A Review of the Research Literature on Teaching about the Small Particle Model of Matter to Elementary Students

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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). Further, the expectations for elementary science instruction were recently raised to a new level. The Next Generation Science Standards (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. 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, 1986). 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 (1986) 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. 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. Recently, a new model of PCK emerged, one 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). Hypothesized relationships among these and other forms of knowledge are shown in Figure 1.

As illustrated in the model, discrete professional knowledge bases—disciplinary content knowledge chief among them—are the foundation for TSPK. Examples of TPSK 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 TSPK—through reading, professional development experiences, discussions with colleagues, reflecting on their practice—and use it in their teaching, it becomes personal PCK.

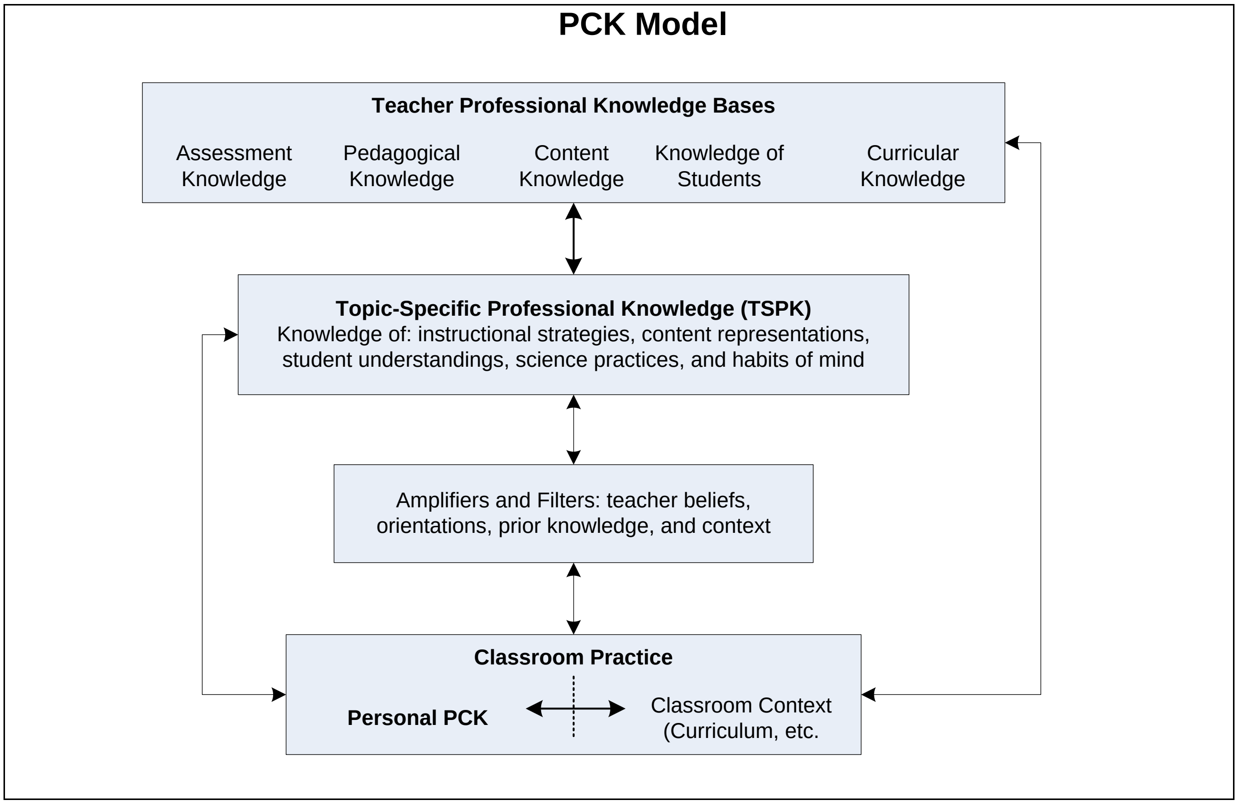

Figure 1

TSPK can help elementary teachers overcome knowledge-related obstacles to science teaching in several ways. Most importantly, TSPK provides a rich resource for helping teachers incorporate what is known about effective teaching of a topic into their instruction (see Figure 2). TSPK 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 TSPK is in instructional materials development (Banilower, Nelson, Trygstad, Smith, & Smith, 2013). Similarly, teacher educators and professional development providers can use TSPK to craft and provide topic-specific support for pre-service and in-service teachers.

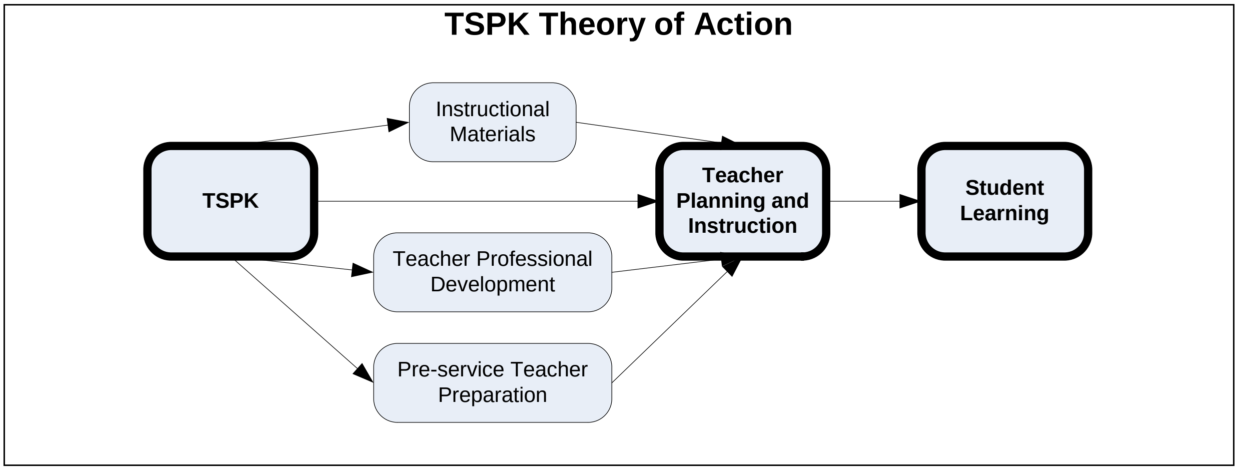

Figure 2

There is a common perception that TSPK is widely available. And although TSPK does exist and has been compiled in a few topics (e.g., empirical research abounds for student thinking about 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 TSPK in many topics. In addition, the literature that does exist is not organized for use.

With support from the National Science Foundation, Horizon Research, Inc. (HRI) is testing a method for collecting and synthesizing PCK from multiple sources, with the ultimate goal of making the resulting TSPK available to teachers as a support for implementing the NGSS. The method uses three sources: empirical research literature, practice-based literature (e.g., professional journals for classroom teachers), and expert wisdom of practice (collected by surveying and/or expert practitioners).

In this report, we describe the results of a review of empirical research literature related to teaching one topic from the NGSS. Our goal was to determine how much PCK for teaching the small particle model to upper elementary students could be "extracted" from the empirical literature. Subsequent reports will describe efforts to synthesize PCK from this source the practice-based literature and expert wisdom of practice.

METHODOLOGY

The literature review focused on the NGSS disciplinary core ideas (DCIs) related to the small particle model at the fifth grade: 5-PS1.A. We selected this topic, along with one other

(Interdependent Relationships in Ecosystems), to test our approach in two diverse areas. The NGSS state the ideas related to the small particle model as:

- 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.

- The amount (weight) of matter is conserved when it changes form, even in transitions in which it seems to vanish. (NGSS Lead States, 2013).

Although not stated in the DCIs themselves, the NGSS Framework states that at the 5th grade level, "no attempt is made to define the unseen particles or explain the atomic-scale mechanism of evaporation and condensation" (National Research Council, 2012, p. 108).

We rearranged the ideas in a way that would more easily allow us to organize findings from the literature:

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.

We began the literature search by identifying a list of key search terms, such as "particle model of matter," "structure of matter," and "teaching methods." The full list of key terms 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), therefore, 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] AND elementary education." To be included in the review, a study had to meet the following criteria:

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[1] In this report, "misconception" is used to denote any idea that conflicts with accepted scientific ideas about a phenomenon, acknowledging that such ideas are neither good nor bad and may represent a productive step in a student's learning progression.

- 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

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

Articles and book chapters were initially screened by reading only the abstract. Those that appeared to meet the review criteria (N = 120) were saved in a reference management program.

The project team created a list of tags to be applied as the literature was read more carefully, and the tags were used to filter the collection. For example, studies 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. The final pool included 49 studies, with publication years from 1978 to 2013 (median = 2004).

Once the literature pool was finalized, researchers began coding the kinds of PCK in each study for teaching the small particle model 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.

Because the studies in the pool varied in the quality of the research designs, the project 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 a study claimed that upper elementary students are likely to have a particular misconception, the rating conveys how confident we are 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. For example, if a study was not designed to identify student misconceptions, but student misconceptions were identified incidentally, the coded misconceptions receive a low confidence rating. However, if the same item of PCK was extracted from many studies in the literature pool, even if it received a low confidence rating each time, the item received 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 the collected literature, applied the coding scheme (comparing codes and confidence ratings), and refined the codebook. This process was tested with five studies in series until the project team reached a consensus understanding of the codes and applied them consistently. The project team then asked a researcher unfamiliar with the coding scheme to code a sixth study in order to confirm that the coding scheme could be applied without in-depth project knowledge. Minor modifications were made to the codebook based on the researcher’s feedback, and then one project researcher applied the coding scheme to the remaining articles in the pool.

In the next section, we summarize the substantive findings from the studies.

FINDINGS

The search and screening processes yielded 49 studies, shown in Table 2. An expanded version of the table, including a brief description of each study, appears in the Appendix.

Table 2
Study Summaries

Author (Year)	Where the study occurred	*n*	Age of subjects
1. Abraham, Grzybowski, Renner, & Marek (1992)	U.S.	247	8th grade
2. Abraham, Williamson, & Westbrook (1994)	U.S.	100	Jr high, high school, and college
3. Acher, Arcà, & Sanmartí (2007)	Argentina	24	Ages 7 and 8
4. Aydeniz & Kotowski (2012)	U.S.	87	Middle and high school
5. Bar & Galili (1994)	Israel	293	Ages 6–12
6. Bar & Travis (1991)	Israel	83	Ages 6–14
7. Beerenwinkel, Parchmann, & Gräsel (2011)	Germany	214	7th and 8th grade
8. Benson, Wittrock, & Baur (1993)	U.S.	1,098	2nd grade-college
9. Boz (2006)	Turkey	300	6th, 8th, and 11th grade
10. Çalik & Ayas (2005)	Turkey	100	8th grade and PSTs
11. Durmuş & Bayraktar (2010)	Turkey	104	4th grade
12. Gómez, Benarroch, & Marín (2006)	Spain	43	Ages 9–22
13. Herrmann-Abell & DeBoer (2011)	U.S.	13,360	Middle sch to college
14. Johnson (1998)	England	147	7th, 8th, and 9th grade
15. Johnson (2013)	England	4624	7th–10th grade
16. Johnson & Papageorgiou (2010)	England	45	Ages 9–10
17. Lee, Eichinger, Anderson, Berkheimer, & Blakeslee (1993)	U.S.	12 classes took test, 24 students did interview	6th grade
18. Liu & Lesniak (2005)	U.S.	US sample from TIMSS data	3rd, 4th, 7th, 8th, and 12th gr
19. Liu & Lesniak (2006)	U.S.	54	1st–10th grade
20. Löfgren & Helldén (2008)	Sweden	25	Longit. from age 7–13
21. Longden, Black, Solomon, Solomon, & STIR Group (1991)	England	442	Ages 11–14
22. Margel, Eylon, & Scherz (2008)	Israel	1,082	Junior high school
23. Mas, Perez, & Harris (1987)	Spain	1,198	Ages 12–18
24. Merritt & Krajcik (2013)	U.S.	122	6th grade
25. Merritt, Krajcik, & Shwartz (2008)	U.S.	57	6th grade
26. Nakhleh & Samarapungavan (1999)	U.S.	15	Ages 7–10
27. Nakhleh, Samarapungavan, & Saglam (2005)	U.S.	9	8th grade
28. Novick & Nussbaum (1978)	Israel	20	8th grade
29. Novick & Nussbaum (1981)	U.S.	576	5th–12th grade and univ.
30. Osborne & Cosgrove (1983)	New Zealand	43	Ages 8–17
31. Özmen (2011)	Turkey	51	6th grade
32. Özmen & Kenan (2007)	Turkey	411	4th, 5th, and 6th grade
33. Paik, Kim, Cho, & Park (2004)	S. Korea	25	K–8th grade
34. Papageorgiou & Johnson (2005)	Greece	24	5th grade
35. Prain, Tytler, & Peterson (2009)	Australia	3	5th grade
36. Renström, Andersson, & Marton (1990)	Sweden	20	Ages 13–16
37. Russell, Harlen, & Watt (1989)	England	~60	Ages 5–11
38. Séré (1986)	France	600	Age 11
39. Singer, Tal, & Wu (2003)	U.S.	115	7th grade
40. Smith, Solomon, & Carey (2005)	U.S.	50	3rd–6th grade
41. Snir, Smith, & Raz (2003)	U.S & Israel	28	5th, 6th, and 7th grade
42. Stavy (1988)	Israel	120	4th–9th grade
43. Stavy (1990a)	Israel	120	Ages 9–15
44. Stavy (1990b)	Israel	?	Ages 6–15
45. Tsai (1999)	Taiwan	80	8th grade
46. Tytler (2000)	Australia	~200	1st and 6th grade
47. Tytler & Peterson (2000)	Australia	15	Age 5
48. Tytler, Prain, & Peterson (2007)	Australia	1	5th grade
49. Van Hook, Huziak, & Nowak (2005)	U.S.	39	Kindergarten

By attempting to code PCK from these articles, it became clear that the literature is almost entirely focused on aspects of student thinking, and within student thinking, on misconceptions almost exclusively. Few studies explored effective ways of teaching the small particle model to upper elementary students. Beyond a sense of what ideas students will bring to the topic and how those ideas might develop, there is almost no topic-specific guidance on how to teach the small particle model to 5th grade students. Below, we summarize our findings organized by four ideas within the small particle model.

1. All matter is composed of particles that are too small to see even with a microscope.

Several studies found evidence that elementary-age students hold the notion that matter is continuous rather than being composed of particles (Nakhleh & Samarapungavan, 1999; Nakhleh, Samarapungavan, & Saglam, 2005; Renström et al., 1990). For example, Nakhleh and Samarapungavan found that students view matter as purely macroscopic and continuous with no underlying structure. Others found that students believe gases in general, and air in particular, are continuous (Benson, Wittrock, & Baur, 1993; Merritt, Krajcik, & Shwartz, 2008; Séré, 1986). As Séré reported, "The majority of the pupils maintained that air could not be transported, often because it is 'all one thing, a single mass,' as one pupil expressed it" (p. 419).

Some researchers have pointed to how students' ideas about weight influence their development of ideas in the small particle model. Young children's ideas of weight are strongly associated with how heavy something feels, often in relation to other objects (Snir, Smith, & Raz, 2003). In some studies, when asked what would happen to a piece of Styrofoam that is repeatedly divided, students could imagine the Styrofoam getting smaller and smaller, but they thought that eventually it would have no weight because they could not feel it (Smith, Solomon, & Carey, 2005). Until students understand that matter has weight even if they cannot feel it, they will struggle with the difference between extensive properties of matter (e.g., weight and volume) and intensive ones (e.g., density). Other researchers argue that students need to understand that distinction in order to develop the small particle model.

> *Children's concept of weight, at first, is felt weight, which conflates weight and density. Because the concepts of weight and density are components of a theory of matter and prerequisites to the atomic-molecular theory, differentiating them from each other is crucial.* (Smith, Wiser, Anderson, & Krajcik, 2006, p. 325)

Some young students do acknowledge a particle nature, but their ideas often appear to be the result of attempts to reconcile this notion with their more common experiences with matter. Some believe that particles are *in* substances, rather than substances being composed of particles (Boz, 2006; Johnson, 2013; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993; Renström, Andersson, & Marton, 1990)

. For example, "The substance unit was believed to be studded with 'small atoms,' or small particles of some kind, just like a cake with raisins in it" (Renström et al., 1990, p. 560). Other students who acknowledge the existence of particles believe the particles are large enough to see with a microscope or even with the naked eye (Lee et al., 1993; Nakhleh & Samarapungavan, 1999; Nakhleh, Samarapungavan, & Saglam, 2005; Renström et al., 1990). Still others see particles of the same substance as having different sizes and shapes, almost like pieces of a broken glass (Nakhleh & Samarapungavan, 1999).

We also found two learning progressions for the idea that matter is made of particles, although both are based on studies of students slightly older than elementary students. Johnson (1998) conducted a three-year longitudinal study of 11–14 year olds in which the students were interviewed and asked to draw pictures of various types of matter. From the findings, Johnson proposed the following progression:

> Model X: Continuous substance.
> Particle ideas have no meaning. Nothing that resembles having particles of any description is drawn.
>
> Model A: Particles in the continuous substance.
> Particles are drawn, but the substance is said to be between the particles. The particles are additional to the substance. There can be varying degrees of 'profile' for the particles (weak to strong) and of association with the substance (none to close).
>
> Model B: Particles are the substance, but with macroscopic character.
> Particles are drawn and are said to be the substance. There is nothing between the particles. Individual particles are seen as being of the same quality as the macroscopic sample—literally small bits of it.
>
> Model C: Particles are the substance, properties of state are collective.
> Particles are drawn and are said to be the substance. The properties of a state are seen as collective properties of the particles. (Johnson, 1998, p. 399)

Merritt and Krajcik (2013) studied 6th grade students' ideas over a unit on the particle nature of matter. Based on pre- and post-tests, student artifacts, and classroom observation, they proposed the progression in Table 3. Clearly, there are points of agreement with Johnson's progression above. For example, the Mixed model in Table 3 corresponds to Johnson's Model A. Both progressions depict students' ideas about matter progressing from a completely continuous conceptualization to a completely particulate one, with hybrid states between.

Table 3
Learning Progression for the Particle Model of Matter

Category	**Particle Model**
Complete Particle	Students use particles (molecules) to explain phenomena. There is empty space between the particles. The students are able to *distinguish spacing AND motion relevant to the particular state* they are in. Different substances have different properties because they are made of different atoms OR have different arrangements of same atoms
Basic Particle	Students use *particles* (may use atoms and/or molecules) to explain phenomena. There is an empty space between the particles. Students have difficulty in explaining the difference in spacing in different states and/or are unable to distinguish the difference in movement for all states. *Different substances have different properties because they are made of different atoms or have different arrangements of same atoms*
Mixed	Students use both *particle* and *descriptive ideas* to explain and describe phenomena. Though they recognize that different substances have different properties, their explanation for why remains at a macro-level
Descriptive	Students describe objects *exactly as they appear* . When an object is broken into smaller pieces, it always has the same properties

2. The particles have empty space between them.

As described above, some students think that particles are embedded in the substance, conflicting with the idea that there is empty space between the particles. Studies have also documented that students think some continuous substance (e.g., air or water) fills the space between the particles (Beerenwinkel, Parchmann, & Gräsel, 2011; Lee et al., 1993; Novick & Nussbaum, 1978, 1981). As Lee et al. wrote, “Some students thought that between the molecules of a substance, the same substance exists. For instance, there is air between air molecules, water between water molecules, and rock between rock molecules. Others thought that there is a ‘generic’ kind of air or air molecules between the molecules of air, water, or rock. Still others thought that there are various kinds of “stuff” between molecules of substances in different states” (p. 257). Finally, some students think that there is no space between particles—i.e., they are packed too tightly together to allow for empty space (Özmen, 2011; Özmen & Kenan, 2007).

3. The particles are in constant random motion.

The third fundamental idea in the particle model of matter is that the particles are in constant random motion. For obvious reasons, students struggle with this idea as it relates to the particles in a solid (Boz, 2006; Herrmann-Abell & DeBoer, 2011; Johnson, 2013; Lee et al., 1993). Students who did acknowledge particle movement often thought that it occurs only when external forces are applied (Lee et al., 1993; Novick & Nussbaum, 1978). For example, Novick and Nussbaum found that, “many pupils believe that air is an essential mediating factor in the movement of substances in the gas phase” (p. 278). Students also tend to attribute particle movement to anthropomorphic reasons (Löfgren & Helldén, 2008; Novick & Nussbaum, 1978).

For example, “The water in the glass goes up and sticks to the cover because it wants to get out” (Löfgren & Helldén, 2008, p. 490). Benson et al. (1993) documented another student conception that conflicts with the idea that particles are in constant random motion. When asked to draw what the particles of gas in a sealed flask would look like after half the gas was removed, some students drew pictures with the particles concentrated in the lower half of the flask.

4. 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.

Change of state

Students come to school having abundant firsthand experience with change of state. As Osborne and Cosgrove (1983) noted, “Children are very familiar with water, ice, and steam as these things have been part of their lives since they first crawled into the kitchen” (p. 825). The particle model of matter explains each type of change, but through their experience with the world, children form ideas that run counter to these explanations. Much research on student thinking has focused on the reciprocal processes of evaporation and condensation. For example, more than one study has found that students attribute condensation on a glass of cold water to seepage of water through the glass (Osborne & Cosgrove, 1983; Prain, Tytler, & Peterson, 2009). Aydeniz and Kotowski (2012) found that some students attributed condensation to steam combining with air. Some students also thought that the cold surface reacted with the dry air to form water—for example, by causing oxygen and hydrogen in the air to form water (Osborne & Cosgrove, 1983).

The particle model accounts for evaporation through the principle that particles are constantly moving in random directions, with some moving fast enough to escape the liquid and enter the gaseous phase. Research on student thinking has documented several student conceptions that are inconsistent with this explanation. One common theme in these ideas is the notion that a liquid must be heated for evaporation to occur (Papageorgiou & Johnson, 2005). Some students believe that evaporation occurs only at a very high temperature, while others think that evaporation occurs only when the liquid boils (Durmuş & Bayraktar, 2010). (Interestingly, several studies have found that students think the bubbles in boiling water are filled with air (Bar & Galili, 1994; Osborne & Cosgrove, 1983; Papageorgiou & Johnson, 2005; Prain et al., 2009).) The idea that liquid substances no longer exist when they evaporate is quite prominent in the literature (Lee et al., 1993; Osborne & Cosgrove, 1983; Russell, Harlen, & Watt, 1989; Tytler & Peterson, 2000). As Lee et al. noted, “Since a substance becomes invisible during evaporation, some students thought that the substance disappears and ceases to exist” (p. 264). Osborne and Cosgrove (1983) found that students think liquids turn into air when they evaporate. But perhaps the most common idea among students is that water is absorbed by a surface (even an impermeable one) rather than evaporating (Osborne & Cosgrove, 1983; Prain et al., 2009; Russell et al., 1989; Tytler & Peterson, 2000; Tytler & Prain, 2007). Russell et al. (1989), for example, studied students’ thinking about water evaporating from wet clothes.

> The laundering activity also gave rise to explanations of the water soaking into the cloth to account for the drying process from about one-fifth of the 8–11 years age range. This response, for many children, implied more than the water being "held" by the material. A similar response was even more prevalent and less ambiguous, when a disappearing wet handprint on an absorbent paper towel was the subject of discussion. The process of evaporation seemed to become confounded with the function of a paper towel in mopping up water (Russell et al., 1989, p. 574).

Based on a study of children ages 5–11, Bar and Galili (1994) proposed a learning progression for students' ideas about evaporation:

> A. Water disappears.
> B. Water was absorbed in the floor (or/and ground).
> C. The water 'evaporates,' meaning it is now unseen and being transferred into an alternative location or medium, etc.: 'somewhat in the sky,' 'sun,' 'ceiling,' 'air,' or 'clouds.'
> D. The water changes into vapour, as small (commonly unseen) droplets, dispersed in the air, or water is transformed into air. (Bar & Galili, 1994, p. 162)

Dissolving

Dissolving is similar to evaporation in that students have to account for the apparent disappearance of a substance. From a particle model perspective, substances do not disappear when they dissolve, they simply cease to exist in aggregate form. Instead, individual particles of the substance (the solute) mix together with particles of the solvent. Much of the research on student thinking about dissolving has been done in the context of salt or sugar dissolving in water, both of which are accompanied by no change in color of the liquid. Other studies found that some students believe the dissolving substance ceases to exist (Lee et al., 1993; Longden, Black, & Solomon, 1991; Stavy, 1990b). Stavy described the challenges this idea presents for students when thinking about conservation of matter, "The older students tended to believe that the sugar/water solution is lighter than the sum of the weights of sugar and water because 'the sugar becomes smaller and smaller until it disappears'" (Stavy, 1990b, p. 503). Finally, Abraham et al. (1994) found that some students believed the water "absorbed" the sugar.

Several studies have documented students describing the process of dissolving in these contexts as melting—i.e., salt melts in water (Abraham, Grzybowski, Renner, & Marek, 1992; Abraham et al., 1994; Çalik & Ayas, 2005; Lee et al., 1993; Papageorgiou & Johnson, 2005) . For example:

> Many students did not understand dissolving and talked about it in ways that did not distinguish it from melting. For instance, some students thought that solid sugar turns into a liquid: "The sugar eventually becomes water," or "solid sugar changes into liquid sugar." (Lee et al., 1993, p. 263)

Conservation of weight[2]

Without a particle model in mind (and sometimes even with it), students can struggle with the idea of conservation of weight during phase change. And, in fact, several studies have found that students believe the weight of a substance changes when it melts, freezes, evaporates, or condenses (Aydeniz & Kotowski, 2012; Durmuş & Bayraktar, 2010; Lee et al., 1993; Stavy, 1990a, 1990b). As Lee et al. wrote, “Many students were confused about the conservation of matter during melting and freezing. For instance, they thought that when ice changed to water, the water weighed less because: ‘Ice is heavier than water,’ ‘the solid is closer together than water,’ or ‘ice has more stuff in it than the water’” (p. 264). Closely related to these ideas about weight, several studies have found that some students believe the size or number of particles changes during phase change and during heating or cooling (Aydeniz & Kotowski, 2012; Özmen, 2011; Özmen & Kenan, 2007; Tsai, 1999). Aydeniz and Kotowski, for example, reported that some students believe a water molecule is smaller in the solid phase than in the liquid phase.

Some student ideas about conservation of weight seem to be intertwined with ideas about density. For example:

- The more air an object has, the less it weighs (Séré, 1986; Stavy, 1988).
- Gases rise because they have less weight than the liquids they come from (Mas, Perez, & Harris, 1987).
- Hot air weighs less than cold air (Séré, 1986).
- Hot water is heavier than cold water (Stavy, 1990b).

CONCLUSION

Our review of the literature suggests that research-based guidance for teaching the small particle model to 5th grade students is thin. Although not discussed in this article, we found that historically, the small particle model has been taught to middle grades students and older, typically employing atoms and molecules. The *Framework* for the NGSS recommends teaching the small particle model to 5th graders but without mention of atoms and molecules: “At this grade level, mass and weight are not distinguished, and no attempt is made to define the unseen particles or explain the atomic-scale mechanism of evaporation and condensation” (National Research Council, 2012, p. 108). What is lacking in the research are studies about teaching the small particle to upper elementary students effectively *without* atoms and molecules.

The review also suggests that the associated conceptual challenges are formidable, among them the necessity for students to grapple with phenomena that are too small and too fast for them to see (i.e., the size and movement of the particles). In other work, we have found it helpful to distinguish between primary phenomena and evidentiary phenomena (P. S. Smith & Esch, 2012). Primary phenomena are the phenomenon under study and may be directly observable (e.g.,

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[2] In keeping with the NGSS, we use “weight” instead of “matter” in talking about conservation with 5th grade students.

objects fall, a force can change the speed or direction of movement of an object) or unobservable (the movement of and interaction among particles that compose matter). Evidentiary phenomena are directly observable phenomena that provide evidence for a primary phenomenon. For example, students can observe that the plunger in a sealed syringe full of air (or any gas) can be pushed in, compressing the space occupied by the air. This phenomenon is directly observable evidence that there is empty space between particles (assuming, of course, that students already entertain the notion of invisible particles). Clearly, making connections between evidentiary and primary phenomena involves inferential reasoning and aligns well with the scientific practice of constructing explanations.

Understanding of the small particle model can also be supported by computer simulations that make the unobservable observable, like those available at PhET (https://phet.colorado.edu/). Our literature review did not uncover any studies of the efficacy of such simulations with elementary students, suggesting an area that is ripe for research. Good computer simulations offer students the ability to manipulate variables involved in various processes—e.g., change of state—and observe the effect at the particle level, something that is impossible for elementary students to do otherwise. However, the extent to which students can transfer their understanding of the simulation to the actual phenomenon is unclear without systematic study.

The NGSS envision three-dimensional learning that interweaves disciplinary core ideas, science practices, and cross-cutting concepts. The small particle model of matter not only invites but demands this kind of learning. Students cannot understand the disciplinary core ideas deeply without engaging in the practices, notably modeling, explanation, and argumentation. Further, the cross-cutting concepts of (1) scale, proportion, and quantity and (2) systems and system models are integral to this content. However, the research base for teaching the small particle model to 5th graders is underdeveloped at best. Much more research is needed to provide teachers the guidance they need—guidance beyond what students are thinking, guidance about effective strategies for teaching the content. The need for research-based instructional materials is similarly great.

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APPENDIX

Article Summaries

Author (Year)	Where the study occurred	*n*	Age of subjects	Description
1. Abraham et al., 1992	United States	247	8th grade	Used written tasks to investigate students' thinking about chemical change, dissolution, conservation of atoms, periodicity, and phase change after they completed a unit using a textbook that addressed the topics.
2. Abraham et al., 1994	United States	100	Junior high, high school, and college	Studied students' thinking about chemical change, dissolution, conservation of atoms, periodicity, and phase change near the end of their respective courses using open-ended questions.
3. Acher, Arcà, & Sanmartí, 2007	Argentina	24	Ages 7 and 8	Analyzed small group interactions during lessons that used physical models to teach the small particle model of matter.
4. Aydeniz & Kotowski, 2012	United States	87	Middle and high school	Administered the Particulate Nature of Matter Assessment (PARNOMA test to study student understanding at the end of a semester in which students were taught matter topics.
5. V. Bar & Galili, 1994	Israel	293	Ages 6–12	Used interviews and written tasks to examine students' thinking about evaporation.
6. Varda Bar & Travis, 1991	Israel	83	Ages 6–14	Open-ended oral and written tests, as well as a multiple choice test, were administered to students to investigate their thinking about evaporation.
7. Beerenwinkel et al., 2011	Germany	214	7th and 8th grade	Randomly assigned students to a "conceptual change text" or a "traditional text" to learn about the particle model and compared differences in their thinking.
8. Benson et al., 1993	United States	1098	2nd grade-college	Students drew representations of highly magnified views of air in two flasks (one "full" of air, one "half full" of air.

9. Boz, 2006	Turkey	300	6th, 8th, and 11th grade	Students responded to a questionnaire of 6 open-ended items about the (a) arrangement and movement of particles in a solid, liquid, and gas, and (b) application of particulate ideas to explain phase changes. Students also completed interviews about these ideas.
10. Çalik & Ayas, 2005	Turkey	100	8th grade and PSTs	Students completed a written test comprising questions requiring open-ended responses and drawings in order to determine their understanding about dissolution, chemical change, and gas particles.
11. Durmuş & Bayraktar, 2010	Turkey	104	4th grade	Administered the "Matter Concept Test" to students before and after a unit on matter. Some students received instruction utilizing "conceptual change texts" and laboratory experiments, while the rest received "traditional" instruction.
12. Gómez, Benarroch, & Marín, 2006	Spain	43	Ages 9–22	Students interviewed to determine their ideas on the particulate nature of matter. The analysis of the interview responses identified many conceptions held by the students as well as coherence in their responses.
13. Herrmann-Abell & DeBoer, 2011	United States	13,360	Middle school, high school, and college	A distractor-driven multiple-choice assessment was given to middle school, high school, and college students to examine the progression of understanding of chemistry across grade levels.
14. Johnson, 1998	England	147	7th, 8th, and 9th grade	Three year longitudinal study identifying students' alternative conceptions and a learning progression for particle theory.
15. Johnson, 2013	England	4624	7th–10th grade	Created, piloted, and revised three assessments (Test A, B, and C). Administered the final assessments to over 4600 middle grades students in order to create a draft of a learning progression for students' understanding of the particle model of matter.
16. Johnson & Papageorgiou, 2010	England	45	Ages 9–10	Students in two elementary schools received a teaching intervention and then interviews were conducted with a sample of students from each class about their understanding of particles in changes of state and mixing.

17. Lee et al., 1993	United States	12 classes took test, 24 students did interview	6th grade	Students completed a paper-and-pencil test and clinical interviews to determine the conceptual frameworks they use to explain the nature or matter and molecules.
18. Liu & Lesniak, 2005	United States	US sample from TIMSS data	3rd, 4th, 7th, 8th, and 12th grade	Rasch modeling was used on the US national sample from the Third International Mathematics and Science Study (TIMSS to identify a learning progression for various matter concepts.
19. Liu & Lesniak, 2006	United States	54	1st–10th grade	Students were interviewed on their conceptions of substances and combining substances in order to develop a conceptual progression for their thinking.
20. Löfgren & Helldén, 2008	Sweden	25	Longitudinal from age 7–13	Longitudinal study followed students from age 7 to 13. Students were interviewed once to twice a year about their reasoning about matter transformations.
21. Longden et al., 1991	England	442	Ages 11–14	Students were asked to write and draw about dissolving in two ways: 1 the observable process and 2 using the particle model.
22. Margel, Eylon, & Scherz, 2008	Israel	1082	Junior high school	Three year longitudinal study in which students were asked to draw and write about the structure of several materials to determine the progression of their learning.
23. Mas et al., 1987	Spain	1198	Ages 12–18	A short test was administered at two schools to students of various socioeconomic levels. The test included questions about vaporization of water and dissolution of effervescent aspirin.
24. Merritt & Krajcik, 2013	United States	122	6th grade	Three teachers from three schools taught a matter unit (How can I smell things from a distance?) to their students. Students completed pretests, posttests, and 3 assessments embedded into the unit instruction. Student responses were scored using a project-developed rubric/learning progression.
25. Merritt et al., 2008	United States	57	6th grade	Students engaged in an 8-week unit from a model-based curriculum were studied to determine changes in their understanding using pre- and post-tests, student artifacts, and video recordings of the curriculum enactment.

26. Nakhleh & Samarapungavan, 1999	United States	15	Ages 7–10	Students were interviewed about their understanding of the particulate nature of matter before they received any formal instruction on the topic. Their ideas were categorized as macrocontinuous, macroparticulate, and microparticulate.
27. Nakhleh, Samarapungavan, & Saglam, 2005	United States	9	8th grade	Students were interviewed about their understanding of the composition and particulate structure of a variety of substances.
28. Novick & Nussbaum, 1978	Israel	20	8th grade	Thirty minute interviews were conducted with middle school students about three phenomena in the gaseous phase.
29. Novick & Nussbaum, 1981	United States	576	5th–12th grade and university	The authors developed the Test About Particles in a Gas (TAP to administer to students from upper elementary school through university. Students were asked to draw pictures and write explanations of various phenomena.
30. Osborne & Cosgrove, 1983	New Zealand	43	Ages 8–17	Clinical interviews were conducted to study students' views about the changes of state of water at different age levels.
31. Özmen, 2011	Turkey	51	6th grade	The effectiveness of animation-enhanced conceptual change texts was studied using a quasi-experimental design. Students in the control and experimental classes completed pre- and post-tests.
32. Özmen & Kenan, 2007	Turkey	411	4th, 5th, and 6th grade	Students' conceptions about the microscopic properties of solid, liquid, and gas matters during phase changes were determined using a 36-item test.
33. Paik, Kim, Cho, & Park, 2004	South Korea	25	K–8th grade	Five students each from kindergarten, second grade, fourth grade, sixth grade, and eighth grade were interviewed about their understanding of condensation, solidification, and melting.
34. Papageorgiou & Johnson, 2005	Greece	24	5th grade	Matched groups were taught one of two parallel lesson schemes; one used particle ideas and the other did not. Pre- and post-intervention interviews were conducted with the students.

35. Prain et al., 2009	Australia	3	5th grade	Case studies of three fifth grade students and their understanding of evaporation, as well as the representational issues involved in their understanding.
36. Renström et al., 1990	Sweden	20	Ages 13–16	Interviews were conducted with 20 students about how they conceptualize matter. Six different conceptions were found: matter is a homogenous substance, b substance units, c substance units with "small atoms," d aggregate of particles, e particle units, or f systems of particles.
37. Russell et al., 1989	England	~60	Ages 5–11	About twenty students in each of three age bands (5-7, 8-9, 10-11 were interviewed on their ideas about evaporation.
38. Séré, 1986	France	600	Age 11	600 students completed a written questionnaire, and 20 completed individual interviews, about their conceptions of air and the gaseous state.
39. Singer, Tal, & Wu, 2003	United States	115	7th grade	One teacher and her five classes were selected for an in-depth study. Researchers collected student drawings, pre- and post-tests, and interviews, as well as video of classroom activities in order to describe students' understanding of the particulate nature of matter.
40. Smith, Solomon, & Carey, 2005	United States	50	3rd–6th grade	50 students participated in clinical interviews about conceptualizations of rational number and of certain extensive physical quantities.
41. Snir, Smith, & Raz, 2003	United States and Israel	28	5th, 6th, and 7th grade	Students engaged with a computer simulation of mixing water and alcohol. Data was collected about their thinking about the phenomenon before, during, and after working with the software.
42. Stavy, 1988	Israel	120	4th–9th grade	Students, including students who had received no instruction on the topic, were interviewed about their ideas about gases.
43. Stavy, 1990a	Israel	120	Ages 9-15	Students were interviewed about changes of states of matter (from liquid to solid or gas and the reversibility of the process. The research examined students' changes in conceptions and differences across age levels.
44. Stavy, 1990b	Israel	?	Ages 6–15	Students were interviewed about their conceptions of conservation of matter.

45. Tsai, 1999	Taiwan	80	8th grade	Students were randomly assigned to a control group, in which they received traditional instruction on matter, or an experimental group, which included an analogy activity. Students were tested for differences in understanding after their assigned instruction.
46. Tytler, 2000	Australia	~200	1st and 6th grade	First and sixth grade students explore challenging activities centered on evaporation and condensation. The students' group discussions, written responses, and interviews were analyzed to explore their nature and coherence.
47. Tytler & Peterson, 2000	Australia	15	Age 5	Five year old students were interviewed about their conceptions of evaporation over the course of their first year in school.
48. Tytler, Prain, & Peterson, 2007	Australia	1	5th grade	A case study of a fifth grade student's response to a lesson sequence on evaporation using representations. The student was interviewed twice again; the interviews were spaced a year apart.
49. Van Hook, Huziak, & Nowak, 2005	United States	39	Kindergarten	Kindergarten students were interviewed about their ideas about air before and after completing a series of hands-on, inquiry based lessons focused on two properties of air (that it takes up space and is made of particles.

PCK Extraction Codebook

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 students cannot "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.	The confidence rating indicates 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 appears several times with a low rating may receive a high rating based on the accumulation of evidence.
Misinformation	In contrast to misconceptions, misinformation is an incorrect fact not derived from everyday experience with the physical world. For example, students might think that water freezes at 32 degrees Celsius (instead of 32 degrees Fahrenheit). 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 indicates 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 appears several times with a low rating may receive a high rating based on the accumulation of evidence.
Teaching Tip	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 appears several times with a low rating may receive a high rating based on the accumulation of evidence.

Code	Description	Extraction Rules	Confidence Rating
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.
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.	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.
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.	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.	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.
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.