SPM

In this section, we describe the approaches we have used to elicit teachers' PCK and how we ultimately arrived at a combined survey-and-interview approach.

Attempts to elicit PCK from teachers are almost as old as the construct itself. In science, as in other disciplines, the purposes of eliciting PCK fall into three categories: characterization, assessment, and measurement. The work of Loughran and colleagues represents attempts to elicit and characterize teachers' PCK (Loughran, Milroy, Berry, Gunstone, & Mulhall, 2001; Loughran et al., 2004; Loughran, Mulhall, & Berry, 2008). Often, efforts to assess PCK (i.e., judge the correctness of one's PCK) go hand in hand with measurement efforts (i.e., to quantify the amount of PCK one has or estimate one's "ability" with regard to PCK). The DTAMS measures developed at the University of Louisville represent such efforts (Saderholm & Tretter, 2008; Tretter, Brown, Bush, Saderholm, & Holmes, 2013). However, it is possible to assess without measuring, and some argue that while assessing PCK is appropriate, measuring it is not (Gunstone, 2015).

All of these efforts, regardless of purpose, face a common obstacle. Shulman described this obstacle 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 rarely have a need to articulate their PCK for themselves, and they are rarely, if ever, asked to articulate their PCK for others. Consequently, their PCK tends to be tacit (Cohen & Yarden, 2009; Henze & 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. Questions were based on the CoRe approach (Loughran et al., 2004), which has been used widely in studies of teacher knowledge (Alvarado, Cañada, Garritz, & Mellado, 2015; Williams & Lockley, 2012). We administered a web-based survey to teachers nationwide about their PCK for SPM. Teachers were recruited from a national mailing list of approximately

400 fourth and fifth grade teachers. Interested teachers completed a registration page, providing information about their teaching experience in general (e.g., number of years teaching science, familiarity with NGSS), as well as their teaching of SPM (e.g., number of times taught in career, how many hours spent on the topic in a typical year). Project researchers then reviewed the registration data and selected teachers with the most experience, both in teaching science and teaching SPM, to be survey respondents.

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 particle model of matter **before** you begin teaching about it."[4] The web-based 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, responses tended to be vague, lacking detail needed to characterize a teacher's PCK adequately. The following responses from a question about activities teachers use in their instruction related to SPM illustrate this quality:

> *I have every student explain what makes a solid a solid.*
>
> *We show a video clip to spark the students' interest and to jump start a conversation.*
>
> *The first activity involves student discussion about objects (similarities and differences), guiding the students to the understanding that at the basic level matter has a building block.*

Because of the compartmentalized nature of the questions, survey responses also did not represent how different types of personal PCK related to each other. For example, the survey asked respondents to describe misconceptions and instructional activities separately in response to different questions, rather than explain which activities they use to address their students'

[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.

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

misconceptions. Therefore, the survey approach was limited in its potential to capture the interplay among elements of teachers' PCK.

We also found affordances and limitations in an interview approach. Teachers were recruited in a similar way as survey respondents. In contrast to the survey, interviews were more likely to elucidate relationships among different types of PCK but at the same time presented a considerable challenge. Interviewers had to be able to follow the teacher wherever he or she went until the network of knowledge was fully articulated, at least to the best of the teacher's and interviewer's ability. Teachers often strayed into content that was not part of the target topic. For example, in discussing their instruction on a particle-model explanation for phase change, they sometimes diverged into a discussion of chemical changes. They also shared multiple forms of PCK in the same response. When asked about activities used in teaching SPM, one teacher described an activity and then abruptly transitioned to talking about a prominent student misconception:

> *One activity we do in here, and it works a lot better when it's warmer outside, and unfortunately, I seem to always do this unit in the cold months. When you have a soda can, or a lemonade can, whatever, one really, really cold, maybe it's been sitting in the freezer for a while, and another one's at room temperature, and being able to pull those out and have them next to each other, and examine and observe what's happening there. It allows them to get this physical idea of well, why is there nothing on this room temperature can, and now all of a sudden this really cold can, and there's beadlets everywhere. That brings up a great conversation, too. Ah, I just came up with another misconception, so, yeah, the can was great. Because sometimes you hear kids saying the can is sweating, or the can is bleeding, and when I dig a little bit deeper into that, like, well, what do you mean by that? Sometimes the kids think the liquid is actually coming out of the can. I think it's like a 50/50 thing in here. Some kids are really thinking it's coming out of the can, and 50 percent of them are knowing that it's not coming out of the can, that it's actually landing on the can, but then for them to understand where it's coming from is a whole new story.*

The response illustrates the richness and connectedness of the teacher's PCK. Those same qualities made it difficult for interviewers to follow the teacher and still ask all of the interview questions.

We ultimately found a combined survey-and-interview approach most effective. Teachers first completed the web-based survey (N = 28). We then conducted follow-up telephone interviews with 22 of the survey respondents,[5] during which we probed on each of their survey responses.

[5] Two survey respondents were not contacted because they had completed an SPM interview previously, and four survey respondents did not respond to requests for interviews.

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 allowed researchers to ask for elaboration on survey responses that were unclear. 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 respondent who provided only a sentence or two about an activity on the survey was asked to expand upon their description during the interview. Interviewers also asked respondents how they used the resources (e.g., lesson plans, student handouts) that they had uploaded in their survey responses. Figure 3 shows examples of survey and follow-up interview responses from two teachers.[6]

[6] For analysis purposes, an individual's survey and interview responses were combined in one document. These documents were then analyzed using qualitative analysis software to identify common elements of personal PCK.

	Survey	Interview
Teacher A	**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.
Teacher B	**Please describe the ideas or misconceptions your students have that make it difficult for them to learn about the particle model of matter.** They don't really see or understand that particles too small to be seen exist.	*I:* Could you elaborate on that idea that they're struggling with, that the particles are too small to be seen exist? *T:* Yeah. I think kids that are 10 and 11 are very literal. I mean, a lot of times, you can't be sarcastic with them, and things like that, because they don't understand it. When you say, "Hey, this stuff out here is made of these particles, and you can't see them," they're like, "Well, I can't see them, so they don't exist." I mean, that's where we struggle with that, and that's what you have to overcome. That would be great to have maybe even more—or a digital microscope or something, that you can actually break it down and show them, and they'd be like, "Whoa." That's the struggle there, is that they're very literal, and if you tell them, they want to be able to see it, or to do it, or to feel it, and you can't. You can't with that. I think that's just a part of their development, is they're very literal. They need to see it, and so that affects a lot of how fifth graders and fourth graders take on the world, and view the world, and learn about the world if they can't touch it. *I:* Okay. Is there any way that you get around that idea, and help the students get past that? *T:* We'll [use] Google images, and we don't have—sometimes I've had a digital microscope. I don't have a working one. The software is old, so I can't show them the microscopic things. I can Google them and show them images and different websites, and we do the things that do make gas visible, like blowing up a balloon, and putting it in a container, so they can see it like that, and different things like that.

Figure 3

The survey responses gave interviewers an overview of the teacher's PCK, which the interviewer could then flesh out with probing questions. We found that the survey responses greatly reduced the processing interviewers had to do in real time, as they could always refer back to the overview to know which areas still needed to be addressed. Further, as illustrated in Figure 3, the interviews added considerable detail to the survey responses.

We began to think of these data collection methods as different approaches to mapping an unfamiliar landscape—in this case, an individual teacher's personal PCK. Although the teacher may have taught a topic several times, she does not usually have to make her knowledge of teaching that topic known to others. In the same way, she rarely needs to explain the layout and landscape of her city. Her PCK likely has tacit connections and explanations known only to her—much like her tacit knowledge of her own city—that she alone draws upon while teaching the topic. When surveyed about her knowledge of instructional activities and student thinking on a survey, the teacher names some aspects of her knowledge (analogous to city landmarks), creating a basic map but without detail, such as why the activities are important or how they connect to one another. When asked to share her knowledge using an interview alone, she may share the same aspects of her PCK, but with probing, may also share more detail (analogous to the significance of landmarks) and relationships among aspects of her PCK (analogous to how landmarks are oriented in relation to one another). However, it is hard for an interviewer to follow these relationships, or to know whether all aspects have been discussed, without also seeing her basic map. The benefit of using the survey-and-interview method is that an interviewer can get a sense of the landscape using the survey, and then use the interview to flesh out the details and get a clear picture of the surroundings, essentially requiring the teacher to make her tacit knowledge explicit.

The Personal PCK that Teachers Express

As we noted at the beginning of this paper, SPM has not been included in elementary grades historically. Consequently, it is not surprising that we see evidence in teachers' survey and interview responses that their PCK for teaching SPM is not well developed. In particular, we note a general absence of three related considerations:

- the explanatory nature of SPM;
- student thinking about particles; and
- conceptual coherence among instructional activities.

Related to the first consideration, the NGSS clearly describe SPM as an explanatory model:

> Matter of any type can be subdivided into particles that are too small to see, but even then the matter still exists and can be detected by other means. A model that shows gases are made from matter particles that are too small to see and that are moving freely around in

space can explain many observations, including the inflation and shape of a balloon and the effects of air on larger particles or objects. (NGSS Lead States, 2013, p. 43)

However, survey and interview responses suggest that teachers' instruction in upper elementary grades focuses much more on properties and states of matter than on a particle model of matter. For example, the survey asked teachers to describe a question or activity they use to elicit students' prior knowledge. Interviewers asked teachers to elaborate on their survey responses. The examples in Figure 4 illustrate the focus on properties and states of matter.

	Survey	Interview
Teacher C	**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.** We use thinking maps at my school. We brainstorm and create a circle thinking map listing everything students know about matter. We then later compare the particles of matter in solids, liquids and gases in a tree map.	*I*: I'm not as familiar with the circle map and the tree map, so I'm just trying to get a sense of them in my head. *T*: Okay. A circle map is what you use to brainstorm. I would take a circle, and I would write the word "Matter" in the middle. Then kids just tell me what they think it is or what they know about it or just any random thought. They might say, "Oh, it could be a solid," and I would write "solid." They go, "Or it could be a gas," and I would write it up there. They go, "Well, it's really most everything." Then I'll say, "Okay, alright." Then I'll go over to the side. This is not part of a circle map, but I'll go over to the side. "Okay, can you name anything that's not matter?" Then that, they really have a hard time coming up with those thoughts. Really, when you come up with what's not matter, you get a better idea of what is matter, because it's so hard to think of something that's not matter. You go up to the famous "It's anything that has mass and takes up space." Then they go, "But the air we breathe doesn't have mass" and those kind of thoughts.
Teacher D	**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 would brainstorm with a KWL activity. What do students Know, Want to know, and Learned [sic]?	*I*: I know that you use a KWL chart. My first question is what topic or idea do you have the students respond to on that KWL? *T:* Really, it will be matter. What do you know about matter? What you remember about, yeah, matter being the topic? If they're like, "What is matter," then I might be like, "What do you know about solids, liquids and gases, because that would be part of matter. What do you know about that," just to clarify. If I just say "matter," they'll just be like, "What's the matter?" I explain a little bit more and then stop right there and just see what they know about liquid, solid, and gas. Then they might bring up water and how it could have different states.

Figure 4

When teachers' instruction did attend to the particle nature of matter, it tended to be limited to description. Teachers frequently wanted students to be able describe the spacing of particles in the different states of matter. Further, their students' understanding of the spacing and other properties of the particles typically comes from what they have been told, rather than through exploration. The following example from an interview is illustrative:

T: We do an experiment where we have them take a balloon, and we'll have that in one station. Then we'll have a pitcher of water or a pitcher of tea at another station. Then *we'll have a solid, like a LEGO block, or like a pencil, or something like that at another station. We'll just talk about how one relates to gas, one relates to liquid, and one relates to solid. We'll have them tell us, "How can you explain how the atoms in the gas are spread out? How are the atoms in the liquid close together? How are the atoms in a solid packed closely together? How can you explain that?" When we do it that way, they're able to explain it a little bit better, because they can conceptually think of it in a better way when they actually have a visual. They're not just thinking of it as water being an ice, or a liquid, or a gas. If we have actual materialistic things, then they're able to conceptually understand it a little bit better….They always draw a picture with their questions. We always have a box where they have to draw what they see, and then they have to explain, on the lines, how it relates to the question. Say, for instance, the balloon, and they—and we'll say, "Well, how does this balloon show gas?" They would say, "Well—" they would draw a picture of the balloon. They would say, "Well, the balloon shows gas because inside the balloon is air, and the atoms in the gas are spread out because it's air."*

I: Okay. Is that something that they already know, just from having read the different articles and watched the video?

T: Yeah.

Other researchers have written about the importance of two closely related considerations in designing instruction: student thinking and conceptual coherence (Roth et al., 2011). By conceptual coherence, we mean a content storyline that ties instructional activities together. With regard to student thinking, the teachers in our study were able to describe aspects of student thinking when asked directly about them (for example, about ideas that students bring to instruction), but they did not tend to justify their instructional decisions with considerations about student thinking. More commonly, teachers gave no explicit rationales (perhaps because they were tacit), or their rationales prioritized engagement. For example, one interviewed teacher said:

We like to have that as much hands-on as possible, because if [the teachers are] doing the demonstration, we're the ones learning. We like for the [students] to do as much hands-on as possible, just so that they can get the full—just—I don't know what the word I'm looking for—just so that it—they can work on it themselves. They can work with their partners. When they make mistakes, they can see what needs to be changed or what data needs to be included, based on what they observe. Because if we're doing it in front of the class, we don't have as many people that are as engaged in the experiment. We definitely try to make everything as much hands-on as possible.

Finally, it was difficult to discern a content storyline in teachers' instruction about SPM. Each interview concluded by asking teachers to describe the sequence of activities or topics they described during the interview. The lack of an apparent storyline does not mean the teacher did not have one, only that it was not discernible. The examples in Figure 5 illustrate this aspect of teachers' elicited PCK.

Teacher E	*I:* Could you give me the 30,000-foot view of how that's sequenced across that week or two? What you're doing first, second, third until you're moving on to the next unit? *T:* Mm-hmm. Usually we'll start off with—the very beginning will be just identifying the states of matter. After we get the states of matter, we'll start talking about physical properties. Once they've got the three states down, then what it's broken down to is a different physical property either weekly or every so many days. Then we'll hit mass. Then we'll hit volume, temperature. We'll just gradually be going through the different physical properties of matter. From there we'll move into freezing point, boiling point, melting point, stuff like that. From there we start moving on to this. By then we've talked about condensation, evaporation, melting, freezing. Now models like this will help them. We'll get the hot plates and get the water—liquid—and make it evaporate. *I:* Okay. In terms of activities, what kind of happens? What's the first activity you do with kids in the early part of this unit? *T:* First thing will be the—well, the very first couple of days, we'll go back and review what they've learned in the grades before. That's when we'll do the hand models. We'll do the where they come up and act out the particles in a gas or them being particles. Then we'll do a couple of little arts and craft things where they can put the particles together for me, matching them. Then we'll start doing the labs when they go through the different stations for solids, liquids, and gases.
Teacher F	*I:* I'm actually going to take a pause from the questionnaire itself, and just ask you if we could zoom out. Could you lead me through, based off of the different instructional activities, and the prior knowledge kind of concepts and activities you do, the sequence of how you approach this unit? *T:* Yes. What I generally do is through informal questioning. There's the years where I've often used the KWL, where they list what they know and then what they want to know. Then they go back and put what they learned. Somehow I activate prior knowledge, usually through questioning, and then introduce the concept of matter being made of particles, through StudyJams and some BrainPOPs that they do individually. Then it leads me to the lab, which they do from the Mailbox Magazine book, which is the solid, liquid and gas investigation using the wood blocks, liquid water, and then the air in the bag. From there we do—I do throw in another investigation I started this year, which is measuring matter, because it talks about the physical property. It also allows them to have better skills when we get into some higher level labs. They'll do the measuring of matter using mass and volume and temperature, because that's important. From there—I'm trying to go through my mind here what we do—I use my interactive notebook, which I'm using two different ones from Teachers Pay Teachers. Using those interactive notebooks, we take notes and make a couple foldables regarding physical properties of matter, how to measure it. Then we get into chemical properties and the physical and chemical changes, so they understand the difference. Using my demonstrations like I have described, with the cup in the water with the paper, keeping it dry, as well as density, I put that in there to further their knowledge and their understanding of the particle model of matter.

Teacher G/B	*I:* The last little bit I wanted to ask you, if you could zoom out to the whole matter unit, and if you could just take me through how you incorporate the lessons and ideas, just the sequencing of that unit? *T:* Okay. Let's see. I'm gonna grab a book to help my brain. We start with what makes up matter, so all of the little particles and—let me see here, flip through—so they start with what makes up matter, and they give different—from the beginning, they talked about all states all together. We talk about elements and things like that. We briefly cover the atomic arrangements. Then we get into physical properties, how can you describe matter, so we talk about color, mass and volume, temperature, texture. In that, we do a lot of those things, describe matter, every which way that we can. Then it goes into states of matter, and how they change back and forth between states. Then it gets into mixtures and solutions, solubility, physical changes or chemical changes.

Figure 5

In summary, what we see in the survey and interviews is evidence of underdeveloped personal PCK for teaching SPM as an explanatory model. We attribute this finding primarily to teachers' lack of opportunity or need to develop this knowledge. Generally, the upper-elementary teachers in our study simply do not teach the small particle as described in the NGSS, even though they indicated that they did when they registered for the study.

Discussion

To test our hypothesis about a synergistic relationship between canonical and personal PCK, we collected, reviewed, and summarized both empirical and practitioner literature. These tasks were straightforward, not substantially different from any other literature review. Eliciting PCK from teachers was far more challenging and at the same time essential.

As noted above, the NGSS stress SPM as an explanatory model—that is, the model accounts for a wide range of phenomena, including change of state and conservation of mass during physical and chemical changes. In our literature reviews, we found a wealth of research on student thinking about the particle model but practically none on effective ways of teaching this concept. As such, the area was ripe for testing whether personal PCK could fill gaps in canonical PCK. However, after surveying and interviewing upper-elementary teachers nationwide, it became clear that the particle model is rarely taught as envisioned in the NGSS. This finding is not surprising given that SPM was not included in national standards documents until the NGSS. Consequently, elementary teachers generally have had neither the need nor the opportunity to develop personal PCK for this topic. When teachers did teach about particles, their treatment tended to be purely descriptive rather than explanatory. That is, teachers might have students act out or draw particle behavior in different phases, but they did not use the model to explain phase change.

However, even when teachers to have extensive experience teaching a topic, other obstacles impede efforts to elicit PCK from teachers. Research on PCK, in particular on eliciting PCK from teachers, documents that it tends to be a tacit form of knowledge for these practitioners (Cohen & Yarden, 2009; Henze & Van Driel, 2015; Loughran et al., 2004, 2008).

As described in this paper, survey methods by themselves did not adequately reveal teachers' PCK, even when survey questions were highly scaffolded and allowed respondents to upload artifacts. The additional information we were able to elicit from teachers in interviews makes us skeptical of the validity of paper-and-pencil approaches to eliciting and assessing teachers' PCK. Such approaches are economical but may not adequately portray the depth, breadth, and connectedness of teachers' PCK. We found the combined survey-and-interview approach more promising, but other approaches are possible, including interviewing teachers about instructional artifacts (e.g., lesson plans, video of instruction). Ultimately, as in most decisions about instrument design and data collection, we had to balance tradeoffs between cost and validity.

However, we are uncertain that the survey-and-interview approach adequately addresses the tacit nature of teachers' PCK that has been documented in numerous studies (Cohen & Yarden, 2009; Henze & Van Driel, 2015; Loughran et al., 2004, 2008). In concluding, we note that we had a very different experience in interviews with a small sample of individuals who developed curriculum materials for SPM. These individuals could consistently describe their instructional approaches *and* their rationales. For example, in describing her approach to developing materials on SPM, one developer described students' need to understand inference first because they would never be able to see the particles, only infer their existence from observable phenomena. Another cautioned against teaching small particle ideas in the absence of a phenomenon that would motivate students' need to learn the ideas.

It is important to note that the sample of curriculum developers was one of convenience drawn largely on personal connections. The teacher sample was also one of convenience. We cannot claim that either sample is representative. Still, the similarities within each group are striking, and the differences between curriculum developers and teachers in their expressed PCK were pronounced and consistent. One explanation is that the work curriculum developers do affects both the substance and the organization of their PCK, making their knowledge qualitatively different from that of most teachers. What is not clear is whether such an explanation would generalize beyond the small sample of curriculum developers we interviewed. Our sample may have shared certain tendencies in how they think about curriculum that other developers do not. However, if there is something fundamentally generative about curriculum development for the development of personal PCK, then the field must consider the affordances and limitations in using curriculum development as a form of teacher professional learning. Asking teachers to develop their own curricula, as opposed to putting excellent materials in their hands and asking them to use their professional judgment in adapting them, seems ill advised. However, there may be affordances in asking teachers to engage in some aspects of curriculum development or analysis for the purpose of developing their own PCK.

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