Makers by Design: Helping Teachers Integrate Design Thinking Into Instruction Through a Sustained Professional Learning Fellowship

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Abstract: This paper investigates the extent to which participants in a professional learning (PL) program learned and implemented design thinking principles within their instruction. In 2022, 17 educators from the northern Virginia region were recruited to an NSF-funded PL fellowship, including K-12 teachers, post-secondary faculty, and public librarians. During the project, fellows completed 20 hours of design thinking PL, practiced teaching at digital fabrication summer camps for elementary and middle school youth and developed and implemented a lesson plan that integrated design thinking into their subject area. Data sources included surveys, teacher-generated lesson plans, and lesson reflections. A mixed methods approach was used for data analysis.

Keywords: design thinking, professional learning, STEM education

Introduction

Integration of makerspace technologies and the practice of *making* has drawn attention as an active learning intervention to cultivate student interest in STEM in an interdisciplinary context. To promote STEM literacy among students, K-12 and post-secondary institutions are integrating STEM pedagogies across the curriculum [1]. The culture and practice of *making* is one approach to STEM integration that centers around student-directed project-based learning, interdisciplinary problem-solving, and collaborative effort [2]. In this context, making typically entails using digital fabrication technologies (e.g., 3D printing, laser cutting) alongside design software (e.g., TinkerCAD, Adobe Illustrator) to design physical objects that solve a given problem. Integrating these techniques into classroom instruction can improve student attitudes toward and interest in STEM disciplines [3]–[5]. However, studies of classroom implementation of digital fabrication technologies also report that teachers struggle to move beyond "keychain syndrome," the tendency to fall back to reproducing simple objects, such as a keychain or coaster, that entail little to no student-driven problem-solving or engagement in authentic design thinking [6], [7].

Design thinking encompasses a set of principles that, when coupled with *making*, may provide a more authentic and meaningful experience for students and help teachers move beyond the “keychain syndrome”. Design thinking is a non-linear cognitive strategy used to approach the design of systems and solutions through collaborative and user-focused practices [8]. In the classroom, preliminary research suggests that design thinking is an effective model for teaching “21st century skills” that are also crucial to the development of science and engineering practices (e.g., collaboration, creativity, communication) [9]–[12]. As an engineering design process, design thinking organizes product creation around an empathetic understanding of the end-user's needs [8], [13]. An understanding of the user is intentionally developed through a variety of data sources, including surveys, interviews, and observations. Rather than moving prescriptively through a rigid series of steps, design thinking allows a designer to move fluidly between stages in response to changes in the users' needs or the extent to which those needs are understood [14].

Teacher PL focused on *making* has generally centered on machine operation, and not pedagogy, cognitive strategies, and processes to situate the technology [15]. This project, Makers by Design (MBD), represents an effort to build teachers' understanding of design thinking so *making* can be situated within meaningful design activities for students that foster interest and skills development. From a STEM workforce development perspective, it is essential students develop proficiency in design-related skills for future success in STEM careers, including technical positions that require problem-solving, communication, collaboration, and other aspects of design thinking.

This paper presents results from an NSF-funded Advanced Technological Education (ATE) project that aimed to help in-service educators integrate design thinking into their practice. Seventeen educators from the Northern Virginia region were recruited to a 9-month fellowship consisting of a) 20 hours of professional learning in design thinking at Northern Virginia Community College's (NVCC) makerspace, b) practice teaching design thinking at a digital fabrication summer camp with middle and high school students, and c) lesson planning to facilitate design thinking into their instructional setting. This cohort of educators had representatives from K-12, public libraries, post-secondary institutions, and a wide range of disciplinary backgrounds. Data collection and analysis were designed to answer two questions:

1. To what extent does participation in the professional learning fellowship foster the integration of design thinking elements into instruction?

2. To what extent does the fellowship improve participants' confidence in implementing design thinking and digital fabrication?

Methods

Effective Professional Learning. Research on PL suggests that interventions that foster sustainable changes in teaching practice include (a) modeling, (b) lesson plan development, (c) practice teaching, (d) coaching, and (e) building a community of practice. Modeling desirable instructional practices provides teachers with the opportunity to experience exemplary, authentic instruction as learners [16]. *Modeling* has shown utility in several areas of STEM education, including engineering instruction [17], digital technology use [18], [19], and reform-based science instruction [20]. *Lesson planning* allows teachers to revisit and apply what they learn in an active way that is relevant to their own instructional context (e.g., grade, student ability, content) [16], [21]. Teachers value opportunities to *practice* using new instructional strategies in conditions without repercussions if a lesson does not go as planned [22]. Individualized *coaching* allows PL implementers to differentiate support based on teachers' needs [23].

Program Recruitment. Educators were recruited for the PL fellowship through contacts with local school districts and library systems and internally at NOVA. The application process required demographic data and brief narratives of prior experiences with design thinking, engineering, and common makerspace technologies. Of the 32 applicants, 17 fellows were accepted to the program using a rubric prioritizing racial and ethnic diversity of students taught, geographic representation across NVCC's service area, and quality of narrative responses. (Table 1).

Table 1. Participant demographics (n=17)

Teaching Environment

K-12	59% (n=10)
Post-secondary	29% (n=5)
Library	12% (n=2)
Gender	
Female	65% (n=11)
Male	35% (n=6)
Race / Ethnicity	
White	41% (n=7)
Other	24% (n=4)
Black	18% (n=3)
Hispanic / Latino	12% (n=2)
Asian	6% (n=1)
Pacific Islander	0% (n=0)

Program Structure. From a content perspective, MBD sought to help participants understand *design thinking* and distinguish it from *engineering design*. Design thinking proceeds through a 5-step process, beginning with identifying a general problem experienced by a group of people (Table 2). As an engineering design practice, design thinking emphasizes gathering and analyzing information from users (*empathize*) prior to the formation of problem statements (*define*). Prior to developing prototypes, a number of solutions are developed (*ideate*) and evaluated against existing constraints and specifications. Initial *prototypes* are typically low-cost and low-fidelity, designed to gather more information from users through *testing* that can be used to refine (*ideate*) potential solutions further.

Table 2: Design thinking process and descriptions

Process	Description
Empathize	Gather data about end-users experiencing a particular problem. Use a variety of methods (e.g., interviews, observations) to ensure an accurate understanding of how users feel about and interact with the problem.
Define	Analyze collected data to produce an actionable and refined problem statement. Statements refine the problem and identify specific user needs that must be met for a solution to be effective.
Ideate	Produce a wide range of potential solutions to the new problem statement. Ideation should alternate between divergence (thinking of a broad range of solutions) and convergence (narrowing down those solutions according to the problem statement).
Prototype	Develop a working prototype of the chosen solution. Prototypes should be low-cost and quick to produce.
Test	Test the prototype in a working environment, preferentially with the user or a designer acting as the user.

Spring PL consisted of online and face-to-face instruction (Table 3). In the workshop, the commonly used bridge challenge was used to distinguish design thinking and other forms of engineering design in the PL. As traditionally taught, bridge-building challenges typically involve students using limited time and materials to build a bridge of a defined length and then testing its load-bearing capabilities. This activity typically defines the problem exactly (e.g., the bridge must be 12 inches long) and defines the parameters for success similarly (e.g., a successful bridge will hold 500 grams without breaking). By comparison, a version of the bridge-building activity centered around *design thinking* would provide information about users first, asking students to consider users' needs as a foundation for the design process. The results of a "bridge building activity" using design thinking as a cognitive strategy might not involve a bridge at all. Instead, students might propose an alternative means of conveyance (e.g., ski lift) or another creative solution. In other words, the users' needs and constraints are crucial in identifying the problem and subsequent solution. These two variants of the bridge challenge were compared and discussed in the first meeting (Table 3).

Fellows then were assigned interdisciplinary groups to consider a design challenge. Specifically, fellows were tasked to develop a storage and sorting solution for a fictional LEGO hobbyist. During each session, fellows were introduced to a concept or strategy in design thinking (e.g., interview users, journey map), applied that strategy to their project, and then observed a guest teacher delivering a model lesson using the strategy in a particular educational context (e.g., middle school science, introductory college engineering). Each session roughly corresponded to one of the five steps of the design thinking cycle (Table 3).

Table 3. Structure of the design thinking PL

DT Step	Description	Model Lesson
Empathize *Virtual,* *2 hours*	• Facilitators introduce fellows to design thinking. • Overview of the LEGO design challenge. • Develop an interview protocol for their users.	N/A
Empathize *Virtual,* *2 hours*	• Implement interview protocols • Expand user profiles	Build-A-Bridge: adds users to an engineering bridge-building exercise.
Define *Virtual,* *2 hours*	• Formulate a user-focused problem statement	Citizen Science: challenge students to identify the problems with a failed science outreach project.
Ideate *In-person,* *6 hours*	• Develop a journey map that follows their user's experiences. • Ideate several solutions to their user's problems.	Board Game Design: play a prototype board game, then propose new rules and test them.
Ideate *Async,* *2 hours*	• Fellows evaluate their solutions using a rubric.	N/A
Prototype & Test *In-person,* *6 hours*	• Fellows develop a physical rough prototype using paper, cardboard, and glue. • Peer testing of prototypes.	Camp Practice: rapidly prototype a LEGO transport method for Suresh, an elementary school student.

After completing the spring PL, fellows *planned* for and then *practiced* teaching design thinking during a week-long summer camp run by NVCC. During camp days, the morning focused on introducing digital fabrication technologies (e.g., 3D printer, laser cutter) and design software (e.g., TinkerCAD, Adobe Illustrator). The afternoon (approximately 2.5 hours) was devoted to design thinking workshops. The MBD fellows led the camp students through a design challenge during these workshops. The camp students were provided with a bio of a user who experienced trouble transporting LEGO creations from one place to another. For example, campers might work with the fictional Suresh, a 12-year-old boy who transports his LEGO sets between his divorced parents' houses on a scooter. Fellows were given broad latitude to structure this time, with the general guidance to try to include each step of the design thinking process. During fellows' *practice* of design thinking instruction, PL facilitators observed and provided feedback at the end of the day during structured debriefs that lasted approximately 30 minutes. Table 4 provides an overview of the structure of the design thinking portion of the summer camp.

Table 4. Camp design thinking framework

Activity and Time	Design Thinking Step	Description
Challenge Overview *5 minutes*	N/A	Explain the challenge to students. On days 2 and 3, use this time to recap previous events.
Meet Your User *15 minutes*	Empathy	Pass out user dossiers to students. Have students review dossiers in their groups. Students may "interview" their users, with facilitators acting as users.
How Might We…? *10 minutes*	Define	Provide students with the How Might We Chart. Explain that students should use the chart to determine what their user requires for the solution to solve the problem.
Brainstorming *15 minutes*	Ideate	Now that students have completed the How Might We chart detailing the requirements of their solution, they should ideate designs. Students should take 5 minutes to draw their designs – encourage students to label and explain their thoughts. Then ask students to converge their designs into one group plan using the Group Design worksheet.
Prototype *60 minutes*	Prototyping	Using the provided materials, groups should prototype their chosen design. While groups are prototyping, facilitators should move around to resolve issues with the prototyping process.
Test *30 minutes*	Test	Using the provided testing worksheet, help teams develop a testing protocol. You may have teams switch prototypes with one another if time permits.
Debrief & Cleanup *15 minutes*	N/A	Teams should take the time to review the results of their testing and decide how they would continue with their prototype (e.g., new design, refine, etc.)

For the last stage of their fellowship, fellows developed a lesson plan integrating design thinking into their classroom instruction. After testing out lessons in their classrooms, fellows provided NVCC with a copy of their lesson plans (required) and a brief reflection (optional) explaining how their lesson went and what advice they would give another educator who wanted to use their ideas.

Data Collection and Analysis. Data sources included participant lesson plans and surveys. Submitted lesson plans were coded for the steps of the design thinking process (*empathize, define, ideate, prototype, test*) as described above, along with three additional codes (*overall process, iteration, and failure*). *Overall process* refers to statements describing the overall process of design thinking, either by explaining the strategy's goals or outcomes. *Iteration* refers to statements that reference the iterative nature of design thinking or the necessity of producing multiple versions of a given product to find the best possible solution. *Failure* refers to statements that reference the necessity of failure in order to gather data on what doesn't work as well as what does. The first author coded the lesson plans. Validity of frequency counts was established by the second author, who coded a subset of the lesson plans (20%). Any disagreements in codes were resolved through discussion.

Patterns in self-reported confidence in implementing four instructional practices (design thinking, human-centered design practices, 3-D printing, laser-cutting) were analyzed through descriptive statistics (Mean, standard deviation). Participants were assigned de-identified numeric identifiers.

Results

Of the 17 educators selected for the program, 13 completed the fellowship, produced design-thinking lesson plans, and provided responses to all survey instruments. Participating educators completed a pre- and post-survey intended to measure their confidence in integrating elements of digital fabrication, design thinking, and user-centered methods into their instruction. Descriptive statistics indicate the mean confidence increased for design thinking, human-centered design practices, and 3-D printing (Table 5). Standard deviations were above .5 for all measures and all time points, indicating quite a lot of variability in participant responses, with variability highest for 3D printing and laser cutting. Design thinking was the construct that showed the greatest mean confidence change and the greatest decrease in standard deviation from pre to post indicating the participants consistently chose a greater Likert confidence score compared with participants on the presurvey. Due to the low sample size, inferential statistics could not be performed.

Table 5. Confidence[a]

Instructional Component	Pre-fellowship (n=15) Mean (SD)	Post-fellowship (n=12)
Design Thinking	3.06 (0.89)	3.5 (0.52)
Human-centered design practices	3.23 (0.62)	3.42 (0.51)
3D Printing	2.60 (1.30)	2.67 (1.23)
Laser Cutting	2.33 (1.23)	2.0 (1.34)

[a]4-point Likert scale, 1 = not at all confident, 4 = Highly confident

Table 6 provides an overview of the lesson plans produced by participating educators. For each lesson, the subject area, grade band, and a brief description of the lesson content are provided. Educators were encouraged to submit a lesson that addressed the context of their teaching practice; as such, the format and content of lesson plans are highly variable across participants.

Table 6. Overview of participant lesson plans

ID	Discipline	Lesson Description
1	Career & Technical Education High School	Taught design thinking as a winter break elective, running 2 hours a day for 5 days. Much of the lesson content is reused from PL workshops.

2	Career & Technical Education Middle School	Lesson is a 9-class sequence in which students create a custom sign for a teacher at their school. Students are required to structure their groups as a pretend business; practicing pre-professional skills.
3	Career & Technical Education High School	Lesson is a design challenge to develop a reaching tool for elderly clients who are vertically challenged.
4	Engineering High School	Lesson involves the creation and fabrication of a board game for 4th grade mathematics students and takes place over 4 90-minute blocks. Lesson has a very rigid structure, with the requirements for the game (e.g., types of pieces, rules, learning objectives) have already been predetermined by the instructor.
5	Biology Post-secondary	Lesson plan is a redesign of the laboratory section of an advanced microbiology course and inten ded to allow students freedom to design and structure their own research lab.
6	STEM Resource Teacher Elementary	Lesson involves reading students a fable, then asking them to use the design thinking process to think of a solution to the problems experienced by the characters in the fable.
7	Engineering High School	Lesson is a collaboration with the Biology teacher for 10th grade students. Students receive a case study of users impacted by dirty water and must create a filtration solution.
8	Physical Education Post-secondary	A workshop for volunteer faculty and staff to brainstorm ideas for a wellness campaign to be prototyped in Fall 2022.
9	Librarian	Lesson is a workshop for a cub scout troupe visiting the makerspace to earn their engineering badge. Scouts build an attachment for a Sphero that can carry a 3D printed container full of candy through an obstacle course.
10	Career & Technical Education Middle School	Lesson is structured as 6 45-minute blocks and asks students to develop an ankle brace for a child with cerebral palsy. Budgeting and financial constraints are a major part of the instruction.
11	Photography High School	Lesson plan is a revised plan from summer camp instruction. Lesson is a two-part workshop, the first being a bridge-building icebreaker and the second a design challenge focused on building a chair for a specific user.
12	Librarian	Project is a train-the-trainer workshop for librarians who develop public-facing programs. Over the course of a 2.5-hour workshop, participants develop a structure for a library program starting with a packet of feedback gathered from prior programming.

Table 7 provides an overview of the frequency of each code identified in each participant's lesson plan. The frequency of each code found in lessons demonstrates the degree to which lessons focused on a particular element of the design thinking process or, in some cases, did not address a portion of the process at all. The overall prevalence of each code among all plans is provided to show the likelihood that participants utilized an element of design thinking in their lessons.

Table 7. Frequency of design process codes in lesson plans

ID	Empathize	Define	Ideate	Prototype	Test	Overall Process	Iteration
1	4	2	2	1	2	0	2
2	2	1	1	2	1	1	2
3	2	0	2	0	0	0	0
4	1	0	1	0	1	0	1
5	1	1	0	0	0	1	0
6	1	2	3	1	1	1	1
7	3	3	0	2	1	0	0
8	2	1	0	0	0	1	0
9	0	0	2	2	2	0	2
10	3	0	1	0	2	0	0
11	2	3	2	2	1	0	1
12	4	1	2	2	1	0	1
Overall Prevalence	**11(91.7%)**	**8 (66.7%)**	**9 (75%)**	**7 (58.3%)**	**9 (75%)**	**4 (33.3%)**	**7 (58.3%)**

Discussion

Collected lesson plans and survey results indicate a small increase in educator confidence and integration of the principles of design thinking within their instruction. Of the 17 participants, 16 (94%) included sections on empathizing with users in their lesson plans. Teachers also taught specific techniques to develop empathy with a user, such as interviewing (1, 2, 3, 12), bodystorming (1, 8), and developing a list of user needs (12, 11, 7). Teachers worked around the lack of immediate users by inventing their own, such as 6, who used an established fairy tale with simplistic characters as a way for elementary schoolers to practice empathy.

Likewise, nearly all educators integrated prototyping and testing into their teaching of design thinking. Following the emphasis on rough prototyping in design thinking, educators frequently used prototyping and testing data to gather more user data. For instance, 2 asked students to send rough drafts and drawings to their clients as soon as possible. Seven instructed his engineering students that their solution "could be a proof of concept, a model, a working device, or any combination of these" as long as it served the function of communicating their idea to their assigned user. Nearly all educators (83%) included a testing plan that involved gathering data from other stakeholders interacting with student work. Some (4, 6, 10, 12) had students test each other's prototypes, while others brought in users outside the classroom (1, 2, 10). Educators also used the prototyping and testing stages as an opportunity to include iteration and redevelopment of successful prototypes, though these gestures towards iteration were tempered by concerns over time constraints.

Teachers were less likely to include a focus on ideation in their lesson plans compared with empathy, frequently preferring to place constraints on the types of products that students could create. Several projects (e.g., an ankle brace for a child with cerebral palsy (8), a water filter for remote use (7)) were constructed to allow students to proceed directly from the empathy stage to the prototyping stage by simply telling students what they had to make. Teachers placed constraints on ideation even with projects that could be open-ended - for example, 4 had students create a board game to teach 4th-grade fractions but strictly required what game elements (e.g., dice, cards, spinners) had to be included. Educators who successfully integrated ideation acknowledged constraints given to students but emphasized what parameters students should have complete control over. For instance, 2 had students create custom classroom signs for other teachers in their school. 2's students were required to conform to a certain size and material restriction but were otherwise free to use whatever artistic techniques were available to them as long as their final product was satisfactory to their client.

Future research should investigate explanations for patterns in the lesson plan data. Specifically, why were some aspects of design thinking included more frequently than others? Furthermore, what benefits of using design thinking as a pedagogy do teachers identify? Educators could also integrate testing, prototyping, and iteration into their plans effectively. However, gaps in integration remained, especially with regard to ideation.

Conclusion

The Makers by Design fellowship showed promise as a PL method to help educators integrate engineering design through design thinking into their instructional practice. In particular, participants successfully included empathy in their submitted lesson plans. This outcome is promising in an age where teachers are increasingly encouraged to foster 21st-century skills, including collaboration and communication. Participants' almost unanimous integration of empathy highlights that focusing on user needs may be an element that resonates with teachers from various disciplines and a facile strategy to promote empathic habits of mind and authentic engineering in classrooms.

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