Developing and Testing a Method for Collecting and Synthesizing Pedagogical Content Knowledge

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INTRODUCTION

Elementary teachers face formidable obstacles when planning and implementing science instruction, including inadequate preparation opportunities, lack of resources, and accountability pressures. Data from the 2012 National Survey of Science and Mathematics Education bear this out (Banilower et al., 2013). Only one-third of elementary teachers have had a course in Earth, life, and physical science. And although the vast majority of elementary teachers have had a course in science education, only 40 percent report feeling very well prepared to teach science, compared to 81 and 77 percent for reading/language arts and mathematics, respectively. When asked about specific subjects within science, the percentage of teachers rating themselves as very well prepared is even lower; for example, only 17 percent consider themselves very well prepared to teach physical science. Instructional resources pose another problem. Although several inquiry-oriented curricula are commercially available (e.g., FOSS, Insights, STC), only 10 percent of elementary classrooms use them. As a result, elementary teachers who are committed to inquiry-oriented instruction are too often left to "make it up" on their own. Elementary teachers also face overwhelming accountability pressures in mathematics and reading; for example, 80 percent of grades 3–5 classes are required to give at least three external mathematics assessments (e.g., district benchmark or state tests) each year, and 36 percent administer five or more of these assessments. All of these factors have created a situation in which science instruction is infrequent and often not of high quality. On average, elementary classes spend only 20 minutes per day on science, while devoting 55 minutes to mathematics and 88 minutes to reading/language arts. A national observation study found that only about one-third of elementary science lessons were likely to have a positive effect on students' understanding of science concepts, their ability to carry out their own inquiries, or their understanding of science as a dynamic body of knowledge (Weiss, Pasley, Smith, Banilower, & Heck, 2003). Data from the 2012 National Survey indicate that elementary science instruction continues to be based predominantly on lecture/discussion, with limited use of hands-on activities and evidence to support scientific ideas (Banilower et al., 2013).

The expectations for elementary science instruction were recently raised to a new level. The Next Generation Science Standards ([NGSS] NGSS Lead States, 2013) are the latest in a series of college and career-ready standards released over the last few years. Together with the Common Core State Standards in Reading and Mathematics (National Governors Association Center for Best Practices & Council of Chief State School Officers, 2010a, 2010b), they put forth an ambitious vision of what students should know and be able to do in these fields as a result of K–12 education. Twenty-six states partnered in developing the NGSS, and 18 states have formally adopted them to date, suggesting the standards will influence the system over the next several years.

To realize the vision of excellent science education for all students portrayed in the NGSS, elementary teachers will need to draw on a wide variety of knowledge. Prominent educators and researchers have proposed the existence of a professional knowledge base for teaching, similar to the specialized knowledge bases for medicine and law (Grossman, 1990; Hiebert, Gallimore, & Stigler, 2002; Hill, Rowan, & Ball, 2005; Shulman, 1986a, 1986b). Efforts to articulate the components of such a knowledge base have been underway for over two decades. Some constituent knowledge forms, such as disciplinary content knowledge, are fairly well understood and widely accepted as necessary, but not sufficient, for effective teaching (e.g., Heller, Daehler, Wong, Shinohara, & Miratrix, 2012).

Perhaps the most widely recognized form of specialized knowledge for teaching—and arguably the one with the most potential for helping teachers overcome knowledge-related obstacles—is "pedagogical content knowledge" (PCK), which Shulman (1986a, 1986b) described as an amalgam of pedagogical knowledge (general teaching knowledge) and content knowledge (knowledge of a specific discipline). An oft-cited example is knowledge of an effective strategy for teaching a particular concept; for example, having students slide an object on progressively smoother surfaces to construct an understanding of the idea that an object in motion tends to remain in motion in a straight line unless a force acts on it. After years of research, there is an emerging consensus that PCK is indeed important for science teachers. Magnusson, Krajcik, and Borko (1999) developed a model of PCK that has strongly influenced conceptualizations of what constitutes PCK in science as well as other disciplines. The model describes discrete forms of PCK, including knowledge of instructional strategies, knowledge of students' understanding of science, and knowledge of science curriculum. Since the introduction of the Magnusson et al. model, PCK-related research in science education has accelerated. Still, interpretation of the construct varies widely. Some researchers contend that PCK is highly personal or idiosyncratic (Loughran, Mulhall, & Berry, 2008; Park & Oliver, 2008; Van Driel, Verloop, & de Vos, 1998), developed over time through teaching experience (Appleton, 2008; Friedrichsen et al., 2009; Nilsson, 2008). Others assert that PCK can accumulate and form a collective body of knowledge independent of the teacher (Fernandez-Balboa & Stiehl, 1995; Veal & MaKinster, 1999).

At a weeklong invitational conference on science PCK in 2012, attended by the lead author, a group of researchers agreed on a revised model of PCK that acknowledges both collective and personal aspects of PCK (Gess-Newsome, 2015). In this model, shared, or collective, PCK is referred to as topic-specific professional knowledge (TSPK); however, for our purposes, we refer to it as collective PCK, or C-PCK. Hypothesized relationships among these and other forms of knowledge are shown in Figure 1.

As illustrated in the model, discrete professional knowledge bases are the foundation for C-PCK. Examples of C-PCK include an instructional strategy that has been found through empirical studies to be effective for teaching a specific idea, or recognition of a conceptual difficulty found through assessment studies to be prominent among elementary students. This knowledge can be applied by teachers to their own unique settings and for their own purposes. As teachers take up C-PCK—through reading, professional development experiences, discussions with colleagues, reflecting on their practice—and use it in their teaching, it becomes personal PCK.

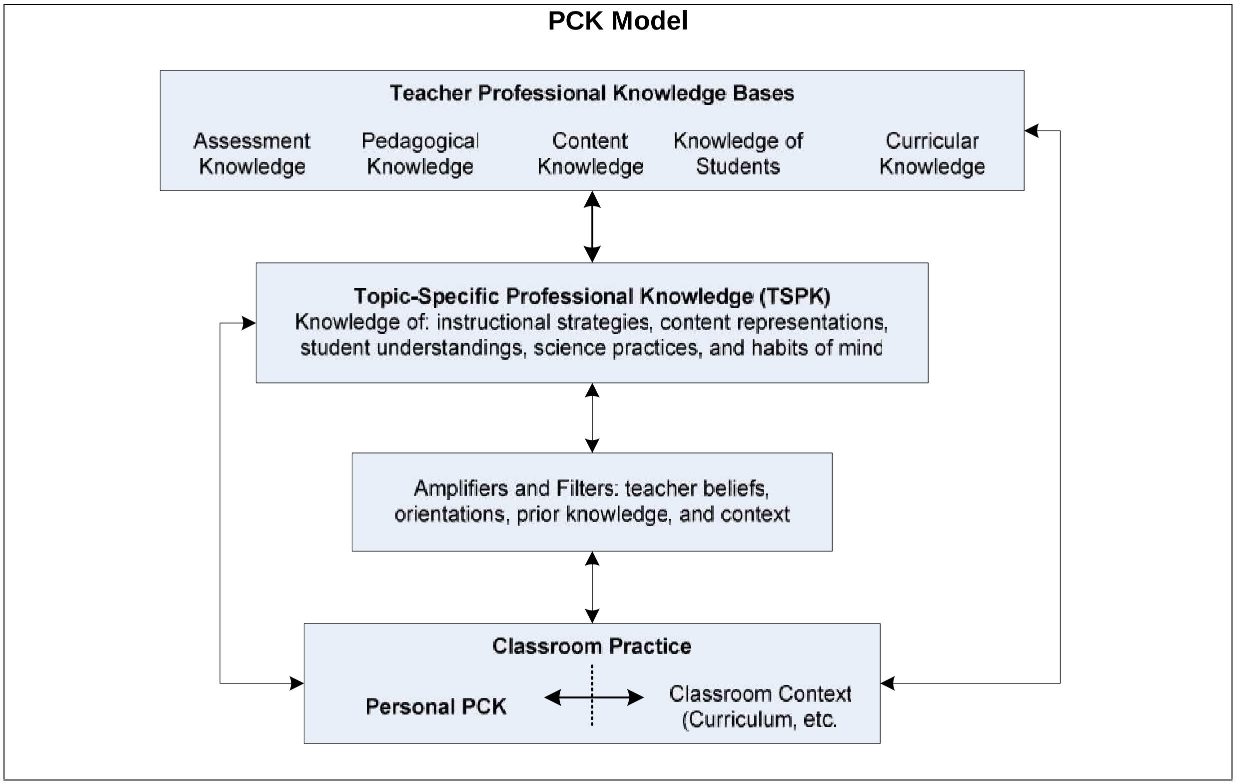

Figure 1

C-PCK has the potential to help elementary teachers overcome knowledge-related obstacles to science teaching in several ways. Most importantly, C-PCK provides a rich resource for helping teachers incorporate what is known about effective teaching of a topic into their instruction (see Figure 2). C-PCK can be a valuable instructional planning resource or it can, for example, be the focus of discussion in a teacher study group or professional learning community. Another high-leverage use of C-PCK is in instructional materials development (Banilower, Nelson, Trygstad, Smith, & Smith, 2013). For example, instructional materials can be infused with C-PCK, making the knowledge directly available to teachers, both through the design of activities for students and in the supports for teachers that accompany those materials, making the instructional materials "educative" for the teacher (Davis & Krajcik, 2005). Similarly, teacher educators and professional development providers can use C-PCK to craft and provide topic-specific support for pre-service and in-service teachers.

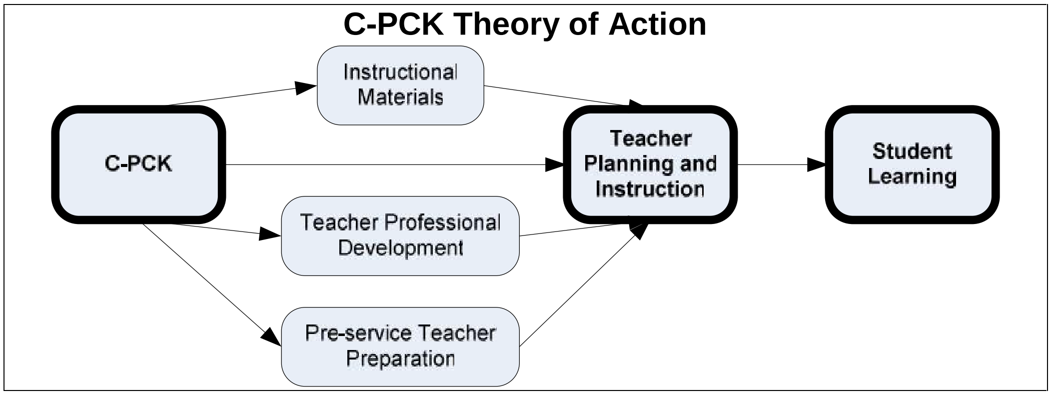

Figure 2

There is a common perception that C-PCK is widely available. Although C-PCK exists and has been compiled in a few topics (e.g., empirical research abounds for force and motion), many, perhaps most, science topics are not well researched. Even a brief search of the literature illustrates the lack of easily accessible C-PCK in many topics. In addition, the literature that does exist is not organized for use. Therefore, teachers are left to winnow through an unorganized literature of sometimes suspect quality, whether it is empirical research or wisdom of practice. To illustrate, a search of peer-reviewed literature in the ERIC database using the terms "ecosystems" and "elementary education" returns 77 results, which seems encouraging. However, only a few of the articles are relevant for an elementary teacher planning a unit or lesson on ecosystems. The following articles appear at the top of the results list (bold text added for emphasis):

- *The* ***Lifelong Learning Ecosystem*** *in Korea: Evolution of Learning Capitalism?*
- *Writing to Learn Ecology:* ***A Study of Three Populations of College Students***
- ***Ecological Psychology****: Potential Contributions to Social Justice and Advocacy in School Settings*
- ***Seeding Evolutionary Thinking*** *by Engaging Children in Modeling Its Foundations*

At the opposite end of the spectrum, a search for a more focused concept—"interdependence" within ecosystems at the elementary level—returns no results. Similar searches in Google (which teachers are probably more likely to use than ERIC) result in several hundred thousand results, but there is no way to vet the quality of these resources.

The vast majority of elementary teachers (92 percent) are responsible for teaching multiple subjects (Banilower et al., 2013). Their preparation time is severely limited, and they feel inadequately prepared to teach science. Elementary teachers do not have the time, and many do not have the necessary background, for extensive literature searches. The immediate goal of our study—titled Knowledge Assets to Support the Science Instruction of Elementary Teachers (ASSET)—is to test a method for collecting and synthesizing PCK, then assemble that knowledge in a C-PCK resource that will transform teacher practice. The larger goal is to create an efficient, scalable method that can be applied to a broad array of science topics. To these ends, our project is exploring the following questions:

1. What are the strengths and weaknesses of a C-PCK collection-and-synthesis method?

2. What factors must be taken into account in applying the C-PCK collection-and-synthesis method across topics?
3. What affordances and limitations does the C-PCK resource present for teachers primarily, and also for teacher educators and instructional materials developers?
4. How does access to C-PCK affect teachers' planning and instruction?

Reporting on our work to date, this paper focuses exclusively on the first two research questions.

METHODOLOGY

To test the robustness of the C-PCK collection-and-synthesis method across topics, our study (titled Knowledge Assets to Support the Science Instruction of Elementary Teachers, or ASSET) focuses on two disciplinary core ideas in the NGSS at 5th grade: (1) Structure and Properties of Matter (which we refer to as the Small Particle Model, or SPM), and (2) Interdependent Relationships in Ecosystems (which we refer to as Interdependence). The work of identifying and synthesizing C-PCK proceeded on two fronts. First, we reviewed empirical research studies and synthesized information on student understanding and topic-specific instructional strategies. Second, we collected and synthesized practice-based knowledge about instructional strategies reported to be effective in developing student understanding of the designated topics. We anticipated that practice-based knowledge, a long-overlooked resource, would be the primary source of C-PCK for some topics in the NGSS. We collected practice-based knowledge through literature searches and through surveys and interviews of teachers, science education researchers, and instructional materials developers, each with topic-specific expertise.

We recognized that before work could begin on these fronts, we needed to be very clear about the science ideas included in the two topics. Therefore, the first step in the process was to unpack and clarify the two topics (SPM and Interdependence). These content clarifications were reviewed for content accuracy by a university scientist or science educator with expertise in the topic. The clarifications were then revised based on their feedback. The final versions of each clarification are shown in Figures 3 and 4.

Small Particle Model

NGSS Disciplinary Core Idea (5-PS1.A partial)

1. 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 showing that gases are made from matter particles that are too small to see and 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. (PE 5-PS1-1; DCI PS1.A)

2. The amount (weight) of matter is conserved when it changes form, even in transitions in which it seems to vanish. (PE 5-PS1-2; DCI PS1.A)

ASSET Clarification

1. All matter is composed of particles that are too small to see even with a microscope.
   a. The particles have empty space between them.
   b. The particles are in constant random motion.

2. A particle model of matter can be used to describe and explain important phenomena, including what happens when a liquid evaporates and when a solid dissolves in a liquid. The model can also explain why matter is conserved when it changes form.

Figure 3

Interdependence

NGSS Disciplinary Core Idea (5-LS2.A)

The food of almost any kind of animal can be traced back to plants. Organisms are related in food webs in which some animals eat plants for food and other animals eat the animals that eat plants. Some organisms, such as fungi and bacteria, break down dead organisms (both plants or plants parts and animals) and therefore operate as "decomposers." Decomposition eventually restores (recycles) some materials back to the soil. Organisms can survive only in environments in which their particular needs are met. A healthy ecosystem is one in which multiple species of different types are each able to meet their needs in a relatively stable web of life. Newly introduced species can damage the balance of an ecosystem.

ASSET Clarification

1. The food of almost any kind of organism can be traced back to producers such as plants and algae.
   a. Food provides organisms the materials and energy they need to grow and function.
   b. Producers make their own food *inside themselves* using (1) energy from the sun and (2) matter from air and water.

2. Organisms in ecosystems are related in food webs
   a. Consumers get their food by eating other organisms. Some consumers eat producers. Some consumers eat other consumers.
   b. Decomposers, such as bacteria, fungi and earthworms, are consumers that break down dead organisms (or parts of organisms).
   c. Decomposition eventually restores (recycles) some materials back to the environment, making necessary materials available to producers.

3. Organisms can survive only in environments in which their particular needs are met. Environmental conditions include, but are not limited to, light, temperature, moisture, amount of oxygen, nutrient availability, and salinity.

4. In a healthy ecosystem, the needs of multiple types of organisms are met in a relatively stable web of life.

5. Natural events and human activity can change the balance or stability of an ecosystem. When the balance, or stability, of an ecosystem changes, the opportunities for different types of organisms to meet their needs can increase or decrease.

Figure 4

Approach #1: Collection of Empirical Knowledge

Project researchers conducted a review of empirical studies (and syntheses of empirical studies) for each topic, which consisted of searching the literature (e.g., refereed journals, conference proceedings, or published books), reviewing studies, and synthesizing findings. Researchers began the literature search by identifying a list of key search terms, such as "particle model of matter," "structure of matter," and "teaching methods" for SPM. The full list of key terms for each topic can be found in Table 1. Individually, these terms returned a broad spectrum of results from the search engines (ERIC and Google Scholar among them), so many of the terms were used in combination in order to narrow the literature to that which relates to elementary teaching. Two examples include, "particle model AND elementary students" and "changes in state AND misconceptions[1].” To be included in the review, a study had to meet the following criteria:

- Reported in a peer-reviewed journal, peer-reviewed conference proceedings, or an edited book;
- Included K–8 students in the study sample;
- Was a systematic empirical study (strictly theoretical pieces were not included); and
- Could not be a literature review only (however, the bibliographies of these articles were used to identify primary sources).

Table 1
Key Search Terms

SPM			
Changes in state	Elementary education	Misconceptions	Science education
Chemistry	Elementary school science	Models	Scientific concepts
Cognitive development	Evaporation	Particle model of matter	States of matter
Computer simulations	Gaseous state	Particulate	Structure of matter
Concept formation	Instructional design	Particulate nature of matter	Student ideas
Conservation of mass	Instructional strategies	Particulate theory	Student thinking
Condensation	Learning progressions	Pedagogy	Teaching methods
Interdependence			
Activities	Ecosystem	Elementary education	Lessons
Concepts	Ecosystem imbalance	Elementary student	Predator
Curriculum	Ecosystem interdependence	Food web	Prey
Decomposer	Ecosystem interdependencies	Instruction	Producer
Decomposition	Ecosystem misconceptions	Learning	Student knowledge
Ecology	Ecosystems	Lesson	Student thinking
Ecology misconceptions	Elementary	Lesson plans	Understanding

Articles were initially screened by reading only the abstract. Those that appeared to meet the review criteria were saved in a reference management program. The project team also created a list of tags to be applied as the articles were read more carefully. These tags were used to filter the collection. For example, articles that were found to focus on high school students, pre-service teachers, or in-service teachers (but not K–8 students) were excluded from the final collection of literature.

Once the literature pool was finalized, researchers began coding the kinds of PCK in each study for teaching the topic to upper elementary students. The coding scheme was both *a priori*, based on the Magnusson et al. (1999) model of PCK, and emergent. Magnusson et al. describe discrete forms of PCK, including knowledge of instructional strategies, knowledge of students’ understanding of science, and knowledge of science curriculum. In some cases, we elaborated on these forms, for example adding *misconceptions* and *learning progressions* as categories of knowledge of student understanding.

[1] 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.

Because the articles in the pool varied in the quality of the research designs, the research team added a confidence rating for each piece of PCK coded. This rating was intended to reflect the reliability and generalizability of the PCK. For example, if an article claimed that upper elementary students are likely to have a particular misconception, the rating conveyed how confident we were that the claim is true. To determine the confidence rating, we adapted the Standards of Evidence (SoE) review (Heck & Minner, 2009). The SoE review assesses the extent to which key components of the research are documented and judges support for findings considering each question that the publication addresses. Key in the assessment of rigor is the consideration of multiple aspects of internal validity. We selected a subset of indicators in order to create an abbreviated review process, focusing on five factors:

1. Sample size;
2. Appropriateness of analyses;
3. Validity and reliability of research instruments;
4. Appropriateness of generalizations; and
5. Potential for investigator bias.

Additionally, we looked at the alignment of the purpose of the research and the coded PCK when determining the confidence rating. If a study was not designed to identify student misconceptions, but student misconceptions were identified incidentally, the coded misconceptions received a low confidence rating. However, if the same item of PCK was extracted from many articles in the literature pool, even if it received a low confidence rating each time, the item would receive a high rating overall based on the accumulation of evidence.

A codebook was developed to provide descriptions of each code, rules for when a code should be applied, and explanations of how to determine confidence ratings. The codebook is included in the Appendix. The project team iteratively reviewed articles, applied the coding scheme (comparing codes and confidence ratings), and refined the codebook.

Approach #2: Collection of Practice-based Knowledge

Given the anticipated limits of empirical literature, and the great need for C-PCK, we decided to tap practice-based knowledge as well. First, we searched for and reviewed practitioner literature; for example, articles that appear in *Science and Children*. In contrast to systematic studies reported in empirical literature, we reviewed practitioner articles for reports of practitioners' experiences using particular instructional strategies to teach a topic. To be included in the review, an article had to meet the following criteria:

- Provided evidence of peer review;
- Included K–8 students in the instructional focus;
- Focused on instructional experiences or findings aligned with at least one of the ASSET clarification ideas;
- Had minimal or no cost;
- Was not dated (e.g., did not include inaccurate statements or culturally insensitive language); and

- Had a strong likelihood of being accessible by most educators.

We applied additional criteria to articles for Interdependence to ensure broad applicability of PCK to a variety of instructional contexts. Specifically, we did not review articles focusing on specific types of ecosystems (e.g., longleaf pine, coral reef), or particular types of organisms (e.g., insects, duckweed, polar bear) when connections to general ecosystem concepts were not evident. Likewise, we excluded many articles that focused on photosynthesis without emphasizing its role in ecosystems.

The second strategy for collecting practice-based knowledge played out much differently than expected. We planned to construct expert panels and elicit wisdom of practice via an online panel format, consistent with Loughran et al.'s assertion that efforts to collect and synthesize practitioners' PCK must work at both individual and collective levels (Loughran, Mulhall, & Berry, 2004). The panels were envisioned as a variation of the Delphi panel strategy, which has been used in many fields to elicit knowledge from expert practitioners (Edmunds, Garratt, Haines, & Blair, 2005; Hauck, Kelly, & Fenwick, 2007; Kingsley & Waschak, 2005; Muijs, 2006; Roff, McAleer, & Skinner, 2005; Wen & Shih, 2008). Panelists would respond in writing to a set of questions (described below) about the topic. Responses would then be analyzed and synthesized to generate draft statements of C-PCK, and iterative panel rounds would be conducted to clarify areas of disagreement.

The panels (one for each topic) were to consist of 12 experts: 6 master elementary teachers, 3 teacher educators, and 3 instructional materials developers. Each panelist was to have expertise in the relevant topic. The master teachers would be individuals who had extensive experience teaching the target topic, had experience supporting other teachers in the topic, and were recognized by their peers for their excellence. As planned, we selected them primarily from recipients of and finalists for the Presidential Award for Excellence in Mathematics and Science Teaching (PAEMST). Teacher educator panelists were to include both college/university faculty and professional development providers, and instructional materials developers would include individuals who had been involved in developing materials in the two topics at the elementary level. For reasons described in the Findings section, we surveyed and interviewed all types of practitioners, but we did not implement iterative rounds. In addition, we collected data from more teachers than planned and from fewer teacher educators than anticipated.

The interview and survey questions for panelists were adapted from the <u>Co</u>ntent <u>Re</u>presentation (CoRe) interview, developed by researchers at Monash University in Australia (Loughran et al., 2004) and used widely in studies of teacher knowledge. Adapted CoRe interview questions for practitioners are listed in Figure 5. The survey followed a similar structure.

Sample Interview Questions for Practitioners

1. What do you think 4^{th}–6^{th} graders need to already know or understand in order to learn [this content]?
2. What ideas, naïve conceptions, or misconceptions do you think 4^{th}–6^{th} graders have that would make it difficult for them to learn about [this content]?
3. What kinds of prompts or strategies might you use to get students to express their initial ideas about [this content]?
4. Can you think of anything about students' development at this age (10–11 yrs old) that may make [this content] difficult for them to learn?
5. Can you think of experiences that kids this age may have had—whether in school or out of school—that you could draw on to help them understand [this content]?
6. How would you go about teaching [this content] to 4^{th}–6^{th} graders? What approaches, activities, or strategies would you use?
7. Can you think of other resources (e.g., readings, simulations, etc.) for helping 4^{th}–6^{th} graders develop an understanding of [this content]?
8. What else, if anything, should someone teaching [this content] know or consider that you have not already talked about?

Figure 5

Synthesizing Findings from the Two Approaches

We are currently synthesizing findings from empirical literature and practice-based knowledge (from practitioner literature and practitioners' responses) about the teaching and learning of SPM. (We are still collecting practice-based knowledge for Interdependence and have not yet started to synthesize across empirical and practitioner sources.) As described earlier, the goal is to use practice-based knowledge to fill in gaps in the empirical literature. Ultimately, the synthesized C-PCK will be made available to the field through a project website. The comprehensive process is summarized in Figure 6.

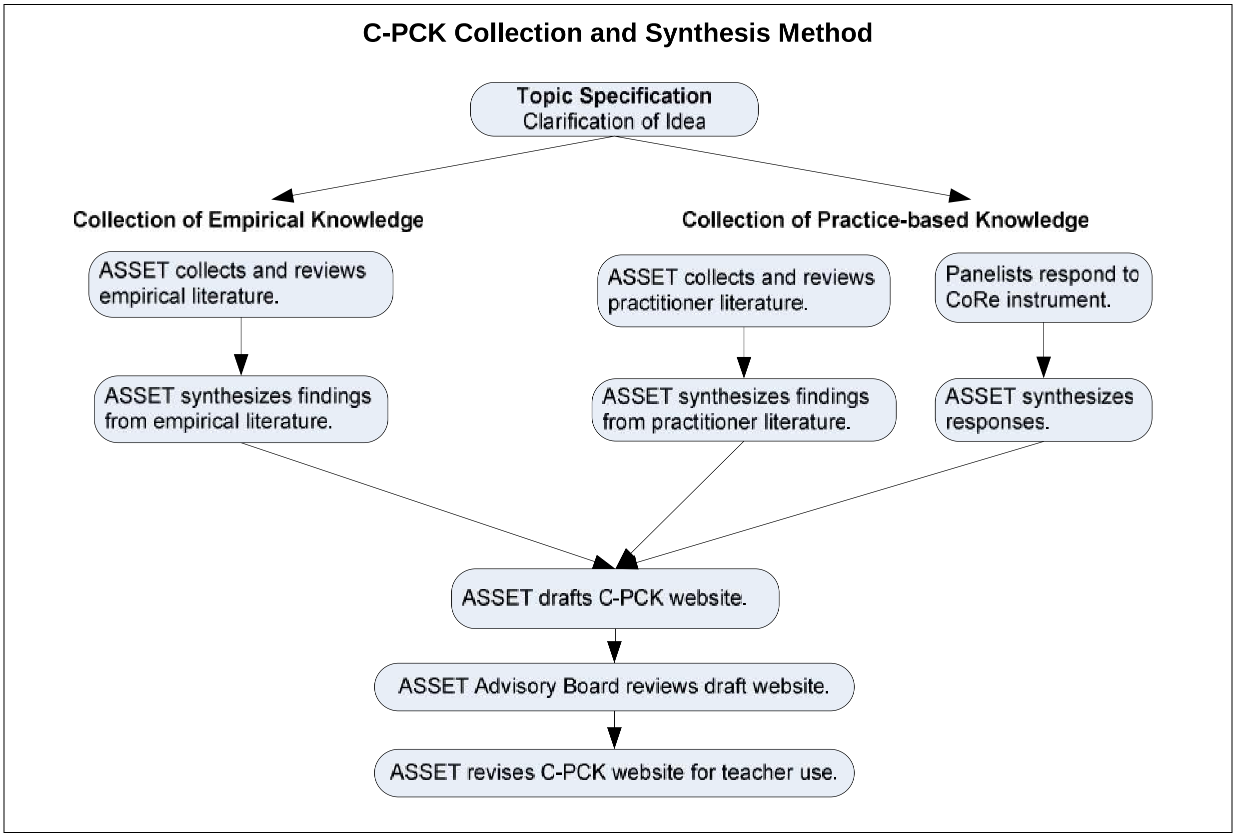

Figure 6

FINDINGS

As mentioned above, we selected two 5th grade DCIs from the NGSS, one from physical science (SPM) and one from life science (Interdependence). This design feature was intentional, allowing us to explore the possibility that the types and amount of PCK available might vary by topic. In retrospect, selecting SPM as one of the topics was probably a mistake. The NGSS advocate a particle approach to this topic, but without invoking atoms and molecules. Historically, the content has not been addressed in this way. *The National Science Education Standards* (National Research Council, 1996) did not introduce the particle model of matter (using atoms and molecules) until grades 9–12, justifying the placement as follows:

> It can be tempting to introduce atoms and molecules or improve [grades 5–8] students' understanding of them so that particles can be used as an explanation for the properties of elements and compounds. However, use of such terminology is premature for these students and can distract from the understanding that can be gained from focusing on the observation and description of macroscopic features of substances and of physical and chemical reactions. (National Research Council, 1996, p. 149)

The *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993) introduced the particle model in middle grades (6–8), but no earlier. The

Benchmarks state that, “By the end of 8th grade, students should have sufficient grasp of the general idea that a wide variety of phenomena can be explained by alternative arrangements of vast numbers of invisibly tiny, moving parts” (American Association for the Advancement of Science, 1993, p. 77).

As noted above, SPM has traditionally been taught using atoms and molecules, as well as atomic/molecular mechanisms, something the NGSS explicitly discourage: “Assessment does not include the atomic-scale mechanism of evaporation and condensation or defining unseen particles” (NGSS Lead States, 2013, p. 43). In the discussion of findings below, it is important to bear in mind that although we are applying our methodology to two topics to test its generalizability, one of those topics may in fact have been an outlier in the sense that it is new to elementary grades instruction.

Searching the empirical literature yields PCK that is predominantly about student thinking related to the content.

The search-and-screening process yielded 44 empirical articles and book chapters for SPM and 55 for Interdependence (bibliographies are included in the Appendix). Although these numbers may seem low, it is important to remember that studies had to meet specific criteria to be included, as described earlier. From these, we coded approximately 300 instances of PCK for each topic. The vast majority of these instances were in the category of student thinking (e.g., misconceptions, alternative conceptions, cognitive precursors, and learning progressions). Examples of coded PCK include:

- For the Small Particle Model
    - Elementary-age students often think of matter as continuous rather than particulate.(Nakhleh & Samarapungavan, 1999; Renström, Andersson, & Marton, 1990)
    - Students who acknowledge a particulate nature of matter sometimes think that a substance (e.g., air or water) fills the empty spaces between the particles. (Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993; Novick & Nussbaum, 1978)
    - Students who acknowledge particle movement often think it occurs only when external forces are applied. (Lee et al., 1993)

- For Interdependence
    - Students often think that organisms can be affected only by those that are directly linked to them in food webs. (Grotzer, 2009; Özkan, Tekkaya, & Geban, 2004)
    - Many students think that dead organisms (or organism parts) are absorbed by soil or simply disappear, and thus see no role for decomposers in ecosystems. (Hogan & Fisherkeller, 1996)
    - Students who acknowledge that plants make their own food often do not realize that they need light, water, and air to do so. (Helldén, 1998)

From these studies, we were also able to code a large number of prompts that researchers used to elicit student thinking (i.e., they were not designed for instructional purposes but might be used as such). For example:

- For the Small Particle Model
    - Imagine you are Superman and can see inside a material (water, clay, stone, wood, etc.) with your x-ray vision. Draw what you see with as much detail as possible. (Acher, Arcà, & Sanmartí, 2007, p. 406)
    - When you fan yourself with your hands, although your hands do not touch your face, you feel that something hits your face. In your opinion, what might this be? (Durmuş & Bayraktar, 2010, p. 501)

- For Interdependence
    - Plants need food for growth, just as animals do. Where does their food come from? (Smith & Anderson, 1984, p. 693)
    - One student I talked to said that bigger animals eat small animals in a food web. Do you agree or disagree, and why? (Grotzer, 2009, p. 26)
    - Where does soil come from? (Helldén, 1998, p. 6)

Nearly all the studies that met our criteria can be divided into two categories with respect to their main focus—examinations of student thinking and instructional efficacy. For SPM, more than three quarters of the documents focused mainly or exclusively on student thinking. For Interdependence, the main focus was more evenly divided with only slightly fewer targeting instructional efficacy than student thinking. For example, we found empirical studies about the efficacy of fieldwork strategies for teaching about Interdependence. We also found studies comparing alternative means for teaching about food webs, including some studies that explored students' thinking in response to teaching approaches that emphasized either concrete interactions among organisms or more abstract system-level thinking.   Finally, a few studies examined the utility or efficacy of role-play or other simulation-based strategies.

We anticipated a focus on student thinking in the empirical literature, and it motivated our plans to incorporate practice-based knowledge. However, we were surprised by the heavy emphasis on student thinking in the research on both topics.

The PCK available in practitioner literature is heavily dependent on the topic.
As mentioned above, SPM has typically been introduced after elementary grades and has typically incorporated atoms and molecules. Our search uncovered only a handful of articles related to teaching SPM to elementary students, and we believe it is because the topic has not broadly been taught as advocated in the NGSS. We did find practitioner literature on properties and states of matter, but the emphasis was on description rather than explanation. We did not find instances in which SPM was invoked to explain properties, changes or state, or other related phenomenon (e.g., conservation of matter during phase change or dissolving).

In contrast, we found approximately 70 pieces of practitioner literature for Interdependence. The vast majority of these focused on ideas for teaching the content. About half described a coherent unit of instruction for content that included, or substantially overlapped with, the ASSET clarification ideas. Activities within many of these units depended on visits to particular types of ecosystems or even specific locations, and may therefore have less general utility. About one-third described a single activity that was intended to be implemented as a discrete lesson (e.g., one or two class periods). We often found these descriptions in practitioner-oriented periodicals such as *Science Scope* or *Science and Children*. Eight of the practitioner pieces described an "approach" (e.g., incorporating simulations into instruction) and used an activity or activities as an example to illustrate that approach. Just 1 of the 70 pieces had an exclusive focus on student thinking and did not center on instruction. Our search surfaced many documents from the 1970s, perhaps reflecting a time of great emphasis on environmental education more generally.

Identifying expert teachers was much more difficult than anticipated.
The first challenge in identifying expert teachers was defining the criteria for expertise. The goal was to recruit teachers with expertise teaching the topic (SPM or Interdependence), but evidence of such expertise was elusive. Instead, for SPM, we recruited teachers who had documented evidence of expertise as science teachers and who had at least some experience teaching the topic. For this purpose, we used the network of recipients of, and finalists for, the PAEMST. One of the individuals who reviewed SPM ideas for the project is a PAEMST awardee and offered to announce the study to various PAEMST social media groups. However, so few individuals volunteered for the study that we were unable to select a subset based on expertise demonstrated through materials submitted (see the finding below related to the CoRe questionnaire). Each of the individuals reported teaching about SPM, but it became clear in reviewing their questionnaire responses and submitted materials that the core ideas were not a central focus of their instruction about matter, and sometimes not a focus at all.

As a result, we decided to cast a broader net and collect more information about teachers before asking them to serve as experts. Using an email list of approximately 600 grades 4–5 teachers in the U.S., we sent an invitation to register for the study. The registration form included several questions designed to help identify teachers with substantial experience teaching the topic (a proxy for expertise), among them:

- Years of teaching experience;
- Familiarity with the NGSS;
- Amount of instructional time spent on the topic;
- Number of times the individual had taught the topic; and
- Attention to ideas within the topic (e.g., within SPM, registrants indicated whether they focused on the idea that particles are in constant random motion).

Well over 100 teachers registered for each topic, allowing us to select those who appeared, based on their answers, to have substantial experience teaching the topic and also to include a focus on the ideas within the topic. We subsequently collected data about teachers' instruction from a much larger number of individuals than we planned, with the idea that PCK would be validated by the frequency with which it appeared in their data rather than relying on evidence of individual teachers' expertise (e.g., being the recipient of an award). The topic-dependent nature of practitioner literature appears to also be evident in teachers' firsthand accounts of their PCK. Data collected from teachers about their instruction related to SPM suggest little actual experience teaching the content, despite their indications to the contrary when they registered for the study. Rather, in their responses, we see an emphasis on properties of matter without a focus on the underlying explanatory power of SPM. For example, many teachers described student thinking and their instruction for states of matter and changes of state, but their descriptions did not indicate that addressing particles or particle behavior was an important aspect of instruction. In contrast, the data collected so far from teachers about their instruction on Interdependence indicate that they actually do teach the ideas as envisioned in the NGSS. For example, teachers provided evidence that their instruction focused on such ideas as producers using light, air, and water to make their own food; transfer of matter and energy in food webs; the role of decomposers in recycling matter within ecosystems; and changes for one population in a food web affecting all others.

Getting teachers to articulate their PCK has been more challenging than anticipated. Despite literature suggesting that teachers may struggle to articulate their PCK (e.g., Loughran et al., 2004), we were surprised at the magnitude of the difficulty. The CoRe questions (see Figure 5) are perfectly reasonable questions, but teachers rarely have an opportunity to consider them in conversation with others. They require a level of reflection that teachers are clearly capable of but have little or no reason to engage in. The questionnaire version of the CoRe questions did yield some PCK (more so for Interdependence than for SPM), but we have found ourselves wanting to follow up on responses with questions like, "Why that activity at that time?" and "How does that activity relate to the rest of your instruction on this topic?"

We believe we have had more success with interviews based on the CoRe, which is the format for which it was originally designed. That said, the interviews are difficult to conduct well, requiring advanced interview skills and a deep familiarity with the content and PCK for the topic. We found that an interview question activates a tacit and not clearly organized network of knowledge. Consequently, the interviewer has to be able to follow the teacher wherever he or she goes until the network is fully articulated, at least to the best of the teacher's and interviewers' ability. Teachers often strayed into content that is clearly not a part of the ideas as laid out in the NGSS; for example, teachers began discussing their instruction about chemical bonding.

In interviews, evidence of teachers' lack of experience articulating their PCK is seen in their frequent use of the phrase, "We talk about…," referring to their instruction about a particular topic or idea. When interviewers probed on this response, it was clear that sometimes teachers literally talked about the ideas with their students. For example, one teacher described talking with the students about what would happen if a bottle of perfume were opened in the classroom, but without ever actually bringing a bottle of perfume to class and opening it. For other teachers, "we talk about…" was just a placeholder for a variety of instructional approaches that went beyond discussion.

Finally, the generative function served by asking teachers to articulate their PCK is worth noting. As teachers respond, tacit knowledge can become explicit, and teachers sometimes form new PCK for themselves in describing their instruction and the underlying assumptions. This fact makes representing a teacher's PCK particularly difficult, as it may not be stable. It was not uncommon for teachers to answer, "I've never thought about that" to some of the CoRe questions, but that did not deter them from elaborating.

Instructional materials developers may be particularly rich sources of practitioner PCK.
To date, we have interviewed three developers of instructional materials for SPM. Although the sample is small and almost certainly not representative, we have found them much more able to articulate their PCK and, consequently, richer sources of PCK. Each of the individuals has substantial experience developing materials and supporting teachers in using those materials. They have clearly thought deeply about the kinds of knowledge teachers need, both in the process of developing materials and in designing professional development experiences. In short, these individuals have had both reason and opportunity to articulate their PCK. An example of each individual's PCK follows:

- One developer reported using the terms "atoms" and "molecules" with 5th grade students. When questioned about this decision, the developer explained that students were more comfortable with those words than "particles." The students did not understand the scientific significance of the terms, but they used them spontaneously when talking about "water molecules" for example. In response, the developer began using "atoms" and "molecules" as synonyms for "particles" in order to facilitate student understanding of SPM. There was no expectation that students understand the scientific meanings of the terms.

- One developer described students' thinking about vacuum as a particularly rich context for developing the small particle model. Students have a deeply held notion that a vacuum is associated with "sucking," when SPM explains that in fact air particles (or those of some other gas) are pushing. Using a computer simulation, students can visualize what happens when air particles are added to or removed from a system.

- When asked what students need to know or understand before engaging with SPM, one developer stressed the importance of understanding the idea of inference—i.e., making claims about things that cannot be seen from things that can. The developer explained that inference is critical for learning about SPM because students will never be able to see the particles. Instead, they will have to infer from phenomena they can see—for example, a balloon shrinking as the air around it cools or the conservation of matter when sugar dissolves in water.

In each of the instances, there is an element of explicitly purposeful thinking that we rarely saw in interviews with teachers. That is, the developers could describe what they did in their materials as well as why, and the why in each case was based on student thinking.

An appropriate grain size for sharing C-PCK is not clear.
Our ultimate goal is to make the PCK we collect available to teachers, teacher educators, and instructional materials developers. For some types of PCK, we anticipate sharing the knowledge in essentially the same form we found it in the literature or learned about it from practitioners. For example, with regard to SPM, we know from multiple sources that 5th grade students are likely to struggle conceptualizing the existence and behavior of particles that are far too small to see. We also know that a particularly common approach to revealing student thinking about this aspect of the model is to ask students to imagine and draw what they would see if they looked at

something (e.g., a glass of water) with very strong magnifying glasses. Similarly, we know that instruction often incorporates students interacting with on-line simulations—for example, the PhET simulations (https://phet.colorado.edu/). We anticipate sharing these instances of PCK essentially as is. Less clear is what to do with an intact lesson plan or curriculum unit, particularly if copyright is involved, which is often the case. On one hand, these resources may be just the ones teachers need. On the other hand, they may be inaccessible (e.g., a lesson plan from a journal that requires a subscription for access) or prohibitively expensive (e.g., a module from a kit-based commercial curriculum). Our current thinking is that we will not share lesson- or unit-level instantiations of PCK but rather the more general (but still topic-specific) principles on which they are based.

CONCLUSIONS AND IMPLICATIONS

The ASSET project was based on an assumption that the PCK available in empirical literature for any given topic would be spotty and that we would be able to fill in the gaps with practitioner knowledge. For SPM, the empirical literature contains substantial knowledge about how students think about the structure of matter but very little about how to teach the ideas to upper elementary students. In Interdependence, the empirical literature was more balanced but still biased toward student thinking. We are not certain how much of the difference in emphasis between the two topics is due to the newness of SPM in upper elementary grades.

In addition to our empirical literature review, a survey of curriculum materials (e.g., STC, Insights, and FOSS) and pre-NGSS state and national standards also supports the claim that SPM is uncharted territory for many if not most elementary teachers. As such, the topic presents unique challenges in terms of available PCK. The newness of the topic also presents a formidable challenge for teachers in terms of availability of instructional materials. Of course, because of the emphasis on 3-dimensional learning, the NGSS present major challenges for all teachers, but SPM is unfamiliar content in addition. We wonder how many other topics in the NGSS are like SPM in this regard and how teachers can best be supported in teaching them.

As we became aware of the widespread unfamiliarity with SPM, we began considering experience teaching the targeted content as a factor when selecting study participants. Despite such considerations and subsequent changes to our recruitment process, our efforts to complement PCK from empirical literature have so far had limited success. In particular, we, like others, have found it difficult to draw PCK out of teachers. The teachers we interviewed seemed to fall in three categories. Teachers in the smallest of these categories were able to describe how they teach a topic and why they employ particular strategies. Another group could explain in procedural terms but did not seem to consider the rationale, and a third group seemed to rationalize their instructional approaches on the spot. If teachers have difficulty articulating their PCK, and if, as we believe, they are sometimes forming it in the moment (e.g., during an interview), we wonder about the implications for the validity of their knowledge. To the extent that their accounts are consistent with other sources of PCK, validity is not such a concern. However, when teachers are the only source for a particular instance of PCK, we think that validity is contingent upon the knowledge being revealed by several teachers. Otherwise, C-PCK could be based on an N of 1, and that seems contradictory to the notion of the construct.

Taking into account sample size and validity, we incorporated a survey approach in our method because of the potential for efficiency, but, as noted above, found that it was not particularly effective. We thought the number of individuals we collected survey information from might compensate for any individual's inability to express their PCK. And although their contributions were somewhat complementary, we found interviews to be more productive. The researchers who developed the CoRe interview approach did so in large part because of their lack of success eliciting PCK through a questionnaire, so although we were disappointed by the ineffectiveness of surveys, we were not particularly surprised. The implication is that collecting PCK from practitioners is more labor intensive (and therefore more expensive) than we anticipated.

Another dimension of our PCK collection efforts consists of interviews with instructional materials developers. Our experience with these individuals contrasts sharply with our efforts to gather PCK from teachers. The materials developers we interviewed were able to articulate both procedure and rationale, but this finding is based on the small number we were able to identify for SPM. We interviewed individuals we knew and asked them to recommend others, but there is an implicit bias in that method. For example, all of them developed what might be called non-traditional materials as opposed to the hardbound textbooks present in many elementary classrooms.

Based on what we have learned, we find it difficult to determine whether findings are representative of the PCK-collection process as a whole or are dependent upon the topic. SPM and its newness at the elementary level have presented challenges that may be unique to such unfamiliar content. Consequently, we are considering applying the methodology to a third topic, one that is more like Interdependence in terms of its traditional place in elementary grades instruction.

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APPENDIX

PCK Codebook for Empirical Literature

Code	Description	Extraction Rules	Confidence Rating
Misconception	Misconceptions are student ideas that are in conflict with accepted scientific ideas. Misconceptions typically arise from students' interaction with the physical world around them. A common misconception is that air does not have mass because they can't "feel" it. 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 the misconception at some point as they develop full understanding.	Extract all misconceptions from an article, even if identifying misconceptions was not the intent of the study. Can modify or paraphrase article text for clarity, brevity. Include missing conceptions with misconceptions. Capture related misconceptions separately when possible. When present, capture the cognitive source along with the misconception.	The confidence rating is about how confident we are that this misconception is widespread among 5th grade students based on the study in the article. If the point of a study was to identify student misconceptions and the article fares well in the rapid SoE review, the misconception gets a high confidence rating. All other misconceptions get a low confidence rating. NOTE: when we synthesize across studies, a misconception that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.

Code	Description	Extraction Rules	Confidence Rating
Misinformation	In contrast to misconceptions, misinformation is an incorrect fact not derived from every day experience with the physical world. For example, students might think that water freezes at 32 degrees Celsius. Students' misinformation is probably not as deeply ingrained in their thinking as misconceptions are.	Extract all misinformation from an article, even if identifying misinformation was not the intent of the study.	The confidence rating is about how confident we are that this misinformation is widespread among 5th grade students based on the study in the article. If the point of a study was to identify student misinformation and the article fares well in the rapid SoE review, the misinformation gets a high confidence rating. All other misinformation gets a low confidence rating. NOTE: when we synthesize across studies, misinformation that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.
Idea-level Consideration	Teaching tips are pieces of advice for teachers and are bigger than an individual activity, things that can be useful for teachers to know when teaching the topic. For example, "Investigating the expansion and compression of air is important for students' understanding of the concept of empty space between particles." NOTE: If a tip can be associated with all big ideas in the topic, it should be coded as a unit-level consideration instead (see below).	Extract all teaching tips from an article, even if identifying tips was not the intent of the study.	If the point of a study was to identify teaching tips and the article fares well in the rapid SoE review, the tip gets a high confidence rating. All other tips get a low confidence rating. NOTE: when we synthesize across studies, a tip that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.
Unit-level Consideration	Unit-level considerations (ULCs) are broader than teaching tips and apply to the entire unit, but they should not be broader than the unit (the latter might actually be pedagogical knowledge instead of PCK). For example, "Having students interact with computer simulations that depict particle-level representations of matter can help students understand the particle model of matter." Code a ULC to all big ideas in the topic.	Extract all ULCs from an article, even if identifying ULCs was not the intent of the study.	If the point of a study was to identify ULCs and the article fares well in the rapid SoE review, the ULC gets a high confidence rating. All other ULCs get a low confidence rating. NOTE: when we synthesize across studies, a ULC that shows up several times with a low rating may receive a high rating based on the accumulation of evidence.

Code	Description	Extraction Rules	Confidence Rating
Prompt	Prompts are questions or tasks that teachers would pose to their students in order to elicit their thinking in writing or orally to use for formative purposes. (Some prompts that are appropriate for research purposes (used in interviews, etc.) may be inappropriate for classroom use.)	Extract a prompt if the reviewer can envision a teacher using it with students as is. Bar for modifying prompt from article text is higher than that for misconceptions. If prompts that accompany activities or activity seeds can stand independently, capture as prompts. If not, don't.	The confidence in a prompt is based entirely on the content of the prompt (e.g., how well aligned it is with the idea, how "usable" it is by a teacher), as judged by the reviewer. For example, a prompt that contains wording that may be inaccessible for students would receive a low confidence rating.
Instructional Activity	Instructional activities are stand-alone, ready-to-use activities that teachers can use in their instruction "as is" with no additional written materials or training. Their purpose is to develop understanding of a big idea. That is, the article should provide enough information so that teachers are able to implement the activity in their classrooms. The learning goal should be explicit or easily inferred. NOTE: Eventually, we will categorize the activities into more general instructional strategies, such as lab experiments, simulations, readings.	Extract an instructional activity if a teacher can use it as is—i.e., it has sufficient context and instructions.	If the point of the article was to investigate the impact of an instructional activity, the confidence rating will be based on the findings of the article and a rapid SoE. If the instructional activity was incidental, the confidence rating will be low. If the article explicitly investigates the efficacy of an entire unit and uses an individual activity to illustrate the material, the activity would receive a low rating.

Code	Description	Extraction Rules	Confidence Rating
Activity Seed	Not a ready-to-use instructional activity, but a fleshed out idea for an activity. The seed must have enough description to determine that it fits some big idea(s) and to give a reasonable expectation that teachers could develop it into an activity.	Do not capture if seed is unsuccessful in implementation or in need of substantial modifications in order to be helpful	In order to have a high confidence rating, an activity seed must meet all three of the following criteria: • Is it explained in a way that is clear and accessible to teachers? • Are students likely to learn targeted content from it? • Is it feasible? (time required, materials required)
Summative Assessment Activity	Summative assessment activities are stand-alone, ready-to-use activities that teachers can use in their instruction to evaluate students.	Extract an assessment if a teacher can use it as is--i.e., it has sufficient context and instructions. Briefly summarize the form and substance of the assessment, and if there's a rubric, describe how it's structured, what kinds of factors it takes into account.	1. If the assessment does not have reliability and validity info, it should receive a LOW rating. (NOTE: if the reliability and validity info are in another article, the assessment should be extracted from that article.) 2. If the assessment does have reliability and validity info, the rating should be based on that information. Reliability should be above 0.7, and there should be at least one form of validity evidence.

Code	Description	Extraction Rules	Confidence Rating
Common Student Experiences	Common student experiences are things that a teacher can capitalize on in instruction, knowing that there is a good chance that most students have similar experiences. For example, most 5th grade students will have firsthand experience with an inflated balloon expanding or contracting based on temperature. Most have also observed a puddle disappear over time. Common student experiences may be keyed to one big idea or more than one.	Extract a common student experience if there is evidence in the article that most students come to instruction with the experience. An article that describes what just one student has experienced is not sufficient. Do not include previous instruction experiences.	The confidence rating is based on a rapid SoE review.
Developmental Challenge	Developmental challenges are things that students struggle with that are broader than misconceptions. For example, 5th grade students and younger may struggle to accept the existence of matter that is too small to see. Developmental challenges may be keyed to one big idea or more than one. Some developmental challenges may have associated ULCs. For example, we think that kids do not apply explanatory frameworks consistently, but rather that it is context specific (e.g., students may understand the particle model in the context of boiling water, but will not apply it to condensation on a cold drink can). The unit-level consideration is that teachers can't assume that just because kids use the particle model appropriately in one context, they will use it appropriately in another.	Extract a developmental challenge if there is evidence in the article that most students come to instruction with the challenge.	The confidence rating is based on a rapid SoE review.

Code	Description	Extraction Rules	Confidence Rating
Learning Progression	A learning progression will probably be identified explicitly in an article. A learning progression is at the topic level, so we do not need to code to individual big ideas. All misconceptions in a learning progression can be coded with the progression.	Extract a learning progression if the article describes a sequence of increasingly sophisticated and scientifically accurate understandings and skills within a domain that learners develop over several years.	The confidence rating is based on a rapid SoE review.

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