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Reconceptualizing Pedagogical and Curricular Knowledge Development Through Making

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ABSTRACT

While making is typically tethered to narratives of entrepreneurship and business, it can provide a gateway to meaningful interaction and deepened understanding of both content and pedagogy. In this article we provide descriptions of two courses—one each at the pre-service and in-service levels—that engage teachers in making and design practices that we hypothesized would inform their pedagogical and curricular thinking. With a focus on the design of new tools to support teaching and learning through the use of human-centered design practices and digital fabrication technologies, these courses have teachers exploring at the intersection of content, pedagogy, and making. Specifically, they inquire about theories of how people learn in interaction with physical tools and how these tools shape and guide content-specific thinking and learning. Several of their final projects are presented along with pedagogical and curricular inferences we made about them that suggest the promise of a making-oriented experience within teacher preparation and professional development.

Keywords: making, design, teacher preparation, teacher knowledge, TPACK

INTRODUCTION

The primary task of teaching is the design of learning experiences for students. Among the forms of knowledge required of teachers to design such experiences are knowledge of the content to be taught, knowledge of a variety of ways in which that content may be presented, represented, and experienced, knowledge of curriculum (Ball, Thames, & Phelps, 2008; Ball & Bass, 2009; Shulman, 1986), and knowledge of "how teaching and learning can change when particular technologies are used in particular ways" (Koehler & Mishra, 2009, p. 65). This article presents a novel *making-oriented experience* within teacher preparation and professional development in relation to these forms of knowledge that is made possible by increasing access to human-centered design practices and digital fabrication technologies. We describe this approach as it was enacted in two courses, a graduate-level course with in-service mathematics teachers and an undergraduate-level course with pre-service teachers from across the content areas.

DESIGNING FOR MATHEMATICAL EXPERIENCE

In the spring of 2016, I, the first author, taught a graduate-level course I designed called "Designing for Mathematical Experience" with in-service mathematics teachers. The course called on teachers to complete a maker project in which they design, produce, and evaluate new physical tools that support mathematics learning and that have students engage in authentic forms of mathematical activity. In documenting the approach I took in this course, I first provide the theoretical and conceptual principles for teachers' design work. Then I present a selection of their final projects along with inferences I made about those projects in relation to these principles. These inferences are suggestions about the pedagogical stance the teachers presumably took as they designed and produced their final projects.

Theoretical Constructs and Conceptual Elements

Discerning the nature of the domain

In order to better understand the kinds of experiences that teachers were designing for, in the early meetings of the course we came to a shared understanding of *mathematical experience* as including not just planning for other people's mathematical activity—like posing a problem or designing a mathematical investigation—but also the experience of what it feels like to solve a complex problem or think deeply about a seemingly simple idea. Before we could come to this shared understanding, we first had to have a conversation about the nature of mathematical activity, or what it means to do mathematics. This conversation was critical to have with teachers, since they do their work within a paradigm of "school mathematics." School mathematics tends to have students memorizing facts and formulas and acquiring other people's procedures for solving other people's problems. Students learn *what* to do, but not *why* they do it. Mathematical ideas and their meanings are given too little attention, and students are unlikely to get the impression that mathematics is actually a creative activity. In designing for more authentic mathematical activity, teachers had to step outside this figured world (Holland, Lachicotte, Skinner, & Cain, 1998) of conventional classrooms to reconsider the essence of what it means to engage in mathematics as a mathematician. In doing so, they spoke about discovering and representing patterns, making and testing conjectures, constructing examples and counterexamples, and devising and defending arguments. This image of authentic mathematical activity became the context for their subsequent design work.

Reconceptualizing curriculum as experience

Because teachers' developing image of mathematical activity was exploratory in nature, designing for student engagement in mathematics as a mathematician also required that teachers' notions of curriculum be broadened beyond conventional visions of learning math in schools. To facilitate this reconceptualization, teachers considered William Pinar's conception of curriculum (Pinar, Reynolds, Slattery, & Taubman, 1995; Pinar, 2012) to include not only instructional materials but to also include the forms of experience that those materials hope to mediate. Then, Eleanor Duckworth's vision of teaching as "providing occasions for wonderful ideas" (2006, p. 7) complemented this broadened conception of curriculum. Whereas Piaget's interest was in the development of knowledge (1970), Duckworth considered the implications of his findings for teaching. For Duckworth, the having of wonderful ideas is the essence of intellectual development, and the essence of teaching is "providing a setting that suggests wonderful ideas to children" (2006, p. 7). By building on teachers' conceptions of mathematical experience and their broadened notion of experience-oriented curriculum, thinking about the design of learning environments as providing occasions for wonderful ideas gave coherence to teachers' developing framework of design principles for new tools for learning mathematics.

Making meaning in interaction with physical tools.

"Manipulatives" are physical tools that have a long history in K-12 mathematics education, especially in elementary school where they have been used to teach such concepts as number, fraction, and place value. In order to understand exactly how these tools can support mathematics learning, the teachers needed a model of how learners make meaning in interaction with physical tools. First, they drew on Vygotsky's (1978) notion of tools as being both technical—in their capacity to act on the environment, and psychological—in their capacity to mediate mathematical thinking. Seymour Papert's (1980) essay, "The gears of my childhood," which conveys the importance that gears played for him as an "object-to-think-with" (p. 183), provided an image of the Vygotskian proposition that "new tools make new things possible." My hope was that if teachers accepted the premise that new tools make new things possible and that these tools could be used as objects to think with, then they would realize the promise of these same tools for providing occasions for wonderful ideas. Indeed, I had conceived of the approach through which teachers would produce new tools to provoke wonderful ideas as a wonderful idea in and of itself.

Compatible with Vygotsky's perspective is Pacey's work (1983), which was used to move teachers' conceptions of technology in two ways: first, to reestablish physical tools as technologies, and second, to broaden the conventional focus on the technical aspects of tools to also include the cultural and organizational aspects embedded within them. Then teachers assimilated Piaget's model of cognitive development (1970) to understand the role of physical tools in learning mathematics. According to this model, which is grounded in a constructivist theory of learning, conceptual thought proceeds from representational thought, and representational thought proceeds from perception. As a learner *manipulates* a physical tool such as a cube, percepts (i.e., an object of perception) of that cube (e.g., its edges, its faces) are reflectively abstracted, coordinated, and synthesized into a coherent whole that is a constructed mental re-presentation (von Glasersfeld, 1995) of that concrete cube. Thus, it is critical to understand that these mental representations are formed through an active process and are not mere copies of those percepts (Kamii & Housman, 2000). Then, all mental operations on that cube (e.g., rotations) are performed on that representation. This is what it means to say that the child's representational thinking develops from his or her sensorimotor intelligence. And this is the process by which learners can use physical tools to construct abstract mathematical concepts.

Design and Production

None of the teachers had any experience with 3D design technologies prior to the course, and I had very little. So, beginning on the first day of the course, a guest instructor with expertise in 3D design taught the teachers how to use Tinkercad (Autodesk, Inc., 2016). Tinkercad is a free and simple online 3D design and printing tool authored by Autodesk. Tinkercad uses a straightforward "add and subtract" scheme for building shapes through compositions and decompositions of built-in solids. For about an hour during each of the early meetings of the class, teachers were taken through a tutorial that had them designing simple objects, like a cup with a handle. They generally had an easy time getting started and then sought out the assistance of the guest instructor whenever they needed it. Later, when teachers' project designs exceeded the capacity of Tinkercad, the guest instructor would assist them with 123D Design, also an Autodesk product.

Teachers printed their projects on Makerbot Replicator 2 printers, and they learned to use MakerBot Desktop in order to do so. MakerBot Desktop is the software that accompanies MakerBot printers and is used to manage those prints according to a variety of model settings (i.e., rafts, supports, infill).

Inferences of Pedagogical Change from Final Designs

Three of the teachers' final projects are presented below along with inferences I made from their designs about the pedagogical orientation they presumably took as they designed and produced these projects. These particular projects were chosen because the design decisions that teachers made most clearly exemplify the theoretical and conceptual principles for the course.

Example 1

The image on the left of Figure 1 is of a cone that two teachers designed in order to support students' learning of conic sections. Conic sections are cross sections of a double cone that are produced when a plane intersects the double cone. They include the circle, the ellipse, the parabola, and the hyperbola.

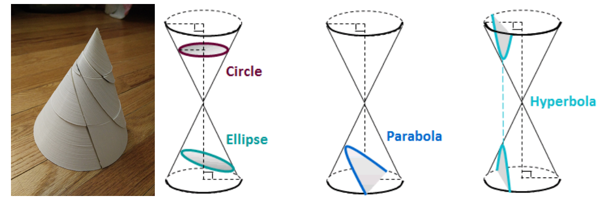

Figure 1. A new cone (left) and four conic sections (right)

These teachers were interested in having students explore the parabola, because they realized that learners of mathematics tend to have a misconception about parabolas that often goes unaddressed. Even the mathematically knowledgeable reader might be surprised to learn that the parabola shown on the right in Figure 1 is actually *not* a parabola; it's part of an ellipse. That ellipse would be evident if the cone were taller. If you imagine shortening the cone that contains the ellipse, you will see that what remains of the ellipse is what appears as the parabola. In fact, in order to produce a parabola, the plane must slice the cone at an orientation that is parallel to the lateral surface of the cone. The parabola in the figure is a cross section of a plane that is not parallel to the side of the cone.

The two teachers who were interested in supporting the resolution of this misconception designed and printed the 3D cone on the left of the figure, which can be decomposed into magnetized components of the cone. They used this new tool to engage learners in a clinical interview (Ginsburg, 1997) about conic sections in order to assess and resolve any misconceptions. The form of engagement that these teachers had with students was made possible using the tool they had produced. What made that engagement productive were teachers' knowledge of the relevant mathematics, their efforts to provoke wonder by having a learner confront his or her misconception, and their knowledge of how learners make mathematical meaning in interaction with physical tools.

Example 2

The image on the left of Figure 2 is of a coordinate plane that was designed to represent a point in the coordinate plane in a new way. The image on the right shows the conventional method for plotting five points in the plane. To plot the point (-5, 2), for example, begin at the origin, move left 5 units (because -5 is negative), and move up 2 units (because 2 is positive). This method of plotting a point treats that point as the endpoint of the resultant of two vectors, one horizontal and one vertical.

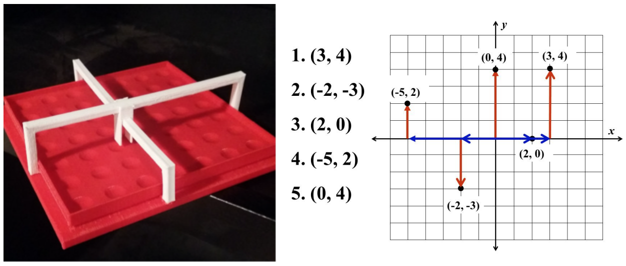

Figure 2. A new coordinate plane (left) and representations of plotted points as resultant vectors (right).

This vector-based method of treating a point in space as a directed distance from the origin had concerned one of the teachers in the course for much of his teaching. With no disrespect to Euclid (whose motivations were purely mathematical and not at all pedagogical), this teacher found it odd to describe static points in the plane as the sums of dynamic movements and also incompatible with his students' prior knowledge. Instead, he hypothesized that teaching students to identify points in the plane as the intersection of a vertical line and a horizontal line might be more effective because it would resonate with the way students are taught to use lines of latitude and longitude to loate points on a map. To illustrate, the tool embedded this new point concept by locating the point (-5, 2) at the intersection of the vertical line through the *x*-axis at -5, and a horizontal line through the *y*-axis at 2.

The new tool that this teacher produced embedded a new way of thinking about a point. His capacity to analyze what might be problematic for learners about the conventional way of plotting a point in the plane and his reconceptualization of the point concept as the intersection of two lines were motivated by the proposition that new ways of thinking hold the promise of engaging new learners. Furthermore, this capacity was made possible by this teacher's knowledge of algebra, a respectful skepticism of conventional curriculum, knowledge of the pedagogical implications of a constructivist theory of learning in terms of the necessity of engaging prior knowledge in order to advance it, and knowledge of how learners make mathematical meaning in interaction with physical tools.

Example 3

The image on the left of Figure 3 is the first set of tools designed and produced by a pair of teachers in the class. These tools demonstrate the concept of the definite integral in calculus using the "rectangle method." The rectangle method computes an approximation to a definite integral (the piano-shaped figures) using the sums of area of a collection of rectangles. As the number of approximating rectangles increases, the sum of their areas provides a better and better approximation of the shape's actual area.

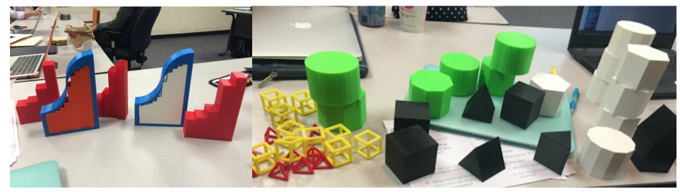

Figure 3. Models of the integral as area (left) and a collection of 3D models (right).

The teachers who developed these calculus tools had the idea to create them very early in the course and they set out to produce them right away. Their aim was to use these tools to make the advanced ideas of calculus accessible to students in middle school. Although Papert (1980) warned us that "For most people, nothing is more natural than that the most advanced ideas should be inaccessible to children" (p. 161), these teachers reduced the concept of the integral to its essential ideas in order to make advanced ideas accessible to younger learners.

Despite their success, these teachers weren't satisfied with what they had done. As they struggled with their tools to devise a task that wouldn't have learners converge upon a single endpoint (Stroup, Ares, & Hurford, 2005)—filling the given space with the given rectangles achieves the one best approximation for its area—they were tempted by the promise of Duckworthian "wonderful ideas."

The image on the right of Figure 3 shows the result of the project they took up next, a collection of solids that can presumably be used to assess students' and teachers' images of mathematical experience. In an interview setting, they would accomplish this assessment by asking a student or teacher to "Use these tools to design a mathematical experience." [Younger students would be asked to "Design something math-y."] In designing a tool for this purpose, these teachers had clearly assimilated conceptual and theoretical principles that they believed to be foundational to the work of designing for mathematical experience. And rather than designing a new tool that could be used to generate such an experience, they designed a tool they could use to assess others' images of what such an experience looks like. These assessments could be useful in designing for mathematics teacher preparation and professional development grounded in the theoretical and conceptual principles of this course.

Summary

In order for mathematics teachers to be able to foster students' understanding of mathematics they need more than mathematical knowledge; they also need to be able to implement an array of cognitive instructional approaches that engage and advance their students' mathematical thinking (National Research Council, 2010). "Designing for Mathematical Experience" aimed to cultivate this capacity in teachers by taking a making-oriented approach to developing their pedagogy. With an end-in-view (Dewey, 1998) of designing new tools for mathematical learning, this approach helped teachers establish a conceptual foundation with respect to the nature of mathematics and mathematical experience, and a theoretical foundation with respect to broadened conceptions of technology and curriculum and a viable model of how students make mathematical meaning in interaction with physical tools.

Judging from their final projects, this approach to pedagogical change was formative for teachers in relation to: 1) enriched images of mathematical experience that include both the learning of concepts and also the diverse forms of authentic mathematical activity by which those concepts are learned, 2) a broadened conception of curriculum that includes both resources and experiences, and 3) a viable model of how students learn mathematics with manipulatives.

DESIGN AS A GATEWAY INTO TEACHING, LEARNING, AND TEACHER EDUCATION

I, the second author, teach an instructional technology integration course for undergraduate students majoring in secondary education, special education, and speech pathology. This course requires pre-service HS and MS teachers, speech pathologists and special education teachers to think deeply about concepts in their field, how those concepts are taught, the nature of technology, the roles technologies play in their field, the ways in which they might use technology in their future careers, and the complexities of integrating technologies into learning environments.

Since the summer of 2015, I have included a group project that focuses on students co-constructing ways to overcome domain-specific challenges to learning and teaching via making and digital fabrication. This maker project requires students to identify difficult-to-understand concepts and practices within their domain and prototype new ways to support student learning via the application of Human Centered Design [HCD] (Both & Baggereor, 2016). HCD is an iterative approach that involves building understanding and empathy for users—in this case learners or clients, defining learning challenges and possibilities, brainstorming multiple divergent ways to overcome said challenges, constructing prototypes based on the most viable ideas, and testing those prototypes with target users.

In homogeneous groups relative to their specific teaching and speech pathology aspirations (i.e., English, Math, Science, Social Sciences, Family Consumer Science, Special Education, and Speech Pathology in School or Hospital Settings)—future students experience their fields from a design perspective. The juxtaposition of maker groups focused on such diverse content areas supports an atmosphere wherein students in other groups can often authentically serve as users when testing designs. This also requires the instructor to ensure that more knowledgeable others in terms of content and the teaching of that content are present during multiple points of the project (e.g., brainstorming, critiques, final showcase).

In the next sections, I outline the theoretical constructs and conceptual elements that influence the making project. Then I describe the practices, processes, and artifacts that have emerged from the maker experiences. Finally, I conclude with some observations about the effects and implications of integrating design and making experiences into a course focused on supporting learning via technology.

Theoretical Constructs and Conceptual Elements

Problems, prototypes, and possibilities

The overall goal with the group maker project is to support open-ended yet scaffolded learning and professionalizing experiences. In an educational sense, scaffolding involves the provisioning of supports necessary to allow students to navigate concepts and challenges they are not yet ready to overcome on their own (Bygstad, Krogstie, & Gronli, 2009). During the group maker project, the scaffolds include HCD-based step-by-step processes, instructor questioning and check-ins, and whole-class critiques. Students work within their content area to either design a device, manipulative, app, or artifact that supports learning, or design a maker project that students in their content area would undertake that supports learning the content and/or practices within a domain.

Students spend part of the first few weeks of the semester familiarizing themselves with a range of practices involving prototyping with digital and physical tools. They meet weekly with group members to identify an opportunity to work at the intersection of their collective curricular understanding and their growing design thinking and expertise. The focus on what problem might be overcome or what new experience might be made possible requires them to simultaneously consider curricular, pedagogical, developmental, societal, and design-related factors. During the project, they develop a shared understanding about ecologies of making and the experience of designing for learning within their content area. The pathways to this shared understanding are a form of scaffolded wayfaring (Ingold, 2007), wherein student groups move conceptually and materially not toward a right answer or pre-plotted final solution but among myriad curricular, pedagogical, and technological possibilities—each with its own set of affordances and constraints.

Reconceptualizing curriculum as experience

Despite the first author positioning curriculum within pedagogy and my positioning of pedagogy within curriculum, our overall conceptualizations and frameworks are highly aligned. Having experienced traditional K16 schooling practices, the majority of pre-service teachers and speech pathologists are acculturated into conventional conceptualizations of curriculum. Namely, ones in which the nature of mathematical, scientific, literate, and/or social scientific activity are broken down into predetermined elements to be learned via planned interaction with prefabricated materials (Taylor, 1919; Tyler, 1949). While the goals-objectives-instruction-assessment approach to curriculum and teaching is the most prevalent, alternatives exist. In this maker project (and in the course as a whole) students are recursively supported in experiencing and reflecting on *curriculum as experience*. These reconceptualized notions of curriculum aim to meet learners where they are and fold relevant and meaningful elements of learner histories and their professional futures into a contextualized present wherein they have domain-related experiences of their own co-creation (Pinar, 2012; Roy, 2003). In having and co-designing these types of experiences in relation to making and design thinking within their content areas, students are supported in a [reconceptualized] curricular form of ideation and professional growth Duckworth (2006) calls a having of wonderful ideas (described further in section II.A.2).

Going beyond off-the-shelf learning artifacts

Manipulatives, apps, and other materials serve as learning and teaching scaffolds by mediating engagement (Vygotsky, 1978) via an embodying of conceptual re-presentations—making knowledge-building interaction possible (von Glasersfeld, 1995) within one or several modal channels (described further in section II.A.3). Such technologies for learning and teaching are most often externally created for school districts and clinicians. From textbooks, to physical manipulatives, to digital apps for mobile devices, teachers and speech pathologists are typically encouraged to think in consumerist ways when it comes to supporting understanding, learning, and teaching with technology. While pre-made tools can support interactive knowledge-building, there are other approaches that offer unique opportunities for building understanding. Thinking only in terms of existing tools and technologies constrains the range of learning experiences that can be designed and the range of design-content literacies that can be developed (Gee, 2004).

Practices, Processes, and Artifacts

Students in the course have access to the College of Education and Human Science's makerspace—known as the CEHS Digital Research and Design Studio. During the first few weeks of the course students familiarize themselves with the studio's 3D printers, laser cutter, sewing and computerized embroidery machines, virtual reality headsets and camera, and an array of sensors controlled by credit card-sized microcontrollers called Arduinos and quarter-sized ones called LilyPads. Part of the process of familiarization includes a five-step group prototyping challenge adapted from Design Project Zero (Stanford University Institute of Design, 2004). Through this prototyping challenge of designing a digital-analog diagramming device, student groups select and try out maker practices and technologies in support of their design ideas. Groups use Tinkercad (Autodesk, Inc., 2016), GrabCad (2016), Repetier (Hot-World GmbH & Co, 2016), Adobe Illustrator, Microsoft PowerPoint, as well as fabric, conductive thread, rubber bands, styrofoam, velcro, and X-Acto knives to bring their designs into existence. Groups leverage the understandings they co-construct during class activities and open studio time to make their projects. In cases where group designs go beyond the capacity of the CEHS studio, they can gain access to the Nebraska Innovation Studio on the UNL Innovation campus.

Curricular Inferences and Connections based on Process and Final Prototypes

Two group projects are presented below along with inferences and connections I made based on observing

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their process and analyzing their final prototypes and designs. I selected these projects based on the high level of resonance between the resultant designs and the aims of the course project.

Example 1

The image at the top of Figure 4 shows two special education teachers in the early stages of designing their prototype. The bottom left image shows their design for an interactive wearable that measures and compares environmental stimuli with the wearer's preferred thresholds for light, sound, and activity based on individual presets, and sensors. The bottom right image is a prototype of the wearable.

Figure 4. Students in the ideation stage (top), the design plan (bottom left), and the prototype (bottom right).

These special education majors were thinking ecologically about supporting students that react atypically—often involuntarily—to everyday classroom ecologies. The project afforded the group the opportunity to focus and deepen their understanding of the complex ecological factors that impact a subset of special and general education students' capacities to learn. The result of their effort on the project was a constellation of wonderful ideas embodied in the processes they used and the artifacts they created. Their final design and prototype are both instantiations of the domain-related understandings they co-constructed during the project as well as their distributed understandings about making.

Example 2

The image at the top of Figure 5 is a sketch of a learning experience to support high school students in understanding Newton's laws of force and motion. This group of future high school science teachers created a making experience for their students that supports the investigation of physical forces as they interact with matter. Part of their design included a standardized vehicle to which students could attach bumpers of their own design—with the ability to change both the shape of the bumper as well as the materials. The group also created an app to receive data from the car (bottom left) to be used in the design and final testing stages.

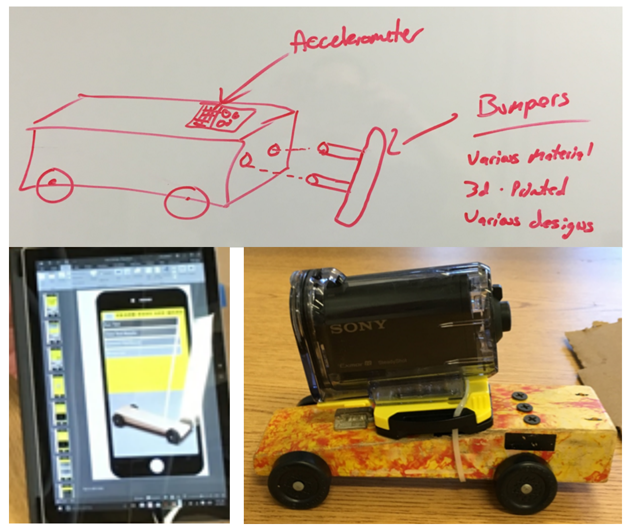

Figure 5. Maker design sketch (top), companion app (bottom left), initial prototype (bottom right).

The maker experience that this group designed affords HS physics students the opportunity to interact with concepts of force and motion in a scaffolded way that materializes abstract constructs and places domain-related ideas at the center of the project.

Summary

As students have experiences with prototyping and making, designing for learning becomes an option. These literacies at the intersection of making and their future profession afford them the ability to ideate, design, and make in a highly focused way. Such experiences support understandings that allow future teachers and speech pathologists to approach the concepts and content of their domain in unique ways. Having thinking and making experiences within the contexts and content areas students plan on teaching creates learning ecologies that meet students where they are and affords opportunities to have professionalizing, meaningful experiences at the intersection of learning, curriculum, and making.

Based on their process, iterative designs, and final projects, this reconceptualized approach to curriculum supports growth and knowledge building in relation to: 1) the evolution of student thinking about materializing understanding, 2) the deepening of their understanding of a particular concept or practice and how it might best be represented, learned, and taught, and 3) the development of their abilities to use digital and analogue prototyping and fabrication practices in the creation of digital and physical tools related to their field.

DISCUSSION AND CONCLUSION

The convergence of digital fabrication technologies, human-centered design practices, and a constructivist (Piaget, 1970) orientation to tool-mediated engagement and learning afford a host of new possibilities. As educators 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 our students. In two different contexts, working independently of each other but coming at the work from a similar theoretical orientation, we each developed an approach to nurturing our 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 evidence of this pedagogical orientation in our students' final projects suggests the promise of a making-oriented experience within teacher preparation and professional development. Furthermore, as prototyping processes and technologies such as 3D printing become more pervasive in schools, teachers whose pedagogies have been informed by making-oriented learning experiences will be well positioned to develop making-oriented learning experiences for their students.

The next steps in this line of research include 1) analyzing teachers' and future educators' pedagogical and curricular thinking as they engage in project design cycles, 2) inquiring into the ways they talk about experiences of field-related making, and 3) investigating the ways in which they design and implement tasks around the tools they produced and evaluate their outcomes.

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