MATHEMATICAL MAKING IN TEACHER PREPARATION: WHAT KNOWLEDGE IS BROUGHT TO BEAR?

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In this paper, we describe an experience within mathematics teacher preparation that engages pre-service teachers (PSTs) in Making and design practices that we hypothesized would inform their conceptual and pedagogical thinking. With a focus on the design of new tools to support mathematics teaching and learning, this Learning by Design experience has PSTs exploring at the crossroads of content, pedagogy, and Making. We report our findings of the variety of forms of knowledge that PSTs brought to bear on their design work. As the engagement and advancement of these forms of knowledge is essential to effective mathematics teaching, these findings suggest the promise of a making-oriented experience within mathematics teacher preparation coursework.

Keywords: Technology, Teacher Education-Preservice, Teacher Knowledge

Preservice elementary teachers typically come to teacher preparation with limited conceptions of mathematics (Association of Mathematics Teacher Educators, 2013) and a model of mathematics teaching based solely on their own classroom experiences as students (Lortie, 1975). These models can be characterized by appeals to rules and procedures (Ball, 1990; Ma, 1999; Thompson, 1984), problems whose solutions are predetermined and predictable (Schoenfeld, 1992; Thompson, 1984), and teaching in which mathematical information is imparted from teacher to student with unquestioning acceptance (Lampert, 1990; McDiarmid, Ball, & Anderson, 1989). This is a problem because this model of mathematics teaching is not consistent with a pedagogy that is viable for learning mathematics with understanding. Consequently, as part of their preparation for elementary teaching, prospective elementary teachers must be presented with opportunities to challenge their current models of mathematics teaching and learning that engage them with both the problems of mathematics and the problems of children's learning of mathematics.

At the same time, the proliferation of spaces for digital design and fabrication suggests new opportunities to teach and learn new mathematical things in new ways and to even think in new ways about what teaching and learning mathematics might look like. However, research is only beginning to identify the mathematical thinking and reasoning that these technologies might make possible. And there is no research that explores what these technologies might offer to support the preparation and professional development of teachers. As such, this proposal presents a novel Making-oriented experience within mathematics teacher preparation that tasks pre-service elementary teachers with designing, fabricating, and evaluating new manipulatives (Post, 1981) aimed at engaging and advancing learners' mathematical thinking and reasoning. Thus, this project addresses the need for better preparation of elementary mathematics teachers through education research that seeks to understand the processes and potential benefits of teacher learning in a Maker context.

Proceeding from the hypothesis that Making and doing lead to new ideas and experiments in embodied (Johnson, 2007), networked (Latour, 2005), and tool-centric (Vygotsky, 1978) engagement that, in turn, will lead to powerful innovation in mathematics teaching and learning, this project seeks to address the following question: *What forms of knowledge are brought to bear on pre-service elementary teachers' design work as they make new manipulatives to support the teaching and learning of mathematics?*

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Theoretical Framework

In the context of math-focused exhibitions in the designed informal learning environments (National Research Council, 2009) of science centers and museums, investigators have identified evidence of visitors engaging in algebraic (Pattison, Ewing, & Frey, 2012) and spatial reasoning (Danctep, Gutwill, & Sindorf, 2015), and also demonstrating qualitative, intuitive understandings of slope (Nemirovsky & Gyllenhall, 2006; Wright & Parkes, 2015). Within Makerspaces (Peppler, Halverson, & Kafai, 2016), where activities are designed with a variety of learning goals in mind, some research suggests that in order to see and support opportunities for mathematical activity, it is necessary to look beyond the content and use a more broadened conception of mathematics – "including mathematical dispositions, habits of mind and identity" – to identify the mathematics in which learners engage (Author et al., 2016a). These findings of mathematical engagement in informal settings point to the possibilities that semi-structured design-centered experiences can offer in relation to mathematics teaching and learning.

As for K-12 educational settings, Shaffer's (2005) use of design tasks in a microworld (Papert, 1980) to teach transformational geometry, and Cochran and colleagues' (2016) suggestions about how middle school teachers can use 3D printing as a context to promote geometry understanding, lend further credence to the proposition that Making can provide a gateway to meaningful interaction and deepened understanding of both content and pedagogy by engaging preservice teachers (PSTs) in the design of new manipulatives and corresponding tasks that generate environments for mathematical thinking and learning. Research can shed light on the creative and participatory practices associated with teachers' Making experiences and how those experiences inform their knowledge and their identities as elementary mathematics teachers.

Teachers as Designers

In investigating the experiences of PSTs designing for mathematical learning, we connect with other researchers' conceptions of *teachers as designers* (Kalantzis & Cope, 2010; Maher, 1987). Svihla et al. (2015) refer to "teachers as designers of learning experiences to emphasize teacher involvement in designing from pre-instructional designing of lessons, activities, units and learning environments to their design work that continues into the classroom" (p. 284). When teachers are given agency to craft their own manipulatives and corresponding curricular materials, they assume ownership over these materials and the learning environments they generate, thereby coming to see themselves as agents of curricular and pedagogical reform (Leander & Osborne, 2008; Priestley, Edwards, Priestley, & Miller, 2012). In doing so, they find themselves moving toward more legitimate forms of participation (Lave & Wenger, 1998) as they develop their identities as designers of mathematical instruction.

Learning Teaching by Design

The premise of this project follows from the proposition that it is productive to develop teacher knowledge within a context that honors the connections between its constituent forms of knowledge. Accordingly, we took somewhat of a Learning by Design approach (Koehler & Mishra, 2005; Koehler, Mishra, Hershey, & Peruski, 2004; Mishra & Koehler, 2003), a methodology that was developed as a means to advance teachers' technological pedagogical knowledge, or TPCK (Koehler & Mishra, 2010). An environment is created in which teachers naturally confront content, pedagogy, and technology so that the connections between are honored and maintained. Within this environment teachers assume the role of designers of technology and work collaboratively in small groups to develop technological solutions to authentic pedagogical problems. "By participating in design, [they] build something that is sensitive to the subject matter (instead of learning the technology in general) and the specific instructional goals (instead of general ones). Therefore, every

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act of design is always a process of weaving together components of technology, content, and pedagogy" (Koehler & Mishra, 2005, p. 95).

Our own Learning by Design approach to mathematics teacher preparation is grounded in several principles. First, constructionism (Harel & Papert, 1991) is the theory of learning that undergirds the Maker movement's focus on problem solving and digital and physical fabrication (Halverson & Sheridan, 2014, p. 497). Second, Piagetian constructivism, a theory of learning that is well suited to the way learning works in an environment of mathematical inquiry (Author et al. 2016b), informs the pedagogy. Indeed, the power of manipulatives lies in their capacity to support the construction of abstract mathematical concepts from sensorimotor engagement with concrete tools (Kamii & Housman, 2000; Piaget, 1970; Vygotsky, 1978), a process grounded in the theory of constructivism. Third, knowledge of the content to be taught and a variety of ways in which that content may be presented, represented, and experienced (Ball & Bass, 2009; Ball, Thames, & Phelps, 2008; Shulman, 1986) informs the mathematics. Finally, Dewey's (1938) and Pinar's (2012) broadened conceptions of curriculum that frame learning as the product of play, experimentation, and authentic inquiry align with our conception of curriculum. Still, the rich scholarship devoted to teacher knowledge reflects the complexity of the question of precisely what forms of knowledge might actually be brought to bear on PSTs' design work (Ball, 1990; Borko & Livingston, 1989, 1990; K. F. Cochran, DeRuiter, & King, 1993; Grossman, Wilson, & Shulman, 1989; Hill, Ball, & Schilling, 2008; Ma, 1999; Shulman, 1986).

Methods

The study took place in two sections of the first of two required specialized mathematics content courses for pre-service elementary teachers at a large public university in the northeastern United States. Our Making-oriented experience began with PSTs' inquiries into the principles that ground our Learning by Design approach and that are among the standard course goals and objectives for this course. Specifically, these include providing PSTs with opportunities to reconceptualize the content of K-6 school mathematics (including number, arithmetic, and algebraic thinking) while also promoting an inquiry-oriented pedagogy by fostering an understanding of the nature of mathematics, assimilating a constructivist theory of learning mathematics, acquiring a model of how learning works in interaction with manipulatives and other technologies, designing instructional tasks that both promote and reveal students' understanding of mathematics, and developing an understanding of the way in which students' content knowledge develops over time, as well as the struggles they're likely encounter. Concurrently, as PSTs learned to use 3D design and fabrication technologies, they engaged in an iterative "Design Thinking Process" (Stanford University Institute of Design, 2004).

As students were permitted to work either individually or in groups on a design project, the twenty-six students who consented to participate in the study comprised a total of twenty-one groups. The data corpus consists of the following three components of each group's "design case" (Boling, 2010): 1) a "Project Idea Assignment," which describes the group's initial thoughts about a manipulative they want to work on; 2) a "Project Rationale Assignment," which provides an account of why and how a group thinks their project should work from a mathematical learning point of view as well as how their design reflects an understanding of what mathematics is and of how learning happens; and 3) a "Final Paper and Design Show," which includes a short research paper about the project and a PowerPoint that describes the intended purpose of the manipulative, the corresponding tasks that were created, and the group's findings from an intended user's manipulative-mediated engagement with those tasks.

To initiate the analysis of that data, we chose three design cases at random. Three researchers individually analyzed the components of those cases and generated codes (Corbin & Strauss, 2008) that identify forms of knowledge that were revealed in the elements of PSTs' written work. Then, the

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three researchers got together to generate a cumulative list of codes and clarifying definitions (Table 1). Next, each of the researchers used those codes to analyze all of the remaining design cases. As the analysis continued, new codes were also introduced and then shared among the researchers.

Table 1: Analytical Framework for Coding Knowledge Types

Code (Knowledge of…)	Description
Mathematics Content	Common content knowledge of mathematics.
Specialized Mathematical Knowledge	Variety of ways mathematical ideas can be expressed and explained.
Content and Students	Common student struggles and misconceptions; planning for student thinking.
Standards and/or Curriculum	Acknowledgement of Common Core and/or curricular materials as an important aspect driving instruction; knowledge at the mathematical horizon.
Distinction between Concrete & Abstract	Abstract ideas are abstracted from concrete representations.
Constructivism	Knowledge is constructed; model of knowing as understanding; role of exploration and experimentation; relevance of prior knowledge.
Research on Student Learning	Use of mathematics education research literature.
Task Design for Problem Solving and/or Assessment	Tasks designed for use with a manipulative require challenge/productive struggle, but can also play a dual role of learning and assessing.
Personal Experiences	Students' personal mathematical experiences (both as learner and teacher) inform their design.
Student Affect	Importance of designing tools and tasks that make learning engaging and fun.
Mathematical Tools	Knowledge of currently available tools (e.g., integer chips, base ten blocks, number lines).
Manipulatives	General comments about how learning works with manipulatives; as embedded representations of mathematical ideas.

Intercoder reliability was calculated using percentage of agreement. Since three coders participated in the analysis, each coder was compared to one another in a pairwise manner. Thus, every coding decision had a total number of three pairs to check for agreement. The number of agreements was noted, and ultimately divided by the total number of possible agreements in order to calculate the percentage of agreement. The data presented here had a percentage of agreement of .82, well within the standard put forth by Neuendorf (2002).

Results

Our analysis showed that students used a variety of forms of knowledge in the course of their "Design Thinking Process," as demonstrated in the table of codes provided above. These knowledge types ranged in frequency of occurrence from 68% to 100% (see Table 2).

Table 2. Code Frequencies and Match Percentages

	Mathematics	Specialized Mathematical	Content & Students	Standards and/or Curriculum	Concrete/ Abstract	Constructivism
Coder 1	21	12	20	12	11	19
Coder 2	20	20	20	17	20	20
Coder 3	21	20	19	14	19	20
Total	62	52	59	43	50	59
Match %	0.97	0.75	0.97	0.78	0.71	0.87

	Research on Student Learning	Tasks for Problem Solving & Assessment	Personal Experience	Student Affect	Mathematical Tools	Manipulatives
Coder 1	17	12	11	7	11	21
Coder 2	13	19	19	9	12	21
Coder 3	14	18	17	8	14	21
Total	44	49	47	24	37	63
Match %	0.78	0.71	0.68	0.87	0.75	1.00

From this analysis, we see that every group drew on both Knowledge of Mathematics and Knowledge of Manipulatives in their design process. Comments such as "the manipulative will aid students in learning geometry because they will be able to turn, rotate, and reflect on the shapes that they will make" and "the main idea behind the design of our tool… is to help students determine the area and perimeter of two similar figures" demonstrate that knowledge of mathematics content was an extremely important aspect of their design thinking. In particular, these excerpts demonstrate some of the ways the groups expressed their knowledge of manipulatives as embedding mathematical principles.

In the course of thinking about content in this way, each of the groups also leveraged their Knowledge of Manipulatives. We saw a diversity of thinking about manipulatives, ranging from the more generic ("Manipulatives are defined as concrete objects that aid in classification.") to the more sophisticated ("Manipulatives not only allow students to construct their own cognitive abilities for abstract mathematical ideas and processes, but they also provide a concept and common language behind it."). Other students professed a more nuanced understanding of the role of manipulatives in instruction, acknowledging they are best used with other teaching techniques: "Fraction circles are a simple, clear 'physical tool' for teaching this challenging concept, and when used in conjunction with other [fraction contexts] (equal sharing, part-whole, etc.) can be very illustrative." One group drew on their own review of the research literature to inform and support their thinking about manipulatives, writing that "These concrete materials are meant to assist children at all levels of education including understanding processes, communicating their mathematical thinking, and extending their ideas to higher order thinking levels (Balka, 1993)."

Evident in the PSTs' Knowledge of Manipulatives is the related Knowledge of Constructivism as a learning theory that can inform design decisions. Phrases such as "help students construct the idea," "children can tinker with the board and the pieces to find the relationships between the pieces and the groups," and "create a way to teach even and odd numbers that does not revolve around memorizing," all demonstrate the ways the groups were thinking about making tools that allowed for exploration and discovery, both hallmarks of the pedagogical implications of a constructivist theory

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of learning. In this way, students began to seriously consider not only features of an inquiry-based pedagogy, but also the ways in which tools can be seen to support those implications in classrooms.

Although their design assignments hadn't explicitly called for students to make connections between their design ideas and the coursework, almost every group conceived of their design and the learning it aimed to promote through the lens of their Knowledge of Content and Students. They drew on class readings, the math education literature, and their own experiences as learners of mathematics to anticipate concepts that students would be likely to struggle with. These considerations were evident in statements like, "Since some children have non-anticipatory coordination between groups and shares, my manipulative serves as a way for students to utilize the pieces to see the distribution of shares to each group."

We also saw evidence of other knowledge categories, though with less frequency than those elaborated above. These forms of knowledge include considerations of the relationship between concrete and abstract representations, knowledge of task design for problem solving and/or assessment, knowledge of currently available mathematical tools, and the importance of considering student affect in their designs.

Conclusion

At the crossroads of digital fabrication technologies, human-centered design practices, and constructivist orientations to mathematical thinking and learning, students and teachers are afforded a host of new possibilities. As researchers exploring how these technologies might be used to engage teachers and students in new forms of learning, we hypothesized that a making-oriented approach to pedagogical and curricular change aligned with the kind of progressive, inquiry-oriented pedagogy we aim to cultivate in students preparing to teach mathematics. Accordingly, we developed an approach to nurturing students' inquiry-oriented pedagogy that leverages design practices and digital fabrication technologies as a resource for their learning. While we recognize that teacher preparation is complex and that pedagogical change is difficult, that we identified in PSTs' design work a variety of forms of knowledge whose advancement is essential to mathematics teaching, these findings suggest the promise of a making-oriented experience within mathematics teacher preparation.

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