INITIATIVES IN

MATHEMATICS AND SCIENCE EDUCATION
WITH GLOBAL IMPLICATIONS

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4.2 CAN THE CONSTRUCT OF MATHEMATICAL KNOWLEDGE FOR TEACHING BE APPLIED TO SCIENCE? A CONVERSATION BETWEEN A MATHEMATICS EDUCATOR AND A SCIENCE EDUCATOR

MARK BLOOM and SARAH QUEBEC FUENTES

Because researchers tend to specialize in a single subject, much of the [teacher knowledge] work has unfolded in parallel but independent strands. Often it is unclear how ideas in one subject area relate to another or even whether findings within the same subject take similar or different views of teacher subject matter knowledge. (Ball, Thames, & Phelps, 2008, p. 394)

The idea for this chapter stemmed from conversations between a mathematics educator (author Quebec Fuentes) and a science educator (author Bloom). Since Shulman (1986, 1987) introduced the idea of Pedagogical Content Knowledge (PCK), it has been the focus of a significant body of research in teacher education and teaching across an array of disciplines (Abell, 2007; Ball et al., 2008). However, as indicated by the opening quote, this research has often been conducted within a discipline and not compared across disciplines. Therefore, with backgrounds in different content areas, we brought distinctive understandings and views about teacher knowledge to our discussions.

At the outset, we want to share two caveats with the reader. First, this is not an exhaustive review of the work conducted with respect to teacher knowledge in mathematics or science. Second, we are not proposing a framework for science knowledge for teaching similar to Mathematics Knowledge for Teaching (MKT) developed by Ball and colleagues (Ball et al., 2008; Hill & Ball, 2009). Instead, this chapter reflects the story of our conversations about teacher knowledge in the context of our practice from the perspective of two different fields. In particular, we look at teacher knowledge in science through the lens of teacher knowledge in mathematics. The order of these sections in the chapter, Pedagogical Content Knowledge, Mathematical Knowledge for Teaching, Pedagogical Content Knowledge for Science Teaching, and Shortcomings of Pedagogical Content Knowledge for Science Teaching, mirrors the evolution of our discussions. Interspersed between the sections, we share our story indicated by italics. We close by sharing how research on teacher knowledge within a specific subject area (e.g., mathematics) can inform teacher knowledge in another discipline (e.g., science).

Pedagogical Content Knowledge

Through his research, Shulman (1986, 1987) categorized teacher knowledge. He believed that teaching required a unique professional knowledge—which extended beyond general pedagogical knowledge to include content-specific knowledge. By considering content, Shulman was addressing what he termed the missing paradigm in the conversations about teacher knowledge at that time. Therefore, in addition to general pedagogical knowledge, Shulman identified three areas of teacher knowledge, which contextualized teaching within a content area: content knowledge, curricular knowledge, and pedagogical content knowledge (PCK). Content knowledge includes an
understanding of the facts and/or concepts and of the structures of a content area such as a comprehension of why an idea or process is valid. Curricular knowledge is comprised of three components: knowledge of the curricular programs and instructional materials for teaching particular topics, the relationship between course content and the content being taught in other subject areas at the same time (lateral curriculum knowledge), and the connections between course content and the content that was previously taught or will be taught in the same subject area (vertical curriculum knowledge). PCK, a type of content knowledge as described by Shulman (1986), includes an understanding of effective means of representing content to support student learning and student conceptions and misconceptions of various content areas. Since its introduction, PCK has been the focus of many studies in a range of subject areas including mathematics and science (Abell, 2007; Ball et al., 2008).

The Conversation Begins

At the time that our conversations occurred, we worked together teaching mathematics methods courses (author Quebec Fuentes; hereafter referred to as Sarah) and science content and methods courses (author Bloom; hereafter referred to as Mark) for preservice teachers. We were conducting research with our common students, which involved weekly conversations about our practice. One of these discussions centered on a conflict in the science content course between the course objectives and the expectations of the preservice teachers (Quebec Fuentes & Bloom, 2011). The preservice teachers thought the class would cover elementary-level content. In contrast, acknowledging the futility of teaching all K-6 science content in a single semester, Mark designed the course with the goal of helping preservice teachers learn how to identify and access content knowledge needed for teaching via a subset of representative topics in science. Mark expressed frustration about how to communicate the goals of the course to the preservice teachers in a way that they would understand. Sarah brought to this conversation her background knowledge of Mathematical Knowledge for Teaching.

Mathematical Knowledge for Teaching

Shulman (1986, 1987) acknowledged that his conception of teacher knowledge was incomplete and called for the further development of a theoretical framework for content knowledge for teaching. Ball and colleagues (Ball et al., 2008) pursued this charge in the field of mathematics; that is, they set out to empirically determine what successful teaching requires with respect to mathematics content knowledge and PCK. In particular, they conducted intensive qualitative analyses of classroom practice to identify the tasks involved in teaching mathematics and the mathematical knowledge necessary for implementing these tasks. In addition, they developed measures of this content knowledge to further refine its various components. Findings indicate that the knowledge for teaching mathematics extends beyond simply knowing the mathematics within the curriculum (Hill, Schilling, & Ball, 2004). For instance, a teacher needs to have mathematical content knowledge to quickly identify errors and sources of these errors, understand student misconceptions based on a particular error, evaluate nonstandard approaches to determine whether a strategy is mathematically correct and generalizable,
explain the conceptual underpinnings of procedures, identify the benefits of different ways to represent the content, and determine an appropriate sequence of examples. Ball et al. developed a framework for the knowledge that is required to perform these tasks called Mathematical Knowledge for Teaching (see Table 1).

Table 1

**MKT Components of Subject Matter Knowledge and Pedagogical Content Knowledge**

<table>
<thead>
<tr>
<th>Type of Knowledge</th>
<th>Definition</th>
<th>Example</th>
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</thead>
<tbody>
<tr>
<td><strong>Subject Matter Knowledge</strong></td>
<td></td>
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</tr>
<tr>
<td>Common Content Knowledge</td>
<td>Mathematical knowledge that is not unique to the teaching discipline</td>
<td>Carry out the procedure for $23 \times 4 = 92$</td>
</tr>
<tr>
<td>Specialized Content Knowledge</td>
<td>Mathematical knowledge that is unique to the teaching discipline</td>
<td>Assess if a student's strategy of changing $23 \times 4$ to $46 \times 2$ to $92 \times 1$ is legitimate (and, if so, why)—generalizable and easier for a particular set of problems</td>
</tr>
<tr>
<td>Horizon Content Knowledge</td>
<td>Mathematical knowledge of the connections between topics at a particular grade level and the preceding and subsequent grade levels</td>
<td>Understand the connection between $23 \times 4$ and the distributive property, i.e., $23 \times 4 = (20 + 3) \times 4$ which also emerges later in the study of algebra, e.g., $(2x + 3)4$</td>
</tr>
<tr>
<td><strong>Pedagogical Content Knowledge</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knowledge of Content and Students</td>
<td>Mathematical knowledge of how students think about different content</td>
<td>Be familiar with common errors and when they will likely occur, e.g., $23 \times 14 = 32$ demonstrates a misconception that will not be apparent in the problem $23 \times 4 = 92$</td>
</tr>
<tr>
<td>Knowledge of Content and Teaching</td>
<td>Mathematical knowledge of the pedagogical decisions that influence student learning</td>
<td>Determine the affordances and drawbacks of sequence of examples to build an understanding of the content, e.g., $23 \times 10, 23 \times 4$, and then $23 \times 14$</td>
</tr>
<tr>
<td>Knowledge of Content and Curriculum</td>
<td>Mathematical knowledge of the variety of curricular programs and instructional materials for teaching particular topics</td>
<td>Choose an appropriate representation and curricular resource (e.g., the area model for multiplication via nlvm.usu.edu)</td>
</tr>
</tbody>
</table>

Subject Matter Knowledge is subdivided into three different components. The two components of Subject Matter Knowledge, *Common Content Knowledge* and *Specialized*
Content Knowledge, differentiate between content knowledge not exclusive and exclusive to the profession of teaching mathematics, respectively. Horizon Content Knowledge parallels Shulman’s vertical curriculum knowledge. Teachers’ knowledge of the content being taught to students is necessary but not sufficient. Teachers also must be able to “unpack” or “decompress” (Ball et al., 2008, p. 400) mathematics content to perform the aforementioned tasks of teaching. This more detailed breakdown of subject matter knowledge is a significant contribution to the field of teacher knowledge in mathematics. Further, the work of Ball and colleagues is practice-based with the subdomains measured and validated. Research surrounding MKT has shown that there is a significant relationship between the MKT of teachers and the mathematical quality of their instruction (Hill et al., 2008) as well as student achievement (Hill, Rowan, & Ball, 2005; Rockoff, Jacob, Kane, & Staiger, 2008). Therefore, MKT is not mere speculation but empirically grounded.

MKT aligns with and elaborates upon Shulman’s (1986, 1987) components of teacher knowledge. MKT consists of two major domains: Subject Matter Knowledge and Pedagogical Content Knowledge (see Table 1). PCK is further divided into Knowledge of Content and Students and Knowledge of Content and Teaching, which relate to the two main aspects of PCK as described by Shulman (student conceptions/misconceptions and representations).

The third piece incorporated into PCK, Knowledge of Content and Curriculum, corresponds to one aspect of Shulman’s curricular knowledge, namely knowledge of curricular programs and instructional materials for teaching particular topics.

The Conversation Continues

The goal of Mark’s science content course reflected the specialized content knowledge component of MKT. He based his course on the premise that teachers need to know more than the content they teach their students and wanted the preservice teachers to understand the unique nature of teacher knowledge. Although these ideas formed the foundation of his course, he did not have the language or framework to articulate them in our conversations or in his classroom. Sarah had the language in terms of the MKT framework. We were curious whether there was a construct similar to MKT for science teaching. So, we looked to the literature and found Pedagogical Content Knowledge for Science Teaching.

Pedagogical Content Knowledge for Science Teaching

Advancing the work of Grossman (1990) and Tamir (1988), Magnusson, Krajcik, and Borko (1999) developed a framework to depict the components of Pedagogical Content Knowledge for Science Teaching (PCK for ST). Their framework consists of four primary components regarding teacher knowledge and beliefs about: (a) science curriculum, (b) student understanding of specific science topics, (c) assessment in science, and (d) instructional strategies for teaching science (see Table 2).
Table 2

*Components of Pedagogical Content Knowledge for Science Teaching*

<table>
<thead>
<tr>
<th>Component</th>
<th>Definition</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knowledge and Beliefs about Science Curriculum</td>
<td>Refers to teacher understanding of goals and objectives of the science curriculum as well as their knowledge of specific curricular programs and materials with which to teach to achieve those goals</td>
<td>Goals and objectives as described in national guidelines such as A Framework for K-12 Science Education (National Research Council, 2012), Benchmarks for Science Literacy (American Association for the Advancement of Science, 1993) FOSS Kits, BSCS, Project Wild, Project Learning Tree</td>
</tr>
<tr>
<td>Knowledge and Beliefs about Students' Understanding of Specific Science Topics</td>
<td>Refers to teacher ability to know what content students must already know before learning new material and their understanding of common student misconceptions and aspects of specific science content students often find difficult</td>
<td>Before learning the relationship between temperature and rate of dissolving, students must be able to use thermometers. Students can conflate the nucleus of a cell with the nucleus of an atom and fail to recognize the drastic difference in scale of the distinct structures.</td>
</tr>
<tr>
<td>Knowledge and Beliefs about Assessment in Science</td>
<td>Refers to teacher ability to choose an appropriate form of assessment to measure student learning</td>
<td>A written test might be appropriate for measuring student ability to interpret graphs, but observational skills might be better measured with an assessment of lab journals or field notebooks</td>
</tr>
<tr>
<td>Knowledge and Beliefs about Instructional Strategies for Teaching Science</td>
<td>Refers to teacher ability to choose appropriate teaching strategies generally within the domain of science (subject-specific) as well as with regard to specific topics within the subject (topic-specific)</td>
<td>Subject specific teaching strategies such as discovery learning or conceptual change-oriented instruction Topic specific teaching strategies such as representations (e.g., analogies) and/or activities (e.g., field work)</td>
</tr>
</tbody>
</table>

The framework also includes a fifth overarching component regarding teacher orientations to teaching science, which shapes and is shaped by the aforementioned knowledge and beliefs components. Magnusson et al. (1999) present multiple orientations for teaching science (i.e., didactic, discovery, inquiry, and conceptual change) which teachers could possess and describe the associated goals of each orientation along with the typical type of instruction that would be employed if a teacher held these orientations. Several examples are presented in Table 3.
Table 3

*Possible Orientations to Science Teaching*

<table>
<thead>
<tr>
<th>Orientation</th>
<th>Goals</th>
<th>Pical Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Didactic</td>
<td>To transmit the facts of science to the learners</td>
<td>Teacher presents information to the students via lectures and/or discussion and questions students to determine if students know the facts.</td>
</tr>
<tr>
<td>Discovery</td>
<td>Students will discover scientific concepts through exploration of the natural world.</td>
<td>Students discover patterns in nature through self-guided exploration and the teacher ensures that students come to accurate conclusions (<em>student-centered instruction</em>).</td>
</tr>
<tr>
<td>Inquiry</td>
<td>To present science as the process of inquiry as opposed to the knowledge generated by the process</td>
<td>Teacher provides materials and opportunity for students to explore phenomena; teacher guides the development of the question and the method of exploration (<em>investigation-centered instruction</em>).</td>
</tr>
<tr>
<td>Conceptual Change</td>
<td>To expose learners to contexts that challenge their misconceptions or expose their knowledge gaps</td>
<td>Students present their views/understandings of science concepts and then are challenged to support their views over alternative explanations; teacher facilitates the discussion to ensure students arrive at accurate explanations.</td>
</tr>
</tbody>
</table>

The Conversation Becomes a Question

Since PCK for ST does not explicitly address subject matter knowledge, we felt it lacking as a framework with respect to the purpose of Mark's course. Therefore, many of our conversations about the science class used MKT terminology. For example, the preservice teachers expected the course to be about common content knowledge, whereas Mark's perspective aligned with specialized content knowledge.
Shortcomings of Pedagogical Content Knowledge for Science Teaching

Perhaps the dissatisfaction with PCK for ST can be explained, at least in part, by contrasting it to MKT, which has been a useful framework within mathematics education. When Shulman (1986, 1987) first presented PCK as the missing paradigm between content and pedagogy, he acknowledged that it was not a fully developed construct and that further research would be needed to develop it into a useful tool for educators. The mathematics research community (e.g., Ball et al., 2008) followed this recommendation and developed the MKT framework, which includes PCK (closely aligned with Shulman’s PCK) along with a complementary component of Subject Matter Knowledge. When MKT and PCK for ST are contrasted, a striking omission in PCK for ST becomes evident. While all of the components of PCK are included in PCK for ST, nowhere within the framework is subject matter knowledge addressed.

Magnusson et al. (1999) acknowledged that their components of PCK for ST are dependent on strong subject matter knowledge. The literature on teacher knowledge in science education (e.g., Abell, 2007; Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008) further supports this assertion about the relationship between PCK and subject matter knowledge. For instance, in her extensive literature review, Abell noted how teachers, who did not possess strong subject matter knowledge in science, were not successful in some of the tasks of teaching such as building upon student ideas, asking high-level questions, and identifying student misunderstandings. Unquestionably, teachers must have strong, deep, and robust subject matter knowledge to effectively teach students so that they develop a conceptual understanding of the content (Abd-El-Khalick, 2013; Anderson & Kim, 2003; Loughran, Mulhall, & Berry, 2004). Loughran et al. utilize language similar to Ball et al. (2008) when describing the interaction between science teachers and the content they teach.

When science teachers begin to ‘unpack’ [emphasis added] their content knowledge ... it helps them to focus on what matters in a content area and to teach in ways that have a clear purpose and focus in developing a conceptualization of the subject area, both for themselves and their students. (Loughran et al., 2004, p. 379)

Rollnick et al. (2008) note that many models of PCK have subject matter knowledge as a component; however, “few give prominence to its central role in the construction of knowledge for teaching” (p. 1380). Further research is needed to illuminate the general descriptors of knowledge such as strong, deep, and robust, and clearly delineate the various components of subject matter knowledge for teaching science (Ball et al.).

Within the context of science education, PCK in general has been criticized as a concept that offers much at first glance, but upon inspection, turns out to be “ineffectual as a research paradigm” and an “intellectual dead end” (Settlage, 2013, p. 1). How can a construct that has been widely used in teacher preparation programs and researched in the science education community since its inception earn such a scathing review? A major criticism of research on PCK is the lack of agreement on the very meaning of the term PCK among science education researchers (Ball et al., 2008; Barnett, 2003). For example, Shulman (1987), who coined the term, described PCK as “the special amalgam
of content and pedagogy that is uniquely the province of teachers” (p. 8) that “goes beyond knowledge of subject matter per se to the dimension of subject matter knowledge for teaching” (Shulman, 1986, p. 9), while Magnusson et al. (1999) describe PCK for ST as “the result of a transformation of knowledge of subject matter, pedagogy, and context” (p. 96). Both of these descriptions are somewhat vague and open to interpretation. Gess-Newsome (1999) explains, “the PCK construct has fuzzy boundaries, demanding unusual and ephemeral clarity on the part of the researcher to assign knowledge to PCK or one of its related constructs” (p. 10).

Barnett (2003) further criticizes PCK in the context of science instruction. Because effective science teachers employ drastically different types of instruction in a myriad of different and changing environments, there is no single best practice in science instruction; that is, what works for one science teacher may need to be altered or completely changed for another teacher in another place. Because effective teachers must be able to adjust their teaching for a variety of settings, PCK is “difficult to unpack” (Barnett, p. 616). However, Ball et al. (2008) counter this argument by claiming that many of the tasks of teaching, which require specialized content knowledge, are common across teaching approaches. Overall, clarity is needed in both definition and interpretation of components of teacher knowledge (Ball et al.; Loughran et al., 2004), in particular subject matter knowledge, in order to make it a useful model for science educators and science education researchers.

Conclusion

To close, the question posed in the title of this chapter is revisited: Can the construct of Mathematical Knowledge for Teaching be applied to science? The answer to this question is both yes and no. With respect to the latter, the MKT framework cannot be directly applied to science. The extensive work conducted by Ball and colleagues was grounded in the practice of teaching mathematics. A direct application of MKT to science would ignore the important role of content knowledge within a particular subject area, precisely what Shulman (1986) advised against. However, Ball et al. (2008) believed their work could inform the work of teacher knowledge in other disciplines—“We suspect that many of these insights extend to the knowledge teachers need in other subjects as well” (p. 399).

This leads to the question: What are the insights from the development of MKT for the field of teacher knowledge in science education? First, Ball et al. (2008) delineated components of subject matter knowledge. In particular, they found that there was a subset of subject matter knowledge—specialized content knowledge—which is unique to the teaching of mathematics. In science education, the importance of subject matter knowledge is acknowledged, but subject matter knowledge for teaching is not addressed. What would specialized content knowledge for teaching science entail? Ball et al. provide further insights to how this question can be answered. Their framework was developed from extensive research based on an examination of the teaching of mathematics and refined through the construction and validation of measures of MKT. Much of the research in science education linking subject matter knowledge and PCK reflects a deficit model; that is, teacher weaknesses in subject matter knowledge are associated with their shortcomings in the classroom. With the connection between subject
matter knowledge and PCK well established (Abell, 2007), future research in teacher knowledge in science education can be modeled on the work of Ball et al.. Through observations of practice, the tasks for teaching science can be identified, and the subject matter knowledge necessary for conducting those tasks can be delineated. Once a framework for subject matter knowledge for teaching science is developed, appropriate measures of this knowledge can be designed and validated (Ball et al.; Peterson & Treagust, 1995).

Shulman (1986) points out that within specific teaching fields, teachers must understand concepts, principles, and facts and how they are structured within a discipline. Additionally, teachers must understand how the knowledge was established and justified. Due to the diversity of subject areas in science, teacher knowledge may vary significantly. Several examples are as follows:

- Teachers must stay abreast of biological content knowledge, which is constantly growing and developing (e.g., genetic engineering), while content in chemistry is relatively static.
- Cultural concerns can hinder student acceptance and learning of topics in some science content areas (e.g., theory of evolution in biology and the big bang in physics), while other content areas rarely meet such skepticism.
- Skill sets differ for teaching different science subjects. When teaching physics, a teacher must often employ proportional reasoning; mathematical manipulation; and the use of graphs, diagrams, and equations. When teaching botany, there are less cross-curricular needs.

How would a framework for teacher knowledge in science address the distinct challenges presented by specific science subject areas? Some researchers have pursued this question; for example, Loughran et al. (2004). Is there a specific type of science knowledge that can address some or all of these concerns? How would Nature of Science (NOS) integrate into a science teacher knowledge framework?

In the field of mathematics, Ball and colleagues (Ball et al., 2008, Hill & Ball, 2009) have built upon Shulman's (1986, 1987) categorization of teacher knowledge and developed a framework for teacher knowledge in mathematics; science has not yet accomplished this goal with respect to subject matter knowledge. Via the conversation described in this chapter, MKT has the potential to inform teacher knowledge in science. The aforementioned preliminary questions can initiate the goal of developing a theoretical framework for content knowledge required for effective science teaching.

References


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