Activating Digital Makerspaces for Authentic Student Learning

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Submitted to the Graduate Faculty of the

School of Education in partial fulfillment

of the requirements for the degree of

Doctor of Education

University of Pittsburgh

2022

UNIVERSITY OF PITTSBURGH

SCHOOL OF EDUCATION

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It was defended on

November 14, 2022

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University of Pittsburgh, 2022

In response to the maker movement, administrators are adding 3D printers, laser cutters, vinyl cutters, and other computer-controlled machinery into school-based makerspaces at a rapid rate. These digital fabrication tools can potentially engage students in hands-on learning across all subject areas. However, adding these extra tools into schools doesn't always lead to the adoption of these digital fabrication tools into the school curriculum. New technologies are often used as novelty experiences or elective-based, stand-alone maker classes. Still, the tools themselves can catalyze innovative learning if integrated into subjects outside of the isolated "technology" or "STEAM" courses. In this improvement science study, four teachers participated in an intervention centering the TPACK framework of teacher knowledge, which included virtual working sessions to develop lesson plans integrating these tools into classroom learning. Participants reported increased confidence with the tools. However, there were mixed levels of confidence in using these tools *with students.* Attention to embedded practice, professional learning communities, and technology integration and pedagogy knowledge show promise for supporting teachers new to this technology toolset.

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1.0 Naming and Framing the Problem of Practice

The maker movement has gained national attention over the past decade and has taken the nation by storm with Maker Faires, DIY channels on YouTube, broadcast television shows about making, and millions of youth identifying themselves as makers through participation in these events as well as social media. While this movement grows, costs for rapid prototyping technologies are steadily declining, making 3D printers and other computer-controlled machinery affordable for more people and organizations. Capitalizing on the powerful momentum of the maker movement and the increased affordability of digital fabrication tools, K12 schools are adding makerspaces with 3D printers, laser cutters, and other computer-numeric-controlled machinery to classrooms, libraries, or other common areas in the building (Bull et al., 2014; Chan & Blikstein, 2018; Martin, 2015; Song, 2018). These tools have the potential to transform classroom learning, with the capacity to provide opportunities for constructionist learning through student-centered iterative and collaborative projects (Blikstein, Kabayadondo, Martin, & Fields, 2017). As makerspaces gear up with computer-controlled machines, the potential for student learning through hands-on and digital making expands.

1.1 Broader Problem Area

Digital fabrication tools can provide opportunities for students to engage in the iterative design process (through prototyping) to create physical artifacts that reflect content learning and personal connections. The method of artifact-making can support content learning outcomes in any subject matter and provide an opportunity to develop STEM student competencies like creativity, problem-solving, collaboration, and artistic expression (PA Department of Education, 2020). In addition, the computer-aided design process, with its emphasis on modeling and visualization, provides an opportunity for more profound student learning in other content areas (Eisenberg & Buechley, 2008; Bull et al., 2014; Bevan, 2017). Through modeling and prototype design, students can explore the content while engaging their STEM competencies deeply. However, this authentic integration of these technologies is not common; instead, these tools are often used as a novelty activity or a one-time experience with technology (Brown, 2015; Cairns, Curtis, Sierros, & Bolyard, 2018). For instance, 3D printing activities in the classroom often consist of students downloading a predesigned shape (cartoon characters are popular) and then watching as the printer slowly extrudes the shape onto the printing platform layer by layer. While this activity excites new learners about the technology, it does not integrate content or activate deeper learning and personal connection with the subject area.

Educators also tend to exaggerate the focus on students learning *about* the technology rather than learning *with* or *through* the technology (Brennan, 2015, p. 289). Schools will often use their digital makerspace rooms for specific elective courses like maker classes or STEAM classes, excluding some students from using these tools. The curriculum in these classes also tends to focus on *using* the technology with little connection to learning outcomes from other content areas.

Though rapidly appearing in classrooms across the United States, digital fabrication tools and technologies are often not used to enhance student learning authentically.

More profound classroom use of digital fabrication technologies depends on teacher preparation to integrate these tools. However, schools are adding digital makerspaces at a fast pace, often without proper training for the educators working in these makerspaces (Lassiter et al., 2013). Teacher training and preparation programs lag behind the sudden adoption of new digital makerspace technologies; therefore, teachers are not prepared to use these tools effectively. Physically adding digital makerspaces into school isn't enough to empower teachers to use these new technologies to enhance authentic student learning; more needs to be done (Oliver, 2016).

1.2 Organizational System

In December 2021, I founded an organization at the intersection of digital fabrication technology and formal education. This organization, eduFAB, aims to support the growth of digital making in K12 education and developed out of my previous work within the Fab Lab Network when I served as K12 Education Director for Fab Foundation. A Fab Lab is a specific type of makerspace, including rapid prototyping technologies and open-source design software. The Fab Foundation is a small organization that facilitates the international spread of this type of makerspace.

As a subset of makerspaces in general, Fab Labs identify in the network as spaces with a shared set of tools and technologies (digital fabrication tools), open source software, and processes and provide these as resources to their local communities (Stacey, 2014). All Fab Labs are makerspaces, but not all makerspaces are Fab Labs. Figure 1 is a Venn diagram that shows the relationship between makerspaces, digital makerspaces, and Fab Labs. In this study, I will use the term "digital makerspace" to mean any makerspace with 3D printers, laser cutters, vinyl cutters, and other computer-numeric-controlled machinery (CNC), whether they identify in the International Fab Lab Network or not.

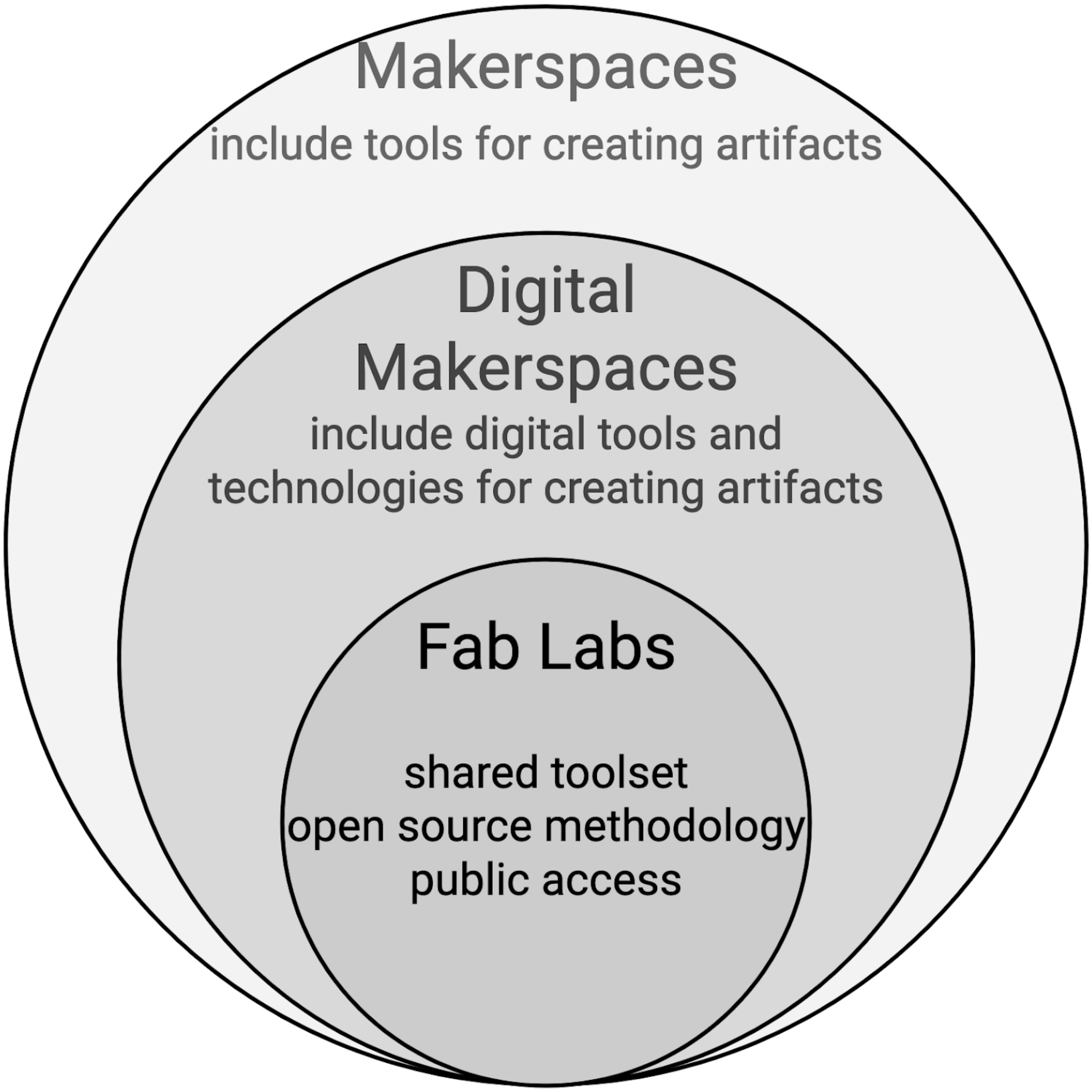

Figure 1. Makerspace Venn Diagram

Neil Gershenfeld started the first Fab Lab out of the Center for Bits and Atoms at the Massachusetts Institute of Technology (MIT) in 2001, where it was "his intention to muddy the waters between software … and hardware." He wanted to learn and experiment with the processes of turning "bits to its" (Stacey, 2014, p.224). His lab became a place where MIT students could learn to build (almost) anything. Since then, the Fab Lab name and principles have been adopted by other digital fabrication makerspaces, and today there are more than 1800 such labs worldwide

(Fab Lab Network, 2020). The network is open to any makerspace that agrees to adhere to the Fab Charter, which states the network's values, and has access to a shared set of digital fabrication tools. Open access for the community and the democratization of this toolset are essential values in the Fab Lab Network (Fab Foundation, 2020).

The Fab Foundation is a small nonprofit organization that has grown to support this growing network of Fab Labs, and it convenes the annual International Fab Lab Forum and Symposium on Digital Fabrication in addition to running multiple projects, training lab managers, working with institutions to install new digital makerspaces, and government lobbying for making and tool access. The mission of the Fab Foundation is to "provide access to the tools, the knowledge and the financial means to educate, innovate and invent using technology and digital fabrication to allow anyone to make (almost) anything" (Fab Foundation, 2020). This mission statement pre-dates the recent surge of Fab Labs into K12 formal education, and the Fab Foundation falls behind in its support of school-based Fab Labs. When Fab Foundation pivoted in late 2021 to focus on the international community and university-based Fab Labs, I transitioned out of the organization and started eduFAB.

"Digital makerspaces have the potential to support culturally reflective, student-centered teaching and learning in K12 education; eduFAB develops and supports digital makerspace ecosystems to support authentic student learning both in and out of school" (eduFAB, 2022). This is the mission of the eduFAB organization, and many of eduFAB's projects center this mission in the international Fab Lab Network. In addition, eduFAB convenes the Fab Educators Summit twice a year and offers consultation and training support for schools building digital makerspaces. The distinction between eduFAB's and the Fab Foundation's work is the focus on digital makerspaces in K12 education. These makerspaces need special consideration and are much different from community or university-based makerspaces. K12 educational makerspaces face unique challenges, especially those located in schools, and eduFAB works within a formal education framework to build success for students in these digital makerspaces. One of these unique challenges is teacher training.

Fab Foundation trains people in digital fabrication through the Fab Academy program. The Fab Academy is a twenty-week intensive program designed to immerse participants in digital fabrication processes through project work. The course is taught through a distributed network of Fab Labs worldwide asynchronously, with the centralized recitations and lectures headquartered in the Center for Bits and Atoms at MIT. Neil Gershenfeld is the professor of this challenging techno-centric curriculum, and the hands-on portions are led by teaching assistants in labs local to the program participants. Currently, the program is located in over 70 labs worldwide, with over 250 enrolled students per year. According to the website, "students are not isolated, but rather gathered in local workgroups with peers, mentors, and machines. Everyone is then connected globally… Knowledge in this course does not run linear; it is the result of multiple global and local interactions" (Fab Academy, 2020). The curriculum for this course is very challenging, and only about 50% of students successfully graduate from the course per year. Those participants who finish the training emerge with a robust project portfolio, a well-documented record of their technological knowledge, and a well-deserved badge of honor.

As the educational network of Fab Labs grows and educators recognize a need for teacher training in these technologies, the Fab Academy curriculum falls short, and Fab Foundation struggles to make K12 educational connections through this program. I graduated from Fab Academy in 2016, and I found the curriculum techno-centric, personally challenging, and ultimately rewarding; however, the course content was not designed for K12 educators. The aim of Fab Academy, being so technology process driven, is for “students to envision, prototype, and document [their] ideas through many hours of hands-on experience with digital fabrication tools” (Fab Academy, 2020). This course is a cornerstone of the Fab Lab network and quite central to the mission of the Fab Foundation, but now that these tools are emerging in K12 classrooms, more needs to be done. A different type of learning experience is necessary for educators to understand these tools and their potential to integrate into formal education, supporting student learning goals in any content area.

1.3 Problem Area in Context

As I began my work with the Fab Foundation in early 2020, I conducted sixteen empathy interviews with network members, predominantly educators, both formal and informal. Transcriptions from portions of four of these interviews are included in Appendix A. Overwhelmingly, a pattern began to emerge from these stakeholders about classroom learning and digital fabrication; specifically, teachers were not finding success in using these tools to support authentic student learning.

Before working for the Fab Foundation, I opened a Pittsburgh-based educational Fab Lab in 2015. This lab was located at a museum, and our programs included direct student workshops and teacher professional development workshops. My team and I designed and delivered workshops for educators to learn digital fabrication technologies, and teachers from various schools attended our training. Registration for these training sessions filled up quickly, even with a fee paid out of pocket by the teacher. One reason these technology workshops were so popular in the region was that teachers did not feel they were getting the training to run digital fabrication technologies at their schools. Often a principal would assign a teacher to be the makerspace supervisor without training. Other teachers would come to the workshops because their school had a 3D printer and wanted to use it with their classes. Over and over again, I saw firsthand the effects of schools quickly adding digital makerspaces but not providing support for teachers to succeed with these tools in their classrooms.

This narrative paralleled my initial findings from stakeholder empathy interviews at the Fab Foundation, and I continue to see the pattern as my work narrows focus through eduFAB. Through convening the Fab Educators Summit, consulting with schools, and training educators in this toolset, I recognize this problem extends internationally as schools across the globe struggle to integrate digital makerspaces for authentic student learning successfully.

1.4 Stakeholders

Working with an extensive network of members worldwide through eduFAB projects, I see this problem across many schools and educational organizations. I am uniquely positioned to identify stakeholders from various positions, schools, locations, and even countries. While this is a widespread problem in my network, each school or district represents a microcosm of this system, and the stakeholders can be generalized.

1.4.1 Students

First and foremost, students are an important stakeholder group in this problem of practice. High school students especially show a significant interest in new technologies such as 3D printing and laser cutting. Yet, their experiences with these technologies are typically brief and overly simplified. In an empathy interview with a high school student, she reported being interested in the laser etching process when her teacher introduced the tool in a technology class. However, she wasn't even able to press the button or put her project on the laser bed herself due to the time restraints of the course. She didn't have any experience in digital design for the tool, though she was also interested in learning about that. This entry-level experience with digital fabrication tools and technologies is apparent in many classrooms, though students are generally interested in learning more and using the technology themselves.

1.4.2 Teachers

From empathy interviews with teachers, I recognized that they could not be easily grouped as a whole. The crucial differentiating factor that caused me to make two different subgroups of teachers is classroom learning objectives. Some teachers focus on technology or engineering classes, emphasizing the tools and processes, and other teachers are siloed into their content areas, with learning objectives dictated by the subject curriculum. Therefore, I divided teachers into two different stakeholder groups.

1.4.2.1 Technology Teachers

These teachers often engage their students with technology, teaching the processes of using technology, and often the learning objectives are about the technology itself. Since most of these teachers are in elective courses or classes without state standard testing, technology teachers develop their curriculum for these classes. "Tech Ed" is one of these classes, and I interviewed one such "tech ed" teacher. The students in his class learn to use hand and power tools, and their learning goals are technocentric in the proper use and safety of these tools. Digital fabrication tools are a novelty experience in the curriculum since Technology Teachers do not feel they have the class time to dedicate to these complicated technologies. Often these teachers are not only responsible for teaching these classes, but they are expected to assist other teachers in the school who are interested in using the technology for their specific classes. Technology Teachers are typically the only ones who have received training on the equipment.

1.4.2.2 Subject Area Teachers

The rest of the teachers fall under this subgroup, as standards, assessments, and curriculum typically drive their class learning objectives. English, history, biology, and other content area teachers are included here. Subject Area Teachers have learning objectives that focus on a particular subject (whether tested at the state level or not). At the same time, Technology Teachers are expected to teach about the tools and technologies themselves. Subject Area Teachers often have no training on the tools and technologies and are unaware of the opportunities for integrating these tools into their subject classes. Typically, if a Subject Area Teacher is individually interested in learning about digital fabrication technologies, s/he must first partner with the Technology Teacher to learn about the tools. This is a tough hurdle for these stakeholders to jump without specific training or enough out-of-classroom planning time.

1.4.3 Administrators

Administrators as a stakeholder group typically include the Principal, the Assistant Principal, and any district role with decision-making authority over spending. These stakeholders are responsible for purchasing this equipment and sometimes finding outside funding to support digital fabrication tools. A common problem with this stakeholder group is that they focus primarily on equipment procurement (because the cost of this type of technology is so high) to the detriment of other support. Rarely does the Administration consider teacher training, support of the space and tools, planning time, or authentic integration into other subject area classes. This stakeholder group also has a lot of different duties to attend to, so their attention is drawn away from the problem of practice. Because this stakeholder group is very influential in bringing these types of spaces into the school buildings, it is essential to consider the administrators' perspectives.

1.4.4 Equipment Manufacturers and Dealers

As price points for this type of technology drop, the education market opens, and Manufacturers and Dealers begin to offer these tools to schools. Though Manufacturers and Dealers are two different positions in the pipeline, they can be combined to represent one stakeholder in this analysis because their relationship with the other stakeholders (namely the Administrators) is the same. Equipment Manufacturers and Dealers sell and sometimes offer more support for these technologies in school buildings. Often the Dealer will come to the school to help set up the equipment and provide safety training to the Technology Teachers. Manufacturers sometimes offer lesson plans or other classroom materials for Subject Area Teachers to use in their classrooms. This stakeholder group reflects a primary concern with financial gains, so their classroom support is a marketing tool more than an authentic tool for technology integration. Their influence on the problem of practice is significant, though, as the Dealer training is often the only technology training teachers receive.

1.5 Stakeholder Analysis and Focus

The above stakeholders in the problem of practice, based on a microcosm of the universal reach of the problem, can be analyzed according to the Power Versus Interest Grid, which is found in Appendix B. This grid is a visual representation of the named stakeholders along the spectrum of subjects through context setters, as described by Bryson (2011). “Subjects are those [stakeholders] that have great interest but little power… Context Setters are those [stakeholders] that have power but little direct interest” (p. 5). In this exercise, power refers to a stakeholder’s ability to make a change in the system.

To begin this analysis, I first arranged the stakeholder groups along the X-axis based on their relative power levels. This order emerged from least powerful to most powerful: Students, Subject Area Teachers, Technology Teachers, Manufacturers/Dealers, and the most powerful School Administration. Once their relative power relationships were established, I moved each stakeholder up along the Y axis to represent the amount of interest each has in this problem of practice. This exercise firmly established the Students as subjects along the continuum and the Administration as Context Setters.

Reflecting on the results of this Interest vs. Power grid, it is evident that the role of the Administrator is very powerful yet has little interest in the problem itself. Administrators aren’t working directly in the classroom with students, so they don’t see the same challenges and successes that teachers see daily. They are, however, in control of the school’s resources, specifically the budget and the schedule, so their ability to make changes in the system is relatively large.

Given the constraints of the sphere of influence defined by my position at eduFAB and within the more extensive Fab Lab network, I chose to focus the research on teachers.

1.6 Problem Statement

From my experience in practice, conducting multiple empathy interviews with teachers and the two semi-structured interviews with administrators, I created a fishbone diagram highlighting the challenges that contribute to this problem area. (This diagram can be found in Appendix C). The following categories contribute to the problem and are visualized as the “bones” in the fishbone diagram: time and space, technology knowledge, pedagogy and integration knowledge, support network, and standardized testing. The problem of practice statement follows.

Teachers are not sufficiently supported to integrate digital fabrication technologies in their classrooms for student learning.

2.0 Review of Supporting Knowledge

2.1 Roadmap for Research

To approach the literature about the problem of practice, I identified two areas of research to consider: how these technologies are currently being used in the formal classroom and how teachers best learn new technologies like digital fabrication equipment.

1. What are key concepts and supporting empirical research on digital fabrication use and integration in K12 formal education?
2. What are key concepts and empirical research on training and supporting classroom teachers to use digital fabrication in K12 formal education?

The first question investigates if and how authentic student learning is happening in the classroom, and here I will clarify the term “authentic.” For this study, authentic student learning will mean subject area content knowledge in any content area. This can include STEM subject areas, the arts, history, or any content other than technology.

Digital fabrication tools and technologies are relatively recent to the school setting. Though there is sufficient excitement about having devices like 3D printers in the classroom, there is little empirical research on the effectiveness of these tools in enhancing student learning. Most researchers agree that educational making has its roots in constructionism, and through this rich body of literature, I focused on the intersectionality of student-centered constructionist learning with design. From there, I studied the recent research into how digital fabrication tools can support this type of learning, and I identified learning themes supported by digital fabrication technologies.

The second question investigates how teachers learn new technologies and how they integrate these technologies into their subject area classes. Both questions approach the overall understanding of the educational integration of these technologies.

I reviewed theories and research into how teachers learn to implement new technology for the second research question. Though there is very little research studying how teachers learn to implement and integrate digital fabrication technologies, there are some articles and theorists that explore teachers' use of computers as technology. I included a theoretical framework describing this process. Drawing on a few studies and a body of research around the theory of teachers' integration of technology into teaching, I included peer-reviewed journal articles and studies, books, and book chapters.

I distinctly define my research about digital fabrication tools and technologies here from the larger body of literature around "making," "makerspaces," and "maker education." However, these latter concepts are more prevalent in the research. I distinctly use the term "digital makerspace" to define a makerspace with digital fabrication tools and technologies, as shown in Figure 1.

2.2 An Overview of Digital Fabrication in Education

K12 school administrators and educators are showing excitement around school-based making, and they are adding makerspaces at a rapid rate. Though there is no shared definition of "making" in the literature, the term itself is broadly determined by researchers to be the act of creating a physical artifact or physically manipulating materials or other objects in the act of discovery or creation (Vossoughi, Escudé, & Kong, 2013). A short and catchy definition of making, a favorite of mine, was introduced in the book, *Every Tool's a Hammer* (2019) by Adam Savage, co-creator of the popular TV series Mythbusters. He defined the term by quoting the former White House Senior Advisor for Making, Andrew Coy, "Making is simply a new name for one of the oldest human endeavors: creation." (p. 1).

Much has been written about making, makerspaces, and the maker mindset in teaching and learning, but makerspaces don't all have digital fabrication technologies. 3D printers, laser cutters and engravers, vinyl cutters, microcontrollers, and computer-numeric-controlled (CNC) routers and mills are all included in the term "digital fabrication tools," and this is the set of technologies on which I have focused my research (Martin, 2015; Stacey, 2014). Digital fabrication tools can be included in a makerspace though not all makerspaces include digital fabrication tools.

Researchers cannot agree on a shared definition of making, but the digital tools are more easily defined. Martin (2015) described digital fabrication technologies as belonging to two groups: digital, physical tools (like 3D printers and laser cutters) as well as digital logic tools (like microcontrollers and programmable electronics), but most other researchers refer to these tools more broadly, grouping them as makerspace tools and technologies that have a dependence on computers (Chan & Blikstein, 2018; Martinez & Stager, 2013a; Eisenberg & Buechley, 2008). While traditional makerspace tools and materials can be used solely by hand, the computer controls digital fabrication technologies. So, students must first learn to design on the computer before beginning the physical fabrication portion, where the computer directly controls the machine.

In 2014 researchers Bull, Chiu, Berry, Lipson, and Xie (2014) reported that since digital fabrication technologies have just recently been included in K12 education, there is very little research into how these tools might be best used for student instruction (p. 676). Six years later, this research gap still exists. Though theorists continue to write about these tools and their use in the classroom, a small portion of empirical research has been added to the field of digital fabrication and school-based makerspaces.

Much of the research on the maker movement in education focuses on non-digital making, like tinkering with processes or exploring tools and materials in new ways with more traditional tools like scissors and hammers. Many researchers focus on the type of learning in a makerspace regardless of digital fabrication capabilities. Martinez and Stager (2013b) are two prolific researchers in the making for education who writes about the student-centered learning, creativity, collaboration, and playfulness that happen in a makerspace. In their seminal book, Invent to Learn: Making, Tinkering, and Engineering in the Classroom, the authors emphasize the overlap between children's natural curiosity and the learner-centered focus of makerspaces. They suggest that making, both with and without digital fabrication tools, cultivates creativity and collaboration in students. Other researchers in this space focus on how student-centered learning manifests in makerspaces through tinkering and play (Petrich, Wilkinson, & Bevan, 2013; Quinn & Bell, 2013). The research behind educational concepts from non-digital forms of making eclipses that of digital fabrication research, but the commonality apparent through both types of making is student-centered learning.

2.2.1 Constructionist Roots of Digital Making

Many theorists trace this type of student-centered learning paramount in makerspaces to the work of Seymour Papert, often referred to as the father of the maker movement (Peterson & Scharber, 2018; Fab Foundation, 2019). Papert's development of the first computer programming language for education and his research in education led him to theorize that children, in building and sharing projects, construct their knowledge. According to Papert, children build knowledge on previously generated models of understanding (Papert, 1980, pp. vi-vii). This definition of constructionism emerges from the constructivist theoretical work by Jean Piaget (1970), Papert's mentor. Piaget's theory of constructivism was expanded to constructionism with Papert's idea that learners construct new knowledge more effectively when they create physical artifacts and mental models of their learning. Thus, many authors refer to Papert as the founder of the modern maker movement and trace its roots to constructionist learning theory.

The consensus among theorists and researchers is that making and the use of digital fabrication tools in making have their roots in constructionism and the creation of student-centered artifacts. Whether these learning artifacts are handmade with cardboard and masking tape, or computer designed and produced with a laser cutter, these projects, designed and created by students, embody the principles of constructionism as put forth by Papert.

2.3 Digital Fabrication Technologies in Schools

In researching the overlap of student-centered learning with digital fabrication tools, distinct themes emerge to answer the first research question, "What are key concepts and supporting empirical research on digital fabrication use and integration in K12 formal education?"

These emerging themes are described as three different objectives in using this technology with students to increase student understanding of technology, to enhance PBL with digitally created projects, and to engage STEM content through the digital design processes.

2.3.1 Increase Student Understanding of Technology

Some researchers argue that including digital fabrication tools in makerspaces will help students gain technological literacy and an understanding of transparency in tools and technologies. According to Martin (2015), students need to learn, among other things, that technology itself is not a black box and that computers and digital tools can be understood and controlled. This type of technological literacy helps improve student identity and confidence with technology, moving students into forming maker identities versus consumer identities (p. 3).

Student understanding of how technology works are referred to as “transparency” by Kafai and Peppler (2018, p. 179). These researchers expand the concept of technological literacy to “technological transparency” by using physical computing projects. In this type of project, where students use digital fabrication technologies to produce artifacts with computing capabilities, students are exposed to the inside of the black box. By programming their digitally created artifacts using microprocessors, students gain a more complex understanding of how technology, combined with computer programming, function (p. 180).

Kafai and Peppler studied ten middle school students who participated in an after-school workshop series for programming and making e-textiles. E-textiles, or electronic textiles, combine sewing with circuitry and programming, often culminating in a wearable piece that infuses technology like sensors and lights into Kafai and Peppler observed an increased understanding of the complex technologies and programming language in this study, which they dubbed “transparency.” In addition, they underlined the importance of student-centered artifact creation, as students personally identified with their projects as they improved their technological literacy in programming.

While Kafai and Peppler used the term "transparency" to describe learning how the technology functions, Blikstein, Kabayadondo, Martin, & Fields (2017) expanded the definition of technological literacy much further. This team of researchers developed a new assessment instrument for technological literacy specifically for digital fabrication tools called the "Exploration and Fabrication Technologies (EFT) Instrument." In distinguishing EFT learning outcomes, this research team separated computer literacy from digital fabrication literacy, focusing on the specific skills and literacies associated with digital fabrication technologies (p. 149). This assessment tool divided the learning into parallel tracts, measuring student confidence and their performance in using the technology.

Blikstein et al. developed this assessment over two years and administered the instrument to children in five schools between 2013 and 2014. All schools selected for the study included a makerspace with digital fabrication technologies, and three schools were located in the United States, one in Mexico, and one in Australia. The instrument was used in a pre and post-survey for middle school students who participated in a unit using digital fabrication technologies. Though the existing student programs were different in each school, all schools showed students' increased confidence in EFT outcomes, and figure 2 shows data from one school in the study.

	Seventh grade				Eighth grade			
Subscale	Pre-	Post-	Effect	*p*-value	Pre-	Post-	Effect	*p*-value
General computing	4.56	4.87	0.49	1.0000	4.16	4.91	1.0	0.0022
ICT production	3.58	3.78	0.07	1.0000	3.27	3.95	0.64	0.0012
EFT production	2.19	3.24	1.12	0.0002	2.01	3.09	1.0	<0.0001

Note: Results are for grades at the beginning (pre-) and end (post-) of the fabrication curriculum, with estimated median effect size and *p*-values from the paired signed ranks test.

Figure 2. Confidence in Technology (Blikstein et al., 2017, p.159)

While Blikstein et al. (2017) argued in this study that the benefit of digital fabrication technologies in student learning could be to increase confidence and performance abilities with the tools themselves, they also recognize the limitations of technological literacy as the only learning outcome and the researchers admit that this approach tends towards technocentrism, (p. 155). In his work on developing the first educational programming language, Papert cautioned about centralizing the learning around technology and defined technocentrism as giving centrality and importance to the technical object rather than the understanding that should occur through that object (Papert, 1987, p. 23).

2.3.2 Enhance Problem-Based Learning

Building on the early work of Papert in constructionist theory, many researchers have described problem-based-learning (PBL) as well-suited for educational makerspaces, especially when combined with the creation of personal artifacts to reflect learning (Bull et al., 2010; Cairns et al., 2018; Chan & Blikstein, 2018; Brennan, 2015; Doppelt, 2003; Smith, 2018). PBL is an educational trend that shifts the focus of classroom activities to student-driven learning instead of teacher-led lessons (Kolmos, 1996). Through PBL, students use contents from a case scenario to define their learning objectives and engage in self-directed learning. Then they often combine with a group to propose a solution to the scenario (Awang & Ramly, 2008, p. 635). The content in a PBL unit is also blended across subject areas, and makerspaces are naturally interdisciplinary, so combining these tools with these types of projects is promising (Vuorikari, Ferrari, & Punie, 2019, p. 13).

Kolmos (1996) theorized that this type of student-led learning could be supported with project work in “problem-oriented, project-based learning.” Soon a new term emerged in 1997 at the Eindhoven University of Technology, “design-based-learning” (DBL), which centralized the design and creation of a learning artifact in a PBL environment (Puente, van Eijck & Jochems, 2011, p. 138). Doppelt, a prolific researcher in both PBL and DBL, and his team described this combined approach as follows:

DBL enables students to experience the construction of cognitive concepts resulting from designing and making individual, inventive, and creative projects to initiate the learning process according to their preferences, learning styles, and various skills. In this way, students combine “hands-on” activities with what Papert (1980) has termed “heads-in” activities. (Doppelt, Mehalik, Schunn, Silk, & Krysinski, 2008, p. 23).

Over three years, Doppelt worked with teachers in Israel to produce DBL lessons with their lowest-performing high school students. The students created authentic projects in an electrical unit using computers and hand tools instead of following a reading-based curriculum. All 54 students in the study passed their matriculation exam, and the researchers concluded that the DBL unit emerged as the “crown jewel” of the student experience in the electricity track (Doppelt, 2003, p. 269).

Another DBL study was conducted by Doppelt et al. (2008) in the United States, focusing on eighth-grade students in two groups: one perceived as high achievers and the other perceived as low achievers. After the DBL unit in science, students completed a written content test and were evaluated on their oral presentation and portfolio. In response, the classroom teacher stated that the perceived low-achiever class learned more and appeared more engaged than their counterpart class. Specifically, the teacher was impressed with the student's level of engagement with the material, collaboration with one another, and the thoroughness of their documentation (Doppelt et al., 2008, p. 33). This study showed that all learners, despite their perceived aptitude, can engage in DBL, create a project, and in doing so, develop content knowledge.

Though these studies did not specifically focus on digital fabrication tools or computer-aided design processes, the researchers highlighted the importance of students' creation of learning artifacts combined with PBL. The addition of digital fabrication tools can potentially enhance the process of fabricating student designed artifacts.

In another DBL study, this one using computer-assisted design (CAD), Smith (2018) showed increased learning outcomes in younger children (aged six to twelve), particularly in visualization skills. The researcher observed a summer program in which the students experienced design with both digital and non-digital tools. She analyzed field notes and think-aloud protocols with the students. This camp combined CAD with analog design processes like sketching and modeling with clay, and the instruction centered on DBL. Though the improvement in visualization skills reported among the students can't be causally linked to the CAD assignment in the camp, the DBL process proved effective in increasing student learning.

All three of these research studies showed the promise of using personally created artifacts and projects to deepen student understanding of content through a PBL unit. However, the specific intersection of PBL with the physical digital fabrication tools is still under-investigated by researchers in the field.

Paulo Blikstein, a well-known researcher leading the FabLearn program at Columbia University and co-developer of the EFT assessment index for technological literacy, studied this intersection of PBL with digital fabrication tools in a 2018 study with Monica Chan. The pair looked middle school engineering classes that used PBL in their school-based Fab Labs. Unlike the Doppelt and Smith research studies, Chan and Blikstein (2018) did not measure student learning outcomes about the subject areas of the unit. Instead, their goal was to provide insight into what PBL with digital fabrication tools looked like about student collaboration and student-teacher interactions. The study's results indicated that the experience encouraged student-driven learning and changed the traditional student-teacher relationship. The research team categorized the most prevalent types of student collaboration presented in the PBL project in the fab labs: “defining specifications with teammates, personal exploration, and communication about discoveries” (p. 5). These specified collaboration indicators in the fab lab PBL lesson were detailed throughout the study, and researchers argued that these concepts were important in the learning process. Though PBL, in combination with digital fabrication tools, did demonstrate increased collaboration and student-centered learning in the fab labs, the researchers admitted that the cause of the teaching could not be specifically attributed to the tools themselves (p. 9). More research is needed on the overlap between PBL and digital fabrication tools.

2.3.3 Engage STEM Content Through Design

The second theme that emerged when investigating how digital fabrication tools are used in the classroom centered around design. Independent of PBL, there are research articles integrating digital fabrication with design work, or what Kolmos (1996) called “project work,” in which students are presented with a specific design prompt instead of a real-world, open-ended problem in a case scenario. Designing a solution to one particular challenge and using CAD as a step in the process can lead to increased learning of STEM content.

Nemorin (2017) described an eight-week project for 9th-grade students in Australia who learned to use the 3D printer to complete a challenge to design and print the fastest miniature race car. In this auto-ethnographic study, the researcher worked with the students in the classroom designing and 3D printing. Under these circumstances, the researcher noted that students individually mastered measurements and scaling objects for their designs (mathematics content) yet struggled with the technology. She identified inherent problems with the complexity of the technology and noted that many students didn't meet their deadlines for the challenge day. This type of structured project work, which is heavily teacher-driven, leading every student to create a similar artifact, didn't realize the potential of student-driven learning and design as identified by Doppelt et al. (2008) in DBL, but still has the potential to lead to more profound understanding of STEM content.

The design portion of the digital fabrication processes lends itself well to learning content in STEM areas. Bevan (2017) coined a term for this type of physical design and model making, "STEM-Rich Making." In this type of making, content learning is focused on the design phase, using the process of iteration to deeply engage with scientific and mathematical concepts (p. 75), and digital tools can enrich that process. Eisenberg & Buechley's (2008) work in educational fabrication also indicated that the machines, creating real-world objects from computer-based models, enriched the learning process even further as students could interact with physical models of their own design (p. 3). This computer-assisted design (CAD) process combined with the physical model that can be 3D printed or laser cut into material offer a unique opportunity for students to learn STEM content both in the virtual design process and in manipulating the physical artifact itself.

Other studies in educational design lessons using teacher-led prompts and CAD technology showed promising results even without enhancing digital fabrication technologies. Hmelo, Holton, & Kolodner (2000) showed that 6th-grade students who participated in an additional design unit using a student-created CAD lung model had higher learning outcomes and a deeper understanding of the lung function than those who did not participate in the design activity. Similarly, Burghardt et al. (2010) published positive results with 8th graders using CAD to augment mathematics lessons. These researchers coined the term "informed design" to describe the process that encourages students to learn the mathematics content before approaching a design solution (Burghardt et al., 2010, p. 2). Both sets of researchers argued that designing with technology, in this case, the computer, gave students an interactive way to explore how systems worked and helped students acquire a better understanding of complex domains (Hmelo, Holton, & Kolodner, 2000, p. 257). Though neither of these studies included a digitally fabricated artifact, incorporating the CAD and design process in the lessons was necessary to increase student learning of STEM content.

Though project work that focuses on design is not an integrated PBL learning opportunity, it is an effective educational practice, especially in STEM content areas, and digital fabrication technologies can support this type of learning. Brennan theorized that challenging students to design activates STEM content and encourages them to persist in hard work (2015, p. 291). Similarly, other researchers identify positive competencies students can develop when engaging in design work, even without the benefit of an ill-structured real-world problem (Eisenberg & Buechley, 2008; Kafai & Resnick, 1996).

2.3.4 Summary of Student Learning in Review of Supporting Knowledge

Research has revealed that there are a variety of theories and practices for using digital fabrication in the classroom. However, there is no agreed-upon strategy for integrating these tools into formal education. The tools' ability to support student-centered constructionist learning is prevalent in all the research. Almost every research article supports Papert's theory that students build new knowledge based on previously self-constructed models of knowledge. Emergent themes identified by both theorists and researchers include using the tools for increased technological literacy, PBL enhancement, and STEM content knowledge. The question of using these tools for authentic classroom learning (not just STEM content) is unanswered in the literature.

However, investigating the potential partnership between in-school learning and an out-of-school, community-based fab lab shows some interesting promise in Finland. Researchers at the University of Oulu brought school groups to Fab Lab Oulu, where their teachers worked with fab lab facilitators to design and implement a PBL lesson using digital fabrication technologies. Pitkänen, Iwata, and Laro (2019) posited that "digital fabrication activities [could be used] as one pedagogical tool to achieve the goals and skills defined in curriculums" set forth by the teachers (p. 1). In one of the school cases, the fab lab facilitators co-designed PBL units with the teachers around the theme of 100 years in Finland's history and which engaged the students in learning to program and design using a microcontroller in the lab. Though this study focused on outcomes around lesson design and implementation rather than content learning objectives, the potential to replicate projects similar to this for classroom learning objectives is encouraging.

Though more research needs to be done on digital fabrication technologies supporting student learning in formal education, the question remains of how to prepare teachers to use and implement these technologies in their practice.

2.4 Teachers' Technological, Pedagogical, and Content Knowledge

Similar to the research gap in digital fabrication tools to support classroom learning, the empirical research in training and supporting teachers to use digital fabrication equipment in the classroom is relatively sparse. Though 3D printers are still new, technology in teaching is not new; from overhead projectors to interactive websites, there is plenty of research about teachers' use of technology. Since computers were introduced to the classroom in the early 90s, theories have emerged among researchers about how teachers can learn and integrate computerized technology into their teaching practice. The following literature review describes a theory of teacher knowledge, how that theory is supported or challenged in empirical research studies, and then identifies two themes prevalent in the research into teaching teachers to use technology.

2.4.1 Technical Knowledge Integrated with Content and Pedagogy

Shulman theorized in 1986 that teachers should have two types, or categories, of knowledge to be effective in the classroom: content and pedagogical knowledge. He argued that the intersection between these two categories of knowledge is as important as the categories themselves. This theory is known as Pedagogical Content Knowledge (PCK) and is a seminal teaching theory framework (Shulman, 1986). Simply put, the two categories of knowledge can be described as follows. "Content knowledge" refers to expert knowledge of the subject matter, or content, that the teacher will deliver, such as mathematics or language. "Pedagogical knowledge" is the teacher's knowledge of how to best meet learning goals, employ teaching strategies, and design lessons. For instance, a language arts teacher will use a different pedagogy than a science teacher, which is intertwined with the content (Khrine, Afari, & Ali, 2019, p. 23). The balance of these two categories and the intersection of these two categories must be mastered by teachers to be effective in the classroom.

With the advent of computers and applications for the classroom, theorists Mishra and Koehler supplemented Shulman's original PCK framework by adding a third category: technological knowledge. To use technology in support of student learning, teachers need to learn how to operate the technology itself and understand it as a category of knowledge, along with content and pedagogical knowledge. In short, "technology knowledge" is the understanding of the technology itself and its affordances (Khrine, Afari, & Ali, 2019, p. 23). Technological Pedagogical and Content Knowledge (TPACK) is a framework that represents both a combination and an intersection of these three types of knowledge that teachers use in practice when working with technology (Koehler & Mishra, 2007).

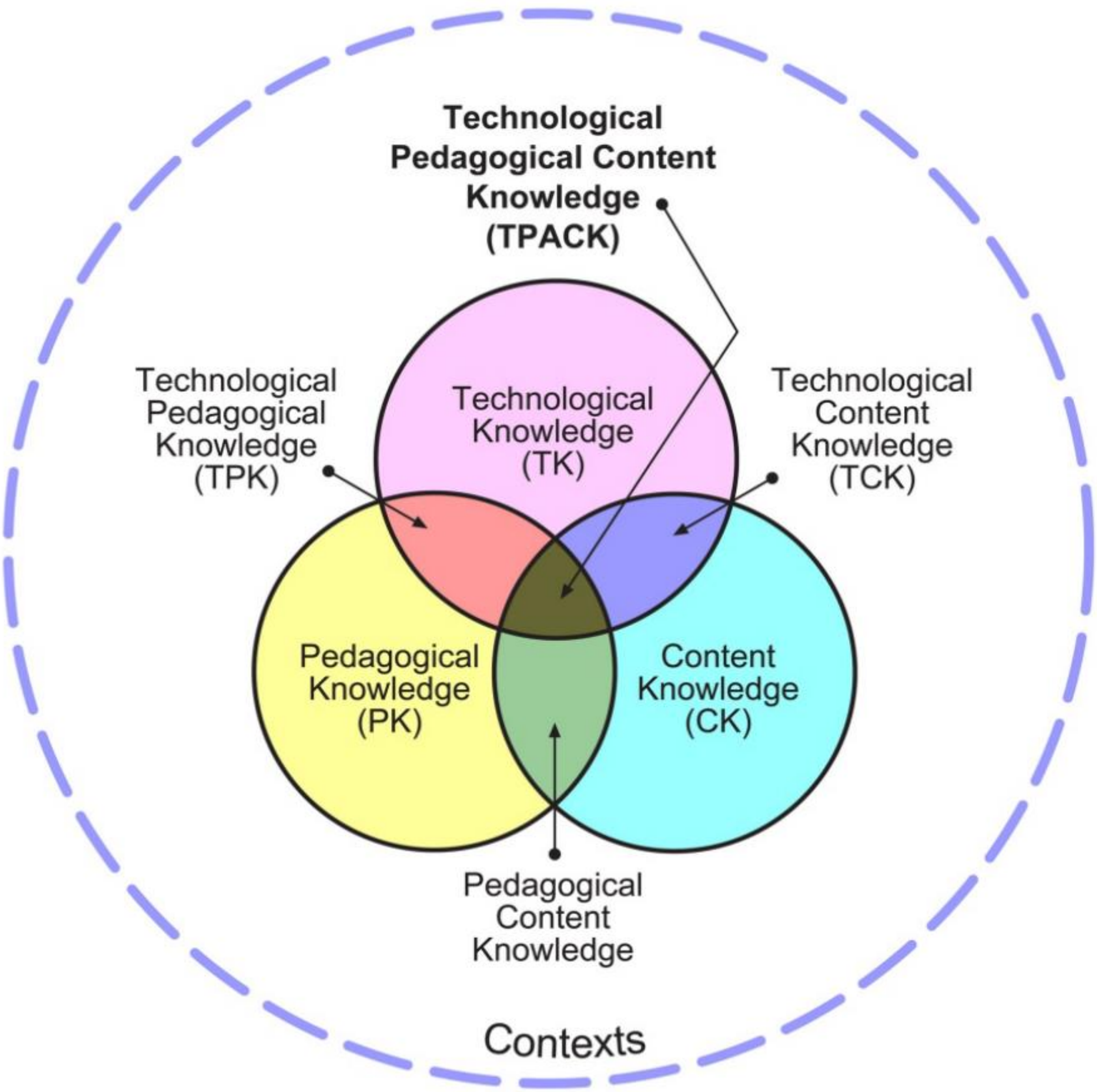

Figure 3. TPACK Venn Diagram (Koehler & Mishra, 2007)

Though this framework originated around the technology of computers and software, researchers Koehler and Mishra (2007) openly defined technology so that it can include the tools and processes of digital fabrication. In supporting teachers' use of technology, whether internet-based software or laser cutters, it is essential to attend to all three categories of knowledge represented in Figure 3. Teachers must continually establish and evaluate the equilibrium between all three, thus spending most of their time in the central intersection of TPACK (p. 67). This theoretical framework is referenced by researchers in the field who evaluate teacher professional development with computer technologies. Still, the framework itself is typically used as an evaluation tool of the teacher's knowledge, not an evaluation of the training itself (Khine, Afari, & Ali, 2019). TPACK is a theory of the interconnectedness and overlap of teachers' knowledge domains in working with technology to teach in the classroom.

Koehler and Mishra (2005) indicated in their research that teacher development programs, in general, do not provide sufficient strategies for teachers to use technology effectively in the classroom (p. 94), and other researchers agree (Song, 2008; Pamuk, 2012; Pitkänen et al., 2019), so a closer look at the research into training programs and best practices is necessary.

2.5 Supporting Teachers' Use and Integration of Technology

In researching the second question, "What are key concepts and empirical research on supporting teachers to use digital fabrication in K12 formal education?" I used the TPACK framework as an evaluative lens for the programs. In many teacher development programs, I recognized two strategies across the literature that help support teachers' use of new technology: connected communities of learning and embedded practice. First, though, I recognized that many trainings have overly relied on technological knowledge in development and implementation, ignoring the content and pedagogy domains altogether.

2.5.1 Attention to Technical Knowledge

Similar to the theme I identified in the research about digital fabrication tools and student learning, teacher training programs tend to focus on learning about the technology first and foremost. A research study done with classroom teachers in Korea used the TPACK framework to evaluate a six-week (60-hour) professional development certification program where pre-service teachers learned to use 3D printers. Song (2018) observed this professional development program and noted that by the end of the training program, most participants were able to design in 3D modeling software and print on the 3D printer. The training, however, failed to address the pedagogical implications of 3D printing in a classroom setting (p. 191). The researcher concluded that since all three aspects of the TPACK framework were not adequately addressed in the certification program, the teachers would have limited success in implementing this technology once in the classroom.

A Turkish study revealed similar findings, emphasizing the failure to address all three components in teacher preparation. This study analyzed data from informal observations, questionnaires, teaching materials, and informal interviews of 78 participants in a teacher training and certification program in Turkey. Unlike the Song study, this research project did not incorporate digital fabrication technologies but focused on computer-based technologies. Similar to the Song study, the participants in this research study identified the need to attend to all three aspects of the TPACK framework. These pre-service teachers had experience with technology and excelled in learning the new software for the classroom; however, the lack of pedagogical training resulted in limited use of the technology with students once back in the school (Pamuk, 2012, p. 433). Neither of these research studies indicated a successful three-prong approach to professional development as described in the TPACK framework, instead centering the technology itself.

In the study at the University of Oulu, researchers interviewed Fab Lab facilitators who had worked with classroom teachers in designing and implementing a unit in the lab. Unlike the above studies, there wasn't emphasis on technology training for the teachers visiting the lab, and the "facilitators described the biggest challenge in conducting the activities to be that teachers were not familiar with Fab Lab nor digital fabrication processes" (Pitkänen et al., 2019, p. 5).

Another researcher, however, argued in support of this technocentric approach to teacher training, at least for 3D printing. Brown (2015) posited that 3D printing is more than a single computer-controlled tool; it is a process that encompasses many technologies (p. 18). The method of printing with a 3D printer involves modeling an artifact on the computer, "slicing" the design for export, preparing and maintaining the printer itself, and finally, printing the model. She argued that these different steps in the process are challenging to master, and most training time should be spent on these processes. Brown's research took a participant observation/ fieldwork approach, and though not empirical, the conclusions about the technology also reflected the technocentrism highlighted in the Song (2018) and Pamuk (2012) studies. With such a steep learning curve for the successful use of a 3D printer, Brown concluded that teachers could learn best by following a learning cycle that includes four types of 3D printing activities. Her hierarchy of 3D printing activities had four types of lessons in which two lessons were centered entirely on the technology: "develop/refine printer technology" and "print trials."

2.5.2 Deeper Learning Through Connections

Connecting the three categories of teacher knowledge is essential when integrating digital fabrication technologies, but so is connecting people to other people. A common theme in the literature is that teachers learn best by sustained connections to other teachers experiencing the same learning trajectory. These networks, both formal and informal, appeared as an important concept in much of the research. Whether referred to as “professional learning communities” (Cairns et al., 2018; Oliver, 2016), “informal learning communities” (Song, 2018), “study-groups” (Hjorth et al., 2017) or simply “friends” (Peterson & Scharber, 2018), these groups of teachers were critical in supporting one another through their learning journeys. Though most researchers indicated success with in-person community groups, Brennan (2018) also developed a virtual support community. Through her work supporting teachers to use Scratch programming in their practice, she developed an online community for educators in which the members network with one another, ask and answer questions, and share stories and resources (p. 293). She described this community as a significant part of successful technology integration.

Hjorth et al. (2017) successfully supported teachers using new technologies in research by design study that included digital fabrication tools and centralized the importance of interpersonal connections with a group of in-service teachers in Denmark. These researchers developed a course on design processes and digital fabrication. Through observations, interviews, and survey instruments, the researchers defined challenges facing teachers trying to implement digital fabrication through design in their classrooms. Their approach to combat these challenges included integrated peer-to-peer collaboration (p. 27). These peer-to-peer collaborations took the form of study groups and, unlike Brennan’s unstructured online community group, were highly structured. In both cases, the teachers’ feedback was positive about the connections made through these groups and how that was an important aspect of their learning. Neither study reported any follow-up results from the training sessions to indicate whether or not the teachers could continue to use these tools in their classrooms beyond completing the training.

In Oulu, a more extended study occurred at the intersection of STEAM and digital fabrication teacher training. Researchers developed a comprehensive teacher training program at the University for in-service teachers to learn pedagogy and digital fabrication technologies; this program included a structured Community of Practice, which had not only teachers but other stakeholders in the area. This structured development of the stakeholders and activities was built as the year went on, and the data collected in the study reflects the successes of the structured activities as part of building the CoP (Milara et al., 2020).

Whether these learning communities are highly structured or more casual, this connection in learning shows up repeatedly in the research into teacher training for new technologies.

2.5.3 Classroom and Embedded Experience

Another prevalent theme identified among researchers is that teachers learn to teach with technology best when they can practice themselves or observe someone else doing the teaching. Hjorth et al. (2017) prioritized embedded teaching experience in their Denmark-based teacher professional development program and their integrated study groups mentioned above. During this nine-month program, this team implemented in-school practice as an integral part of the training. Participating teachers developed and taught design lessons with digital fabrication tools during the program and reflected on this experience as an essential part of their learning.

The concept of classroom practice was also specified by Pamuk (2012) in the Turkish study mentioned above. The pre-service teachers were observed and interviewed about their classroom experiences during their training; most reported that they felt under-practiced. These pre-service teachers reported having trouble implementing the new technologies they had learned without embedded practice or lesson modeling.

In their research project, Cairns et al. (2018), which involved a three-year teacher training program, incorporated classroom practice as well. These teachers learned how to integrate 3D printing into authentic lessons, and one of the teacher development program's critical components was the program's embedded aspect. These in-service teachers developed lessons in the training and then implemented them with their students, analyzing the results in their professional learning communities within the program. This study showed teachers' increased use of digital fabrication technologies, and the program incorporated both embedded practice and learning communities.

2.5.4 Teacher Support Summary of the Literature

Throughout the research on effectively preparing teachers to use digital fabrication tools, it is clear that merely concentrating on the technology itself isn't sufficient. This conclusion echoes the same conclusion from the research into classroom practices with digital fabrication; just learning about technology doesn't support authentic student learning. Thus, teachers, and those who train teachers, should beware of centering learning on the technology itself. Instead, a more holistic approach to supporting teachers to integrate technology is supported by research. In addition to the TPACK theory of teacher knowledge, there are other themes identified in the research to help teachers: embedded experience and learning communities, but more research needs to be done in this field to establish causal links between teacher training strategies to classroom usage.

2.6 Synthesis of Supporting Knowledge

In reviewing the literature on digital fabrication technologies in formal education, several promising components of integration have emerged both in classroom practices and teacher preparation strategies. Though there is not one agreed-upon approach to preparing classrooms and teachers for these tools, the data shows the potential for them to support authentic student learning. Administrators, educators, and students are fascinated by 3D printers, laser cutters, and other CNC machines, but the tools should not be the learning goal. Papert (1987), the father of the maker movement in education, cautioned about the potential to centralize technology above everything else. Yet, much of the research suggests that same tendency both in classroom use and teacher professional development curriculum.

The work of Koehler and Mishra, who theorized that technical knowledge is merely one category in a trio of teacher competencies, is referenced by researchers who have identified this technocentric oversight in many studies. Attending to all three types of teacher knowledge is important, but there are few examples of a successful TPACK approach in practice. A research gap here is the extension of the TPACK framework into the practice of preparing teachers for digital fabrication.

3.0 Theory of Practical Improvement

The problem of practice focuses on K12 in-service teachers, and these teachers have a significant amount of experience with their content. They also typically have a content-based curriculum or specific standards to follow. Teachers need to know the technology to integrate new technologies into their practice. Still, they also need support in understanding how to use that technology in a classroom setting (pedagogy). There are many other contributors to a teacher's successful integration of digital fabrication technologies. I addressed five common areas in my fishbone diagram (Appendix C): “time and space, technology knowledge, pedagogical and integration knowledge, support network, and standardized testing.”

Research shows that with thoughtful training that includes pedagogical knowledge and integration combined with additional support structures like embedded practice and professional learning communities, teachers can successfully integrate digital fabrication tools into their classrooms, even in subject areas beyond the traditional STEM disciplines.

3.1 Driver Diagram

Reflecting on the practice problem through professional experience, empathy interviews, semi-structured interviews, and supporting literature review, I have developed a driver diagram that visualizes the theory of improvement in Figure 4. Perry et al. (2020) define the driver diagram as a graphical means to display potential drivers for improvement across a system, working towards a specific improvement aim. My aim is to increase the number of teachers within the eduFAB network using digital fabrication tools to support student learning. The term "teachers in the network" is broad phrase. With over 800 members in the eduFAB network from many different areas of the world, the stakeholders of this problem are not localized in a particular school or district. Instead, they are located across various national locations within varying social and economic conditions. My place of practice is broad, and the network of teachers is global. Ideally, all teachers in my network would increase authentic tool use to support classroom learning objectives through my focused change idea and its subsequent dissemination through the network.

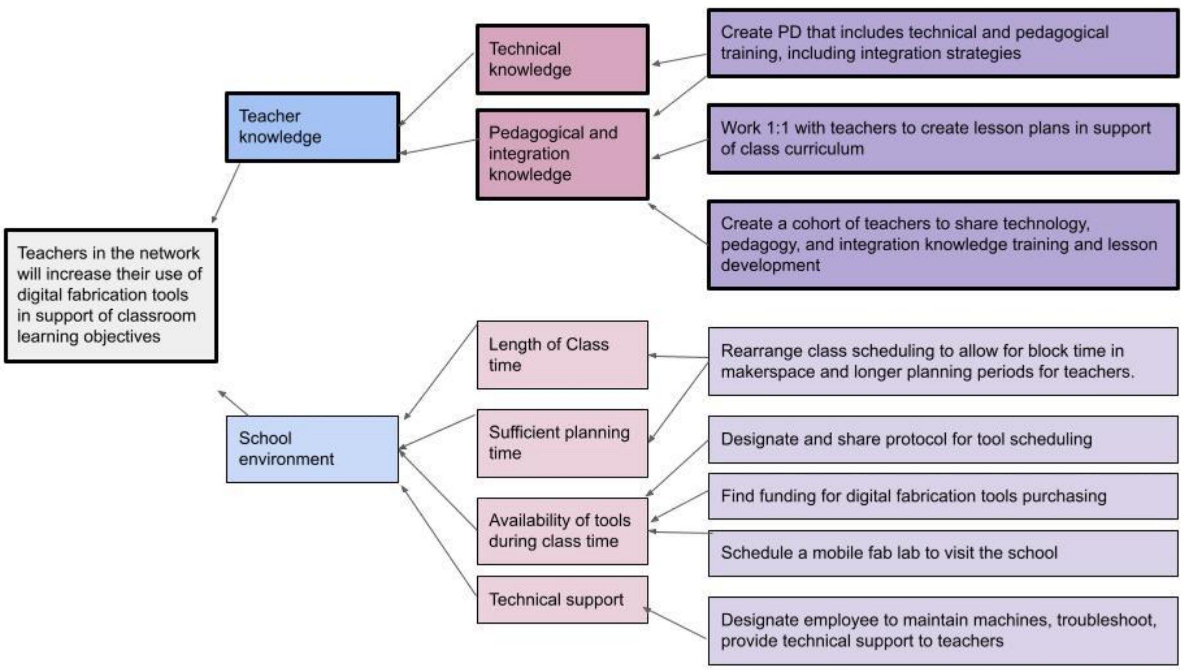

Figure 4. Driver Diagram

3.1.1 Primary and Secondary Drivers

The driver diagram illustrates two primary drivers in blue: "teacher knowledge" and "school environment." Primary drivers are broad approaches that, if pushed, can affect the overall aim of a theory of improvement (NYC Department of Education, 2018; Perry, 2020). “School environment” is essential in working towards improvement, and teachers most often cite it as the primary challenge for not integrating digital fabrication technologies. Through my empathy interviews with teachers and semi-structured interviews with administrators, I concluded that many secondary drivers (in pink) falling under “school environment” are challenges for teachers, like “length of class time, sufficient planning time, availability of equipment, and technical support.” The third column in the driver diagram, in purple, illustrates change ideas that could affect the secondary drivers affecting the primary drivers. The drivers under “school environment” not only fall out of my locus of control, but implementation would need to vary significantly from school to school. This primary driver will not be the focus of the intervention.

The bold top half of the driver diagram accentuates the top primary driver, which is the focus of my change idea. In my place of practice, with access to teachers in the network, my concentration will impact the primary driver, “teacher knowledge.” The secondary drivers describing the types of knowledge teachers need are “technical knowledge” and “pedagogical and integration knowledge.” Here I have included the term “integration” to pedagogical knowledge to better describe the process of using these tools for authentic student learning.

The second research question demonstrates that teacher training needs are broad when introducing new technologies. Teachers should understand the pedagogical theories and practices associated with making and the equipment as an integrated learning tool for subject content. “Introduction [of digital fabrication] is not only a matter of using machinery or technology but there are important pedagogical concepts to develop as well, such as integrative learning approach, interdisciplinary and project-based learning” (Milara, 2020, p. 11). By including the term "integration knowledge" in the driver diagram, I include pedagogy as well as classroom practices and strategies for using technology in the confines of a classroom.

3.1.2 Change Ideas

With the primary driver of "teacher knowledge" centralizing the work in my research study, I have identified three change ideas that contribute to this driver, outlined in bold on the driver diagram. These change ideas are supported by the review of supporting knowledge about how teachers learn to use and integrate new technology with their students. The themes I identified in the research are linked to the change ideas of the driver diagram and are visualized in Table 1.

Table 1. Change Ideas Aligned with Research Theme

Change Ideas	Research-Identified Themes on Teacher Training
Create PD that includes technical pedagogical training, including integration strategies.	attention to technical knowledge
Work one to one with teachers to create lesson plans in support of class curriculum.	attention to technical knowledge, deeper learning through connections, classroom and embedded experience
Create a cohort of teachers to share technology, pedagogy, and integration knowledge and lesson development	attention to technical knowledge, deeper learning through connections

Of the three change ideas impacting teacher knowledge on the driver diagram, only one view is supported by all three themes that emerged from the research question. This change idea, to "work one to one with teachers to create lesson plans in support of classroom curriculum," has great potential and can fall under my locus of control. I focused my intervention on this change idea and its progress toward shifting secondary and primary drivers and the overall system.

Incidentally, the change idea emerged from my organization's reaction to the challenge of COVID-19. When the pandemic shut down schools in the Boston area, where Fab Foundation has a central office and operates two mobile Fab Labs, the Fab Foundation's education team was forced to re-imagine our school outreach efforts. The staff shifted to virtual learning for student programming and added virtual teacher professional development as a temporary measure so teachers could learn to handle the tools themselves. During our first COVID virtual engagement, Fab Educators delivered vinyl cutters and 3D printers directly to the teachers' houses and then trained them virtually to use their tools. In addition to this technical component, Fab Educators met one to one with each teacher to help develop a lesson plan using the new technology. After this pilot program, each teacher shared their lesson plan with the cohort of teachers and published their lesson on an open-source lesson repository website to share worldwide. These creative lessons integrated digital fabrication tools into different content areas, and the final lessons were a great addition to the online community of practice. This intervention, conceived from the challenge of difficult times, was easily implemented in a virtual setting, and the participating teachers were excited to get back into the classroom and implement their new lesson plans. This change idea may be the most promising practice to emerge from COVID-19 for the work at Fab Foundation.

3.2 Methods

In designing this research study, I used an improvement science approach (NYC Department of Education, 2018) which considers stakeholders, organizational context, and relevant literature in defining a problem space and developing a theory of improvement. To test the theory of improvement, I used a methodology described by Hinnant-Crawford (2020) called Plan, Do, Study, Act (PDSA) to transform the theory of improvement into intervention and check for any progress toward my aim. PDSA is a continuous improvement cycle based on “developing a theory, testing that theory, and then revising that theory based on the results of that test” (p. 153). PDSA works best with more than one testing cycle, and I completed two cycles. For the intervention, I worked virtually and one to one with four teachers to learn new technology and then embed that technology into a lesson plan for their classroom.

3.2.1 Inquiry Questions and Predictions

Embedded in a theory of improvement are many ways of measuring results that must be considered when practicing improvement science. The metrics that assess the project's overall success are called outcome measures. This study's outcome is partly based on teachers' perceptions of the relevance of digital fabrication technologies for content-area learning. Teachers can be “critical when confronted with new educational technologies,” so attention to teacher perceptions of the tools and their relevance is essential to understanding when measuring the outcome (Fernandez, 2019, p. 101).

Driver measures investigate the process of developing the outcome; they identify how the intervention contributed to the intended result if it did or not. In this study, the driver measures will indicate *how* the lesson development sessions affected (if any) the teacher's perception of technology relevance.

Process measures in improvement science are formative and used to determine the immediate effect of the intervention and how that can be improved. This measurement is embedded in the research questions but was also continually measured in direct visual cues when working with study participants. During the one-to-one sessions, I adjusted the process based on immediate feedback in the form of interest, fatigue, confusion, or other factors demonstrated by participants during our virtual sessions.

Finally, balance measures respond to the overall context of the improvement science project. How will concentration on a specific context area affect other (non-centered) areas? For this work, I considered teachers' language when referring to their place of practice.

The inquiry questions guide the PDSA cycle, which address outcome measures (both leading and lagging), process measures, and system measures (Hinnant-Crawford, 2020). Table 2 lists the inquiry questions and predictions I will seek to answer through my PDSA cycle. My predictions are based on empathy interviews and my impressions of the success of the initial cycle of this change idea which emerged in my practice over COVID-19.

Table 2. Inquiry Questions and Predictions

Inquiry Question	Category	Hypothesis
IQ1. To what extent will the lesson plans developed by the participants integrate technology into their subject area lesson?	Outcome measurement	The lesson plans completed by the teachers will show a "substitute" or "augmentation" level of integration based on the SAMR framework.
IQ2. How comfortable will the teachers feel about using these technologies with their students?	Outcome measurement	Teachers will report feeling comfortable using this technology with this lesson plan.
IQ3. What aspects of lesson development were most useful in this process?	Process Measurement	Providing technology expertise.
IQ4. How does the lesson plan requirement affect the participants' perception of technology relevance in their own classroom?	Driver measurement	Teachers will perceive this technology as more relevant to their classroom learning after the lesson plan development intervention.
IQ5. How does the lesson plan development affect participants' likelihood of using these tools with their students?	Driver measurement	Teachers will be more likely to use this technology in future lesson plans after the intervention.

3.2.2 Participants

Engaging with teachers virtually after the two years of COVID disruptions proved to be very challenging. With limited interest in participation from my network teachers, I reached out to other teachers local to Western Pennsylvania and completed two rounds of the intervention cycle with a total of four classroom teachers.

In the stakeholder analysis, I identified two types of teachers, technology teachers and subject area teachers. Ultimately, given the recruiting challenges, I ended up working with both types of teachers: two technology educators completing the first PDSA cycle together and two elementary classroom teachers completing the second PDSA cycle.

3.2.3 Procedure

Because of the qualitative aspect of this research, the small number of participation, and my relationship to the study myself, this PDSA cycle can be described as a case study. My role in this improvement science study cast me as the trainer and researcher, and I spent much one-to-one time with each participant. As a researcher, I was not able to simply make observations, and my actions were impactful on the outcomes of the theory of change. As I worked with each teacher independently, my words and actions were different, and I adjusted the sessions as each teacher needed based on the real-time feedback I noticed in the sessions and accounting for the differing needs of each teacher.

I completed two PDSA cycles in the research, and they included approximately 4-7 hours of one-to-one sessions with each participant. Table 3 illustrates the procedure for the intervention cycles with a time range and goals for each session.

Table 3. Intervention Procedure

Introduction	30-60 minutes	brief introduction of myself, teacher introduction, explanation of the intervention process
Technology Training	60-120 minutes	(depending on teacher) installation of software, walk through design and making steps, practice
Ideation and Research	30-60 minutes	discuss learning goals, browse other lesson plans on SCOPES-DF website, brainstorm ideas for lesson
Lesson Development	30-90 minutes	using the SCOPES-DF lesson planning template, identify learning goals and begin work on lesson plan
Additional Development	30-60 minutes	some teachers worked additionally on their own time before presenting the lesson plan
Lesson Sharing	45-60 minutes	teachers presented or shared their lesson plan

3.2.3.1 Introduction Session

Each cycle began with a short introduction (30-45 minutes), and this part of the session was the most similar in all four cases. The purpose of this introductory session was to get comfortable with the teachers and attend to the pedagogy component of the TPACK framework. I introduced myself and my experience with digital fabrication and teaching, including a brief overview of the research. Then, I asked the teacher some introductory questions about their teaching style and classroom and asked them to describe their experience with digital fabrication technology. In the research overview, I summarized the review of supporting knowledge, highlighting the "Key Affordances in School Use of Digital Fabrication Tools" section describing how digital fabrication technologies support student learning. Each introduction session finished with an overview of the intervention's upcoming steps and scheduled the next working session.

3.2.3.2 Technology Training

The next step of the cycle attended to the technology component of the TPACK framework. For cycle two, I worked with both teachers to install software and set up a vinyl cutter. With virtual guidance, the teachers designed and cut using the vinyl cutter several times until they felt comfortable with the technology. The cycle one teachers had ample experience with digital fabrication technologies, so this session was skipped.

3.2.3.3 Ideation and Research Session

In this session, I began by asking the teachers about their learning goals for their students and whether they had any specific ones to center on in the lesson plan. I introduced them to the SCOPES-DF website with its lesson repository, and together we explored open-source lesson plans from teachers throughout the network. These examples inspired lesson plan ideas, and I also introduced the lesson plan template for the website. After this session, the teacher would have two or three ideas for lesson planning.

3.2.3.4 Lesson Development Sessions

For three of the four teachers, there were two separate lesson plan development sessions, and with one teacher, there were three sessions. In these sessions, we isolated learning goals from their previous ideation session, and then we worked together in combining technology with the content and learning goals identified. In this step, I asked each teacher if they had a lesson plan format for development; if they didn't, we used the SCOPES-DF lesson plan template (Appendix D). I developed this template when I worked for Fab Foundation, which is used to upload shared lesson plans on the website. We worked through the template together, beginning with stating learning goals, identifying standards, listing materials, and supplies, and then describing each step in the lesson. Some participants in the study continued the work on the lesson plan template between sessions with me, and others did not.

3.2.3.5 Lesson Sharing

Finally, the last step in the cycle was to share the lesson plan with others. This step was intended to serve as a deadline for the completion of the lesson plan template. It was also an attempt to encourage connections with others, as the literature review suggested. However, only the first two teachers in cycle one could share their lesson plans, the following cycle was unable to find a suitable meeting time for both to attend.

3.2.4 Measures and Analysis

Throughout this study, I took a mixed methods approach. I collected both quantitative and qualitative data to provide a rich understanding of the link between embedded lesson design practice with one-on-one support and teachers' perceptions of these technologies for use in the classroom. Table 4 outlines the inquiry questions, data collection techniques, and sample protocol questions.

Table 4. Inquiry Questions and Measures

Inquiry Question	Type	Collection Protocol	Data Collection and Analysis	Protocol Questions
IQ1. To what extent will the lesson plans developed by the participants integrate technology into their subject area lesson?	Outcome measurement	Sample lesson plan	Quantitative: analysis based on the SAMR model of technology integration	How is the technology integrated? 1-Substitution 2-Augmentation 3-Modification 4-Redefinition
IQ2. How comfortable will the teachers feel about using these technologies with their students?	Outcome measurement	Post-survey	Quantitative: Likert scale survey question.	How comfortable are you using these technologies with this lesson plan in the classroom?
IQ3. What aspects of lesson development were most useful in this process?	Process Measurement	one to one sessions Post-Interview	Qualitative: visual cues during sessions open-ended questions in post-interview	Visual cues: frustration, boredom, etc. In our 1:1 session, what did you find most useful?
IQ4. How does the lesson plan development process affect the participants' perception of technology relevance in their own classroom?	Driver measurement	Post-Interview Post-survey	Qualitative: Open-ended question in interview, inductive coding of transcript. Quantitative: Likert scale survey question	Do you see any other ways or lessons in which you can integrate the technology that was learned during the training? How relevant are these technologies to learning in your classroom?

Table 4. Inquiry Questions and Measures (continued)

IQ5. How does the lesson plan development affect participants' likelihood of using these tools with their students?	Driver measurement	Post-survey Post-Interview	Quantitative: Likert scale question Qualitative: Open-ended question in interview, inductive coding.	How likely are you to use these technologies with your students in the upcoming school year? How will you use these technologies with your students?

Participants in the study completed a pre-survey and a post-survey. The pre-survey questionnaire also served as a screening tool, since I used it in recruiting efforts for teachers to show interest in participating. In addition to the surveys, I conducted short, semi-structured interviews with all participants after the intervention. The survey questions are included in Appendix E, and the semi-structured interview questions are in Appendix F.

Additionally, after the intervention, I collected the lesson plans and analyzed them with the Substitution, Augmentation, Modification, and Redefinition (SAMR) framework (Puentedura, 2006). SAMR was developed to analyze teachers' use of technology in learning activities for K12. The four rungs of the ladder build from the lowest level of integration, "substitution," to the highest level, "redefinition," in which the technology provides the means of creating a novel task that couldn't be conceived without the technology itself (Hamilton, Rosenberg, & Akcaoglu, 2016). Figure 5 illustrates the levels of the SAMR hierarchy. The two lower levels fall in the category of “enhancement,” and the higher two levels are categorized as “transformation.” I used this ladder to determine the technology integration level reflected in the teachers' lesson plans.

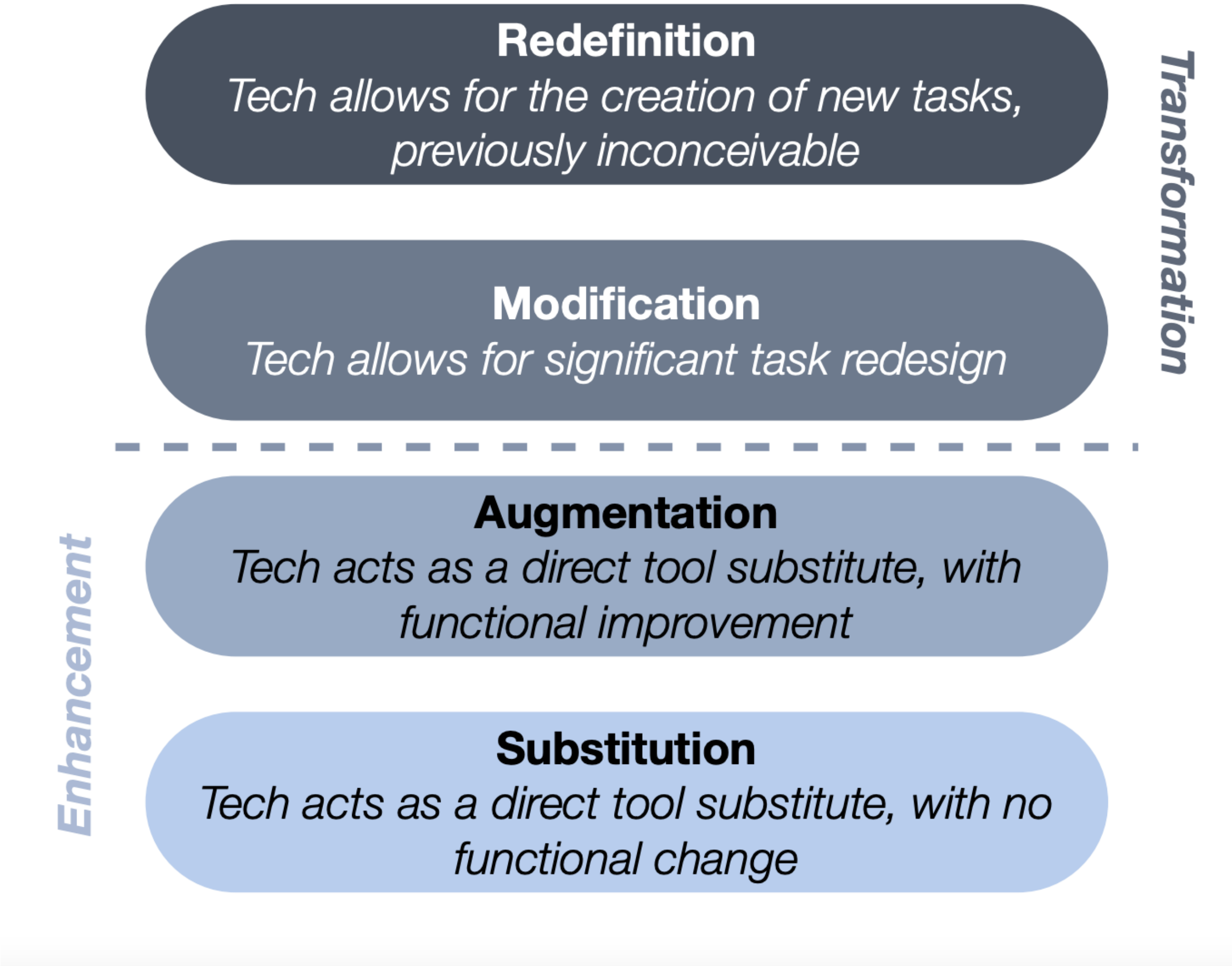

Figure 5. SAMR Hierarchy (Puentedura, 2006)

4.0 Results

Using the improvement science approach, I conducted two PDSA cycles of the research intervention. With some time in between cycles, I adjusted the lesson development procedure. In this section, I will describe research results chronologically, concluding each cycle.

4.1 Cycle one

The first cycle of the research study occurred during the spring semester of the 2021-2022 school year. Recruitment began in March, and the virtual intervention occurred from late April through May 2022.

4.1.1 Cycle one Participants

In a broad recruiting effort, I used my eduFAB network and personal social network to broadcast to in-service teachers, and twenty-nine people from my networks completed the questionnaire. This questionnaire doubled as a pre-survey and a screening mechanism for study participation. Eliminating respondents who didn't meet all the questions, those who were out-of-school-time educators, and those respondents who were not classroom teachers left eight viable candidates for the research study.

I had initially planned on conducting an introductory session with all the participating teachers present in a virtual setting. Scheduling participants for shared virtual meeting times was tough and quite unsuccessful. After four weeks of going back and forth with attendance polls and calendar invitations, many teachers dropped out. Several shared that they were just too busy with end-of-the-school-year responsibilities, and some just, and some stopped responding to my communications without comment. Adjusting the introductory meeting schedule, I eventually met one to one with each teacher and completed this session five different times. Scheduling conflicts continued after this session, three participants dropped out, and only two teachers were able to complete the entire cycle.

Interestingly, both cycle one participants were technology education teachers, one from middle school (MS) and one from high school (HS). They both came from affluent districts in the Greater Pittsburgh area and had access to digital fabrication technologies in their classrooms. As described in the stakeholder analysis section, these types of teachers center the student learning around technology learning goals. Both were already well versed in using 3D printers, laser cutters, and vinyl cutters. From here, I refer to them as the initials HS and MS.

4.1.2 Cycle one Methods

Since both participants in this cycle were very comfortable using the technology, neither participated in the virtual technology training session. After the introduction, both moved directly into the ideation and the lesson development sessions. After our one-to-one lesson development sessions, both teachers met virtually for a presentation session, as indicated in the above methods section. Each teacher shared their lesson plan with the other, asked questions, and answered questions from myself and the other participating teacher. Altogether, HS and I spent about four hours working together, and MS and I spent about five hours together for the duration of this cycle.

Both teachers completed the written lesson plan template to a certain extent, though not with very much detail. For example, MS's completed lesson plan is in Appendix G. Both teachers indicated that they would work on it again in the following school year after the summer break.

4.1.3 Cycle One Findings

Each participant in this cycle approached lesson development with attention to non-technology learning goals and their usual technocentric instruction goals. My involvement and focus on other content learning during the introduction session influenced this approach for both of them. Through our conversations, we drew out different goals for student learning and formed lesson ideas around those goals. In addition to technology learning goals, MS centered their lesson around practicing creativity with their students. However, HS was more interested in redesigning a lesson that would interest young girls in their technology classes.

4.1.3.1 Cycle one Lesson Plan Analysis

For an outcome measure, I analyzed each completed lesson plan concerning the first inquiry question, "To what extent will the lesson plans developed by the participants integrate technology into their subject area lesson?". I assessed the completed lesson plans for both participants using the SAMR hierarchy, and both lesson plans showed technology integration in the “transformative” tier. MS's lesson plan featured the technology (vinyl cutter) at the “modification” level. In this lesson plan, MS's students use technology to decorate and label their creativity journals. At the "modification level, the technology requires a significant redesign of the ask," (Hamilton, Rosenberg, & Akcaoglu, 2016, p.434). This modification of the task decorating significantly changes the lesson and offers new options and processes than non-digital tasks such as coloring or drawing. It also provides an opportunity for learning about creativity within certain constraints, such as only one color of vinyl, size, ease of weeding the vinyl, etc.

HS's lesson plan ranked at the highest level of integration on the SAMR scale, "redefinition." This teacher's lesson plan included more than one digital fabrication technology and was a significantly longer lesson plan than the other participant in cycle one. HS developed a lesson plan incorporating research, design, and fabrication to build a website with a sales fundraiser to support a cause. In addition to researching and building a website, students would learn how to design using 3D CAD software and a 3D printer or laser cutter to make a sales product for their fundraising projects. At the "redefinition" level of the SAMR hierarchy, the technology integrated into this lesson plan creates opportunities for projects that would not exist otherwise. Additionally, an important part of HS's lesson plan was to introduce the students to generative design, and this process would be impossible without the use of technology.

4.1.3.2 Cycle one Survey Data Analysis

With such a small number of participants, the quantitative data from the surveys is best directly paired in T-sample tests without generalizing the results across all of the survey results. The size of the study is just too small for larger implications, however, I did analyze the data within each cycle without processing it together.

Through pre and post-surveys, I was interested in comparing the comfort level with the technology, the likelihood of using the technology, and the perception of the relevance of the technology in the classroom. Comparing pre and post-surveys with a paired sample T-test about the second inquiry question, "How comfortable will the teachers feel about using these technologies with their students?", the data showed no change for either participant. Both reported that they were comfortable using these technologies with their students in the pre-survey and the post-survey. Additionally, inquiry question five, "How does the lesson plan development process affect participants' likelihood of using these technologies with their students?” there was also no significant difference based on the pre and post comparisons data. MS indicated that they used digital fabrication technologies more than three times a week in their classroom before the intervention. Afterwards, they reported that they are "likely to use" this technology in this lesson plan with their students. HS said similarly, already using the technology in their classroom; on the post-survey, they reported that they "definitely will use" this lesson plan following the intervention.

The data set for inquiry question four, "How does the lesson plan development process affect the participants' perception of technology relevance in their classroom?" was different between the two participants in cycle one. While HS indicated a high perception of relevance in both pre and post-survey questions about the technology, MS responded "yes" to the post-survey question, "Did this lesson plan development process change your view of the above technology in classroom use?". They explained that through collaborative lesson plan development, "I now realize there are so many other purposes it can exist for, and that students should be using it themselves more than even I am!"

Survey data showed little change in confidence level or likelihood of using the technology and limited growth in the perceived relevance of the toolset in cycle one. Both participants perceived the technology as relevant before and after the intervention and ranked their likelihood of using it with students high before and after. Perhaps this is because both teachers reported a high rate of technology use with their students on the pre-survey; they were already integrating the technology three or more times per week before the intervention.

4.1.3.3 Cycle one Qualitative Data Analysis

Using the transcript from each participant's semi-structured interview and field notes from the lesson development sessions, I analyzed inquiry questions two, four, and five, which address comfort level, perception of relevance, and the likelihood of using the technologies with students. I used inductive coding methods to develop categories and themes in the data based on their verbal responses to my questions and other comments. This qualitative data helps develop a more nuanced understanding of the survey data and uncovers some new and surprising concepts to consider.

Concerning inquiry question one, confidence level using these technologies with students, neither participant mentioned an increase in confidence level, which aligns with the qualitative data from the survey. However, a theme did emerge around using these technologies with students rather than by themselves. MS developed a lesson plan integrating a vinyl cutter, which they have used often for projects but never with students. Though they reported high confidence in using the technology, the idea of using it embedded in a lesson plan with students was different. Though they were willing to "give it a try" with this technology, they did not demonstrate confidence in our interview when asked about attempting this lesson with their students. MS was planning on using this lesson four times during the upcoming school year, each with a different class based on quarters. They spoke of room for development and growth of the lesson plan throughout the year based on the technology, "kind of like you're fine-tuning this lesson and your last quarter of the year gets the best that you have to offer." This "give it a try" theme did not present itself with the other participant in cycle one.

Regarding inquiry question five, regarding the likelihood of using these technologies, both participants reported that they plan to use the lessons developed through this process in the upcoming school year. This reflected the findings from both surveys as well.

Concerning inquiry question four, however, an interesting theme occurred around the teacher's perception of technology relevance in the interviews with participants in cycle one which I labeled "expanded learning opportunities." Though both participating teachers reported on the survey that they understood the relevance of the technology for their classroom, both participants reported a different understanding of the technology and its potential for use after the work we did together. During our one-to-one ideation and working sessions, I admittedly pushed these technology teachers to think about non-technological learning outcomes, so perhaps that is where this theme began to emerge. In the interview, HS mentioned that though they have been using digital fabrication technologies with students for years, reaching girls with this technology had never before been "brought to life as part of the class." MS, on the other hand, started to think about the vinyl cutter tool as a springboard for other ideas and learning opportunities in their class and school-wide, something not previously considered. They stated that working on this lesson plan “just changed my mindset in terms of what the value of the fabrication equipment is." They added that thinking about the potential of using this particular technology in a new way was "exciting."

4.1.4 Cycle one Reflections

Overall, teachers are exhausted and find it difficult to schedule, which is understandable as their schools are still reeling from years of interrupted learning during COVID-19. This cycle also occurred at the tail end of the 2021-2022 school year, so the timing of the intervention could have influenced participants' abilities to commit. The two that completed the study were already focused on using these tools with their students and had been doing so for years. These participants already understood the relevance of digital fabrication technologies to their student's learning, and it was easier getting them to virtual sessions, which were often in the evenings or over the weekends. Participants in this cycle plan on using their lesson plans in the upcoming school year in their technology education classes. Considering the large number of potential participants who dropped out of this cycle, perhaps because of this direct relevance to their classes, both technology teachers committed to finishing the intervention.

The results uncovered through data analysis about the second and fifth inquiry questions with this cycle of teachers were not unexpected, as their comfort and likelihood of using the technology started quite high without much room for growth. Both participants in cycle one fall squarely into the stakeholder category of "technology teachers" identified in the stakeholder analysis.

Though the participants in cycle one didn't show any growth in their comfort level with the technology or the likelihood of using the technology with students, they both experienced a shift in perception about the relevance of the technology in their classroom. The concept of using these tools not solely for technocentric learning represents a shift in the perception of the relevance of these tools. The new understanding of the relevance of technology, specifically for MS, the “expanded learning opportunities” theme was unexpected in the qualitative analysis. This growth may be explained by my involvement integrating pedagogy and research through the introduction session and my push to think about other learning outcomes during the lesson plan development sessions. The sessions consciously approached all three domain areas of the TPACK framework, and this result could reflect the design considerations in the intervention procedure.

The discovery that not all in-service teachers use lesson planning in their daily practice was an important revelation, and it exposed a gap in the theory of practical improvement. The underlying research for developing this intervention was grounded in a theme identified in the review of supporting knowledge, teachers integrate new technologies best when there is an embedded practice in the training. From this research, I assumed that lesson plan development was a teaching practice and that embedding this practice in the training sequence would help push the drivers of change. From interviewing cycle one participants, I uncovered this assumption. In reality, lesson planning is not always a teacher's practice. If teachers do not usually develop lesson plans in their practice, then this intervention did not include embedded practice; instead, it was a novelty experience.

An interesting takeaway from the qualitative data in cycle one was that the one-to-one lesson development sessions were helpful to the participants not because of the embedded practice detailed in the theory of practical improvement but because of the community support aspect. Developing the lesson together allowed them to lean into a professional learning community (though relatively small for this study) and offered an opportunity for growth. One theme that emerged from the review of supporting literature identified professional learning communities as helpful in supporting teachers learning to integrate technology into their practice. By working with these teachers and providing a shared lesson presentation session, each teacher commented on the community support aspect of the intervention.

Another theme, independent of the original inquiry questions but not surprising, emerged through the interview process in cycle one which I labeled "technocentric student learning." Both participating teachers spent a great deal of time in the interview discussing machines, software, and projects. HS mainly veered all their answers back to the project work. When asked about the learning outcomes for these lesson plans, both cited technocentric outcomes first and repeated them often, sometimes to the exclusion of the expanded opportunities for learning.

A similar theme that emerged when analyzing qualitative data from field notes was "focus on the project, not the learning." When coming up with lesson plan ideas, cycle one teachers started thinking about the final project instead of focusing on what they wanted their students to learn. This was reflected in the field notes after the ideation session and (less so) in the final interviews. It was apparent that both teachers were similar in their approach to curriculum; they concentrated on the final project that the student would complete and then worked their way back, with my assistance, to the why of the project. The answer to the question "what do you want your students to learn in this lesson plan" for one participant was, "I want them to design a plastic package for a mini skateboard." This focus on the project over the learning is related to another theme I noticed during the final interview sessions.

In response to the interview question about the process of lesson plan development, stemming from the third inquiry question, I discovered that neither teacher typically prepared lesson plans to the extent that they included learning goals and standards. Under the theme of "focus on the project, not the learning" that emerged from the lesson plan development sessions, both tech ed teachers reported they do not develop lesson plans in their typical practice but instead make detailed instruction lists for completing the project. In the interview, HS stated, "This is the first time I've ever done [such a complete] lesson plan, and it really made me think about my approach to the students, the girls, in my class especially." MS also rarely used a templated lesson plan, and in response to my question about how it might have helped, they replied, " I think the [lesson plan] template certainly served its purpose in terms of getting me to really think through this as opposed to just do it how I've done it before."

A final concept discovered in the qualitative data is the theme of "peer support in planning." Both participants in cycle one mentioned this as a very helpful aspect of the lesson development process. "Just having someone to bounce ideas off of and help shape [the lesson plan]" was very helpful, according to MS. Neither teacher has opportunities for shared lesson planning in their practice. Both commented on this process helping create a plan. This theme reflects another of the research-identified conclusions that teachers integrate technology best by being involved in a professional learning community. In this intervention, I unintentionally provided the learning community component to this process and discovered that even a small community could help teachers integrate digital fabrication technology. In addition to my one-to-one learning community member participation, the cycle one participants met each other at the end of the intervention. In the final virtual session, MS and HS presented their lesson plans, asked questions, and offered suggestions on each other's plans. They both cited this in their interviews as especially helpful.

4.2 Cycle Two

Taking lessons learned from cycle one of my improvement science research, I reframed the recruiting strategy a little in hopes of working closely with subject area teachers instead of technology teachers. This cycle occurred at the beginning of the school year 2022-2023, so the schedule proved challenging for teachers in a different way. These teachers participated in August and September when they were gearing up for the new school year, so time was limited.

4.2.1 Cycle Two Participants

For the second cycle of the study, I specifically recruited classroom teachers through connections I made during a summer workshop at a local school district. Both teachers in cycle two had participated in a three-day digital fabrication workshop where they were exposed to 3D printing, vinyl cutting, and laser cutting. These teachers both showed interest in learning new technology to help their classrooms, yet they were not currently using digital fabrication technologies with their students. Both teachers worked in elementary schools; one was a 4-6 music teacher (MT), and the other was a K-5 librarian (KL). Both schools were located in Western Pennsylvania, and one had various digital making technologies available, but neither participating teacher had ever used digital making with their students before.

4.2.2 Cycle Two Methods

Since neither of the two participating teachers had the technical knowledge, I virtually spent time on the technological session as described in the methods section. Each teacher received a 12" vinyl cutter for their classroom, and I worked one to one with each teacher to set up their vinyl cutter, install the software, and learn how to design for cutting. These technical training sessions lasted about two to three hours each and were done completely virtually. From there, we moved to the lesson development sessions and the intervention proceeded much the way it had in cycle one. However, faced with the difficulty of scheduling participants, the teachers did not meet at the end of the cycle to share lesson plans. Neither teacher completed their lesson plan template to the extent that the participants in cycle one did; the plans were only partially completed after the intervention. The total time spent in virtual sessions was about six and a half hours for KL and seven hours for MT. This time was significantly higher than the time spent with cycle one participants because of the additional technology training sessions that these participants received.

4.2.3 Cycle Two Findings

Both participants used the vinyl cutter in their lesson plans and focused on non-technological learning goals for their students. MT created a lesson plan for their 5th-grade music students that explored graphical interpretations of band logos. KL created a lesson plan that integrated the computer programming of a robot with researching and designing graphic representations of cultures from different countries. These lessons were much different than in cycle one, with a focus on subject area learning goals instead of technology-specific learning goals.

4.2.3.1 Cycle Two Lesson Plan Analysis

To measure the outcome of the first inquiry question, I analyzed the lesson plans according to the SAMR scale as I did in cycle one. Though the lesson plans were not finished to the extent that they were in the first cycle, I had enough data to proceed with the analysis, including field notes from the lesson plan development sessions.

KL's lesson plan for their library class integrated the vinyl cutter at an augmentation level according to the SAMR scale. "At the Augmentation level, technology is exchanged, and the function of the task or tool positively changes in some way" (Hamilton, Rosenberg, & Akcaoglu, 2016, p.434). In this lesson plan, students research and design graphical representations of their assigned country and then cut the graphics into stickers using the vinyl cutter. The students place the stickers on a shared world map (on the floor) and then program robots to visit the countries. KL had done this lesson plan with their students before using markers to draw pictures representing each country's culture for the world map. Integrating the vinyl cutter augmented the lesson itself and positively changed the task with this adaptation.

For the music teacher, MT, the lesson plan was a new one, designed specifically with the vinyl cutter. The lesson uses the technology at the level of "modification" on the SAMR scale. In this lesson, students research the logo designs of their favorite bands and look at how logos change over time to reflect the culture. Then the students recreate their band logos for cutting on the vinyl cutter, and they put their new stickers on their music notebooks. This lesson is similar in scope to the creativity lesson in cycle one and lands at the "modification" level.

Neither of these teachers landed at the highest level of the SAMR hierarchy, "redefinition," as one of the tech ed teachers in the first cycle was able to do.

4.2.3.2 Cycle Two Survey Data Analysis

With only two participants who completed cycle two, the quantitative data was best paired between pre and post responses directly for each participant. It was just too small of a sample to read implications for the study as a whole. During this round, however, the pre survey did provide some insight into the practice of lesson planning for participants. After cycle one, I added questions about participants' typical lesson planning practices. Both responded that they use lesson plans five days per week in their classroom. They each reported spending some time on lesson plan development during their average school week as well; one reported 1-2 hours, while the other teacher reported 2-3 hours a week for lesson planning.

I analyzed the quantitative data on the surveys to investigate the second inquiry question, "How comfortable will the teachers feel about using these technologies with their students?" In contrast to cycle one, both participants in cycle two reported an increase in confidence level using the technology itself, though the percentage of increase differed. One teacher reported a higher level on the pre-survey than the other, but they both ended with "comfortable" during the post-survey. In contrast, cycle one participants showed no increase in the confidence level from the pre to post-survey.

Additionally, the likelihood of cycle two participants using this technology in their classroom increased. In the pre-survey, both teachers reported that they had never used this technology with their students before. After the intervention, both participants responded that they were either "likely to use" or "definitely will use" this lesson plan with their students, demonstrating positive movement on the fifth inquiry question, “How does the lesson plan development process affect the participants’ likelihood of using these tools with their students?”.

In contrast to this increase in comfort level with the technology and the likelihood that both teachers will use this lesson plan with the technology in their classes, the post-survey data showed that neither participant reported confidence in using the technology with students. Responding to the prompt "I feel confident that I can use a vinyl cutter with a class," one responded "unsure" while the other replied "disagree." Though both participants reported that they could integrate the vinyl cutter into a classroom lesson and feel confident in using the technology, the confidence level using the technology with their students in a classroom setting was not high.

Investigating the fourth inquiry question with survey data, only one cycle two participant demonstrated a change on their perception of the relevance of these tools to their content area. In the pre-survey, KL reported that they do not see the relevance of this technology, and in the post-survey, they reported that they can now apply this technology to other lesson plans in their classroom. The other teacher did not report any growth in the perception of relevance, as the answer to the pre-survey question about this inquiry was high already, there was not much room for growth.

4.2.3.3 Cycle Two Qualitative Data Analysis

I used the same inductive coding process for field notes and the transcripts from semi-structured post-interviews with participants for cycle two. This data set shared similarities with the previous cycle's codes and brought new themes to light. It provided a deeper understanding of the quantitative data collected pre- and post-surveys.

With regards to the second inquiry question, “How comfortable will the teachers feel about using these technologies with their students?” a thematic review of the interview transcripts revealed "confidence in technology" growing for both participants. In this cycle, since neither participant had previous experience with the technology, a significant portion of time was spent learning how to set up and use the vinyl cutter, including 2D design programs and methods, as well as troubleshooting the vinyl cutter itself. Both teachers indicated that this was a beneficial aspect of the intervention, perhaps the most helpful.

In the interview's third inquiry question, "What aspects of lesson development were most useful in this process?” cycle two participants cited the actual time spent on technological learning. One participant said, "Learning how to troubleshoot the vinyl cutter and trying several art programs helped to give me confidence that I could figure out how to do what I see in my mind's eye." The other teacher mentioned that my collaboration in the development process was helpful, specifically for the technological expertise I brought to the process. Neither of these teachers had ever used a vinyl cutter before, so this confidence increase was very apparent in the qualitative data.

While “confidence in technology” increased for cycle two participants, confidence in using the technology with their students, in contrast, was not well reflected. This paralleled the quantitative findings from the surveys. With this qualitative data set, I again discovered the theme noticed in cycle one called, "give it a try." Both teachers felt that they were prepared to try this lesson with their students, however, the success of the technology in the lesson itself was not guaranteed. The distinction between confidence in using the technology and confidence in using the technology with students was much better described in the qualitative data than the quantitative data. When the teachers talked openly about their technology confidence and the reality of using the lesson with students, it became apparent that there was a distinction. Both reflected that they were confident in using the technology alone but were not confident in using it with students. One teacher, MT, stated that they worry about their students' lack of technology competence coming into this lesson- whether or not the students could use the computer programs needed for the design portion. "I'm not confident with my student's ability to use their software; I don't know how tech-savvy they are … I don't want to have to teach the tech end as well as the music end." The other teacher stated that they would try the lesson on a day when they would have extra time after class to troubleshoot anything that went wrong in the lesson. This reflected the theme from cycle one, in which one participant noted that the lesson will continue to improve the more they do it with their students and gain experience with the technology.

The cycle two teachers were likely to use their lesson plans with their students even if their confidence level in using the technology with their class was still low. KL planned on using the lesson plan as early as October, while MT planned to wait for their students until later in the year.

Regarding the fifth inquiry question, about the teachers' perception of the relevance, KL spoke very little about this, instead focusing on the novelty of the lesson. On the other hand, MT showed a significant increase in their perception of relevance and demonstrated this by brainstorming about different ideas they could do in their music classroom with the vinyl cutter tool. They even spoke about other content areas and the technology's relevance to those. They said, " I think this kind of technology can enhance anybody's curriculum, music, art, science … Once the kids have the basics, then their creativity will kick in, and that creativity will make all subjects more meaningful to them." Expanding their understanding of digital fabrication tools to enhance all student learning falls under the theme identified in cycle one of "expanded learning opportunities." One participant in each cycle commented on this theme.

Regarding student learning, both teachers in cycle two were enthusiastic about their classroom learning goals integrated into the lesson, and both were able to match standards to their lesson ideas. This was not the case in cycle one, where for both participants, the entire curriculum centered around technology, and so the other learning goals were inserted through our development process, with no standards alignment. With both participants in cycle two, the ideation meeting began with learning goals and integrated the technology to meet those learning goals. Compared to cycle one participants who focused on “the project, not the learning,” this was the complete opposite process.

In discussing those learning goals, however, a theme that emerged here was that using these technologies could be a novelty for the students and engage them more with their content learning goals through excitement. This theme of "student excitement" was well reflected in KL's post-interview, "Obviously, they're going to learn something from a different country, but the technology is just gonna be so different they're gonna be excited about it … this will be a more memorable project because of it." The theme of "student excitement" also resonated with the other teacher in cycle two, they reflected that this lesson plan would be so different than what they are used to doing in music class. In contrast, this theme did not come up at all in the data from cycle one participants.

4.2.4 Cycle Two Reflections

The second cycle of the research study took place during the beginning of the school year, and teachers were busy differently than in the previous cycle. Both participants in this cycle were subject area teachers, as described in the stakeholder analysis section, and they each had little to no prior experience with this technology. Even so, both teachers in this cycle plan on using the developed lesson plan with their students in the upcoming year. This positive data could be the result of a successful intervention in which both teachers realized the potential of this toolset. Possibly, however, there could be some selection bias in those teachers who chose to participate. In this cycle, the participating teachers each received a vinyl cutter tool for their classroom. This reward might have been a factor for these particular teachers choosing to participate in the study. Participants who completed the entire intervention cycle showed interest in the technology and a level of perceived relevance of the technology itself before starting, even if they did not have previous experience. Since I recruited these teachers from a small number who attended a workshop over the summer, the selection bias of the sample could have had affected results.

Though these teachers participated with an interest in the technology and the process itself, they both began with minimal technology experience. Unlike cycle one, there was a significant amount of time spent attending to the technological knowledge domain from the TPACK framework with this cycle. Of the time spent during the intervention, 50% and 60% (two to three hours) were spent learning how to use the technology with these participants. The increase in the confidence level of the technology itself is explained by the amount of time spent in the intervention's technology aspect.

A difference in the findings between cycle one and cycle two participants was the degree to which the final lesson plan was completed. Although cycle two participants reported that they spend time each week lesson planning while the cycle one teachers do not, their lesson plan templates were not finished to the same extent. Neither teacher worked on their lesson plan independently of the virtual lesson development sessions, and neither mentioned that they would work on them again after the intervention. The difference between the two cycles could be explained by the lack of a deadline in cycle two. For the first cycle, there was a final lesson-sharing session in which teachers presented their lesson to each other and received feedback. Without having a scheduled deadline and presentation, the cycle two teachers were not compelled to spend any extra time on their lesson plans.

An unexpected learning from cycle two of the study was the attention to the novelty of the technology itself. Though this novelty effect was researched in the review of supporting literature, I did not expect it to surface as a theme in the qualitative data the way that it did. This too could be a result of selection bias; however, it could also be a result of the inexperience of the teachers involved in the second cycle. “Student excitement” did not come up as a theme with the more experienced tech ed teachers from the first cycle. Both teachers in cycle two were elementary-level teachers, and the previous cycle included middle and high school teachers, so perhaps this result could reflect the age of students, with elementary students having more opportunities to be excited about new cool technologies. More likely, though, it was another effect of the different types of learning in the different classrooms, technology-centered learning versus content-centered learning. The elementary librarian and music teacher had never used digital fabrication tools with their students, and they both commented on the novelty this machine would bring to their classroom lessons.

5.0 Learning and Action

5.1 Virtual Development Sessions

The virtual nature of this intervention created some expected complications in conducting this study and some unexpected challenges. The predominant frustration was scheduling time with the teachers to complete all study-related tasks. Each participant spent between four and seven hours on this intervention and the accompanying data collection (surveys and interviews). This is a significant commitment considering that 85% of the virtual sessions were scheduled for evening and weekend hours. As difficult as it was to design one to one working sessions with teachers, group scheduling was almost impossible. Through group sessions were planned for the introduction and the lesson plan sharing, only cycle one teachers were able to meet simultaneously and only once. Much of my time was spent trying to assemble groups of participants, through email communications, group scheduling apps (Doodle), and even automatic scheduling apps (Calendly). An additional challenge I experienced was a high percentage of "no-shows" for previously scheduled meetings. Whether teachers forgot about the meetings or were overwhelmed, the rate of "no-shows" was about 25% of scheduled interactions. This complication was not just time-consuming from the research standpoint but ultimately exhausted potential participants, and the sample size suffered because of it.

Since the start of hybrid and virtual learning at the beginning of the pandemic, teachers have adapted to virtual teaching, learning, and meetings. This shift is a strain on teachers and anybody else using virtual communications at a high rate, and this strain leads to "Zoom fatigue," which could explain the difficulty in scheduling and even the no-show effect I experienced when scheduling teachers for virtual sessions (Bullock et al., 2022).

While teachers struggled to find four to seven hours to spend virtually on evenings and weekends, it might have been simpler to participate in an in-person, one-day intensive training session with all aspects of the intervention scheduled back to back. This one day could have included pre and post-surveys even further simplifying the pull on the teachers' schedules. This could have made the sample size bigger and created the professional learning community aspect, which might have benefitted participants.

5.2 TPACK Framework Revisited

In the review of supporting knowledge, the TPACK Framework resonated with me from my experience working with educators and technology. Seeing firsthand the disappointing effects of technology training without attention to pedagogy or content, this expanded understanding of teachers' knowledge domains explained the problem area along with a roadmap for improvement. Through the intervention procedure, I attempted to address all three areas of teacher knowledge: pedagogy in the introduction, technology in the technology training session, and content in the lesson development sessions.

Though all three areas were covered with the participants (apart from the technology training for the two tech ed teachers in cycle one), the data showed that the cross-section areas in the framework, specifically the "Technological Pedagogical" intersection (Koehler & Mishra, 2007), needed more attention. The TPACK framework stresses not only the three domains but the intersection of those domains. The participants' lack of growth in confidence in using this technology with the students demonstrates this gap in attention to the intersectionality of the framework.

Future iterations of this development series should include strategies to practice the "Technological Pedagogical" intersection of the framework. This could include developing best practices, sharing strategies for classroom management with the toolset, or even embedding practice by leading the lesson plan with others.

5.3 Considerations of Teacher Support in Technology Integration

The data collected to investigate the inquiry questions was also helpful in uncovering different concepts that challenge the intervention's initial design and lead to additional research.

5.3.1 Contributing Domains to the Problem Statement

The fishbone diagram in Appendix C includes contributing factors I originally established through empathy interviews, research, and professional experience. The contributing factor domains are: "time and space, technology knowledge, pedagogy and integration knowledge, standardized testing, and support network." While analyzing the data, a new contributing factor emerged: the concept of technological literacy, not for teachers but students. MT specifically considered this when they commented on their concern about teaching the students "the tech end as well as the music end." From this concern, I searched the transcripts from cycle one and found that concern was embedded for both participating teachers, though I did not pull out that theme at first.

Both tech ed teachers in cycle one mentioned the sequence of their lesson plan as important in their classroom, specifically what technology skills already covered with their classes going into the lesson. For instance, HS planned to insert their lesson into their curriculum after the students had already successfully learned the CAD and the 2D design programs from a previous lesson. Originally, I arranged those comments under the "technocentric student learning" theme, but after cycle two a more nuanced understanding emerged. The learning sequence for technological literacy is important in using these technologies to teach classroom content. That sequence, which could occur outside of the subject classroom, informs the question: what technology experience do the students have before coming to the content class? Working with students who are not literate in technologies coming into the lesson, subject area teachers are at a disadvantage in using digital fabrication because of this gap in preparedness. Whereas tech ed teachers can prepare their students throughout their entire curriculum (provided they have the "time and space"), the subject area teachers in the study did not have that same freedom. Pitkänen et al. (2019) describe this challenge of "scaffolding for student learning" in their research which explores teachers and Fab Lab facilitators working together to design makerspace activities. "Designing the activities considering students' prior knowledge, learning experiences, and skills in digital fabrication relates to feasibility" of the project (p. 8). My findings parallel this study, with a distinct need, from the teachers' perspectives, to provide grounding instruction or competencies with the technology before starting a lesson.

An update to the fishbone diagram for the problem area is in order, and I would add the contributing domain of "student preparedness" as a bone leading to the problem statement. The additional domain and its supporting factors are included in figure 7.

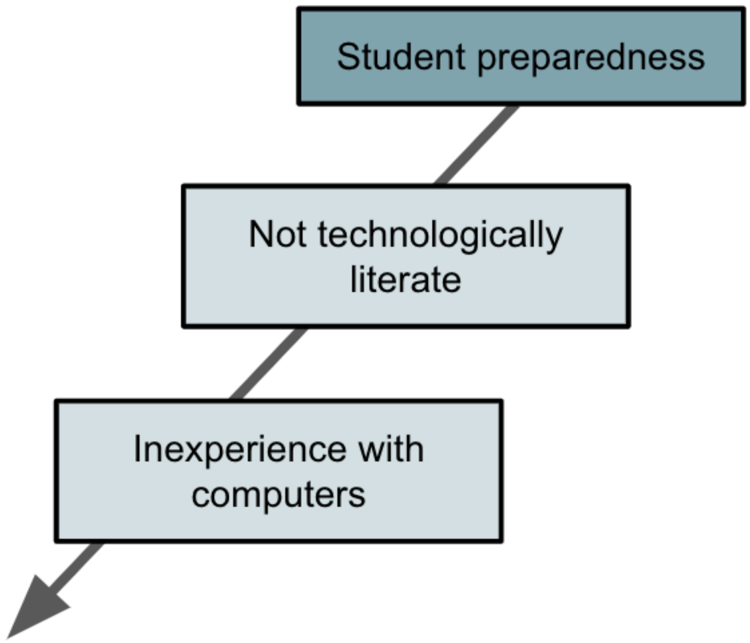

Figure 6. New Contributing Factor to the Fishbone Diagram

5.3.2 Embedded Practice

The change idea for this intervention, “work one to one with teachers to develop lesson plans in support of class curriculum,” appears in the driver diagram in Figure 4. This original change idea was based on an identified research theme of “classroom and embedded practice, " described in section 2.5.3. The assumption of lesson development as a daily teacher practice was challenged during this study with only half of the participants indicating that they use lesson plan development weekly in their jobs. Even for those that do practice lesson plan development, however, our work together virtually developing lesson plans did not seem to reflect the theme of embedded practice, as originally assumed. These sessions were a unique experience for all teachers, the tech ed teachers because they typically do not write out lesson plans, and the subject area teachers because of the novelty of working with another person in the process. Those teachers usually do lesson planning alone. So, the assumption that these virtual development sessions would support teacher technology integration by providing “embedded practice” was inaccurate.

An update to the procedure, which would include a deeper type of embedded practice, would be to add another element to the intervention: leading this lesson plan to others. “Modeling effective use of technology in teaching throughout the teacher education program is necessary, (Pamuk, 2011, p 435). This additional session would more authentically qualify as embedded practice and would help build teacher confidence in the Technological Pedagogical intersection of the TPACK framework as well. With practice leading this lesson at least once (even if not to students), I believe that teachers would report feeling more confident about using this technology with their students.

5.3.3 Professional Learning Community

The review of supporting knowledge suggested that developing a professional learning community (PLC) is helpful when teachers are integrating new technologies in the classroom. Though planned as an element in the procedure, the final session being a shared lesson plan presentation, I could not complete this step with both cycles. While teachers in cycle one responded positively to this session, learning from the interaction with the other teachers, cycle two participants did not have the same opportunity. I believe both sets of teachers would have benefited from this attention to a professional learning community.

However, a theme of the qualitative data analysis suggested that participants benefited from a type of professional learning community differently. All teachers commented on how helpful it was to have me there for the lesson development sessions. While I assumed that my participation would prove resourceful as an “expert” in the technology, the data shows that the benefit to this participation during the lesson development sessions was more strongly as a collaborator, with the two of us creating a small community of practice.

Future iterations of this development series would prioritize this PLC component. Perhaps including the embedded practice of leading a lesson to another teacher would help support the growth of a small PLC. Otherwise, prioritizing the lesson presentation session where all participants interact with each other would help or offering the one-day intensive through an in-person session.

5.4 Digital Makerspaces Through an Equity Lens

Though digital fabrication technologies are making their way into school-based makerspaces rapidly, only certain students benefit. There is no denying that affluent districts are leading in the makerspace race while lower socioeconomic school districts are lagging. “For schools that hope to create a makerspace, support for technology, upgrades, technicians, and supplies to initiate and then maintain their labs are contingent upon grant funding or administrative budgets, and can be inconsistent” (Garber et al., 2019, p.9).

In this small case study, for instance, three out of four participating teachers came from a self-described affluent district, while only one participant worked at a school at a lower socioeconomic level. This teacher, MT, was very excited about the technology and their lesson plan for the music classes in their elementary school; however, there are not any other technologies available at that school nor any staff, training, or support. The vinyl cutter they received to participate in this study was the first digital fabrication tool to enter that school. Paradoxically, two of the three other participating teachers had access to a full Fab Lab suite of tools and technologies at their schools, and the third teacher had access to many types of technologies (makerspace or otherwise) in their classroom, a library.

As demonstrated in Appendix C, the fishbone diagram that describes the problem of practice and contributing domains to that problem does not centralize the main factor of funding and how that disproportionately affects students of color. The only reference to this inequitable factor is "equipment is not available in the school," which is listed as a contributing factor under the domain "time and space." To explore this contributing factor through an equity lens, an entirely new fishbone diagram can be included solely to describe that single box. Though this study did not deeply explore this contributing factor, I feel it is an important component of any discussion of the problem area. "Teachers are not using digital fabrication technologies to support authentic student learning" is a problem area only for those schools and districts that have digital fabrication tools. That, unfortunately, does not always include the most underrepresented and underserved students.

5.5 Future Possibilities

Throughout this dissertation, I investigated how to better support teachers in integrating digital fabrication tools to support classroom content. After completing two cycles of this study with two sets of different teachers and analyzing the data collected, I found that the results predominantly supported the research themes identified in the review of supporting knowledge section 2.5. Specifically, reinforced themes are the attention to the TPACK intersections, the embedded practice components, and the professional learning community themes. Ideally, I would like to know what happens in these teachers' classrooms following this intervention. An extension of this work could include additional data collection after implementing the lesson plan. This additional data collection would answer the following inquiry questions.

In what ways did the teacher integrate the technology into the lesson plan?

What adaptations were made to improve the lesson plan?

In what ways was student learning affected by the lesson plan?

How likely is the teacher to modify additional lesson plans to integrate the technology?

An extension of this study would focus on the growth and adaptation of the lesson plan itself but, perhaps more relevant, could focus on student learning. Based on the learning goals teachers identified in the development lesson plan, how do students show this learning? A study of this sort has the potential to answer the research gap identified in the review of supporting knowledge section and could initiate findings on how this technology does support authentic student learning in formal K12 education.

5.6 Implications for K-12 Educational Systems

It is important to consider what implications such a small study has on schools and districts that are adding digital makerspaces into their buildings. Through my work with these four teachers, it became apparent that authentic technology integration cannot be left to the classroom teacher alone. The system of schooling must adapt to support classroom teachers using digital fabrication technologies so that all students can experience making.

5.6.1 Digital Making in all Classrooms

A relevant analogy to the development timeline of digital makerspaces in education is the journey of computers into formal classrooms. As Bull et al. (2010) stated, we can "anticipate a number of parallels between the advent of personal computing and the advent of personal fabrication" (p.5). When computers were first introduced into schools, they were installed in a computer lab where a computer teacher taught the students how to use this technology. Even Papert's Logo programming language, as foundational as it was to constructionism, began by engaging the students in technical content through programming (Papert, 1980). Today, though, computers are present in many classrooms and not confined to a computer lab anymore. Students learn with computers in history, math, art, and even foreign language classes. If digital fabrication technologies are following a parallel track, schools are currently in the "computer lab" phase in which the makerspace technologies are confined to one room where often students go to learn the technologies themselves. We need to prepare our teachers for the next step of the timeline, where the machines move into various classes and are used differently in education. 3D printers, vinyl cutters, and laser cutters are tools that can be used to teach any content.

This study was designed to investigate how teachers can integrate these tools into lessons that meet classroom learning objectives. For the participating teachers, these included technological learning objectives, music concepts, and library lessons. Even though I had only a small sample of teachers, I posit that every classroom can benefit from digital making integration in respect to subject area content. With proper attention to the root causes on the fishbone diagram: student preparedness, time and space, TPACK knowledge domains, support networks, and standardized curriculum, every teacher should be able to use these technologies to reach their students with a hands-on approach to the content.

5.6.2 Implications for Administrators

Each teacher in the study benefitted from co-developing a lesson plan that activates student learning with digital fabrication tools. This intervention especially affected the two subject area teachers with no previous technology training, as they both appreciated the technical expertise I provided in the process. How can this process be scaled and maintained for wider effect within a school or district?

The role I played in this intervention is an important one and needs attention when schools and administrators develop plans for sustainable makerspace integration. With respect to computers and software, many schools now have a technology integration specialist or a similar role. This person helps maintain school computers and, to various degrees, assists teachers with software training and lesson integration. Similarly, this role is especially vital to support subject area teachers using these digital makerspaces and tools in their own classes. While some schools hire makerspace managers and some schools give that responsibility to a teacher, many administrators ignore this role completely. The findings from this study indicate that administrators should focus efforts on supporting teachers with a makerspace integration specialist role: this person can manage the equipment as well as work with teachers to develop classroom lessons that integrate makerspace technologies into their subject areas.

5.6.3 Implications for Policy Makers

In consideration of the "student preparedness" root cause which I uncovered through this study, policy makers should contemplate broad technical learning sequences for students across their districts. As school districts or even state educational agencies invest in makerspace technologies and makerspace integration specialists, student preparedness also needs investment. School boards can develop technological learning benchmarks from kindergarten through high school that build skills and competencies in students over time.

This same process is already in place for reading development; students move through grades with an expected reading ability level. A biology teacher in 9th grade can expect their students to read at a certain level and thus they can develop their lessons without having to teach this skill. The same could be true for technical competencies. With a broad technical leaning sequence in place across all buildings in the school district, that biology teacher should be able to develop lessons with makerspace technologies without having to teach basic competencies like downloading files or navigating with a mouse. When a student reaches the ninth grade, all subject area teachers should have an understanding of their students' technological competence so that they can design appropriate lessons for the subject without taking time away from the class to level the students' technical knowledge.

The music teacher in cycle two summarized it best when they said, "I don't want to have to teach the tech end as well as the music end." If the tech end is already embedded into a district-wide learning trajectory, subject area teachers can focus the learning on content while using these technologies to excite and engage all students.

Appendix A Empathy Interview Transcripts

In developing an understanding of the problem of practice, I conducted sixteen empathy interviews with teachers in the SCOPES-DF network, and from there, I narrowed down the types of teachers and transcribed the four most relevant respondents. Of the original sixteen interviewees, eleven were from the US, and from those, only seven were based out of a digital fabrication makerspace based within a school. From these seven US school-based teachers, I concentrated on the high school teachers, and I divided them into two categories. These categories emerged during all the interviews, as I noticed a pattern in the types of teachers that I interviewed.

Appendix A.1 Lab Teachers

The first category I will call lab teachers, and these are the teachers that use the makerspace daily as a classroom. These teachers tend to teach technology-based courses like "Engineering" or "Fab Lab" which are electives, and all of their students' opt-in to these classes. These lab teachers are also sometimes expected to manage the space, fix mechanical problems, and work with other teachers who want to use the space.

Appendix A.1.1 Lab Teacher Transcripts (partial)

Question: How did you learn about the technology in your makerspace? What was your training like?

LT1: It wasn't anything, um, specialized. Like, I didn't have a big training when I started here, but I knew about 3D printing before we even got one here because I used one before at my old school. When we got them here the dealer, Stratsys, came in and showed us how it worked. They also left some paperwork, like operating manuals which we lost. I don't know, I usually look it up on the internet if I need to learn anything or how to do something, I'll watch a YouTube video. The hardest thing to learn is the software, since we are an Autodesk school, we had like a two day training on Fusion 360 about three years ago. That wasn't that helpful for me because I already knew how to use it, but it helped [the other two tech teachers] quite a lot.

LT2: My principal gives me my in-service days if I don't have to participate in the group trainings with all of the other teachers. I get time to set-up the equipment and learn as I do or fix the machines too. We don't have IT support for the equipment so I am the one keeping everything running. I didn't have any formal training on anything but I do have a lot of computer experience, so the software side of things is easy for me. I end up looking things up if I can't figure it out myself. I wouldn't say that I have every had any formal training on the equipment in the space, but it's not that hard to figure it out.

Appendix A.2 Content Area Teachers

The second category that emerged is the content teachers. These teachers have a designated subject area like English, Music, or Biology, and they do not use the makerspace room daily. These teachers have courses that are mandated, students do not self select into them. Also, the content teachers sometimes have one or two pieces of digital fabrication equipment in their classrooms, but they must work with the lab teachers if they are to use the makerspace as a classroom.

Appendix A.2.1 Content Area Teachers Transcripts (partial)

Question: Have you had any training on how to use the digital fabrication tools in your makerspace or your classroom?

CT1: I got a grant to buy my 3D printer and it came with a professional development training. It was 2 days long, and we all got to keep the 3D printer at the end. So, yes I had training on how to use it.

CT2: For one PD session we got to pick a breakout, and I went to the Fab Lab, so I got to make a, uh, it was a sticker on the vinyl cutter. It was fun, but the workshop was only like 50 minutes long, so I don't know if I learned anything. I did get excited about it, though, and it got me interested. But I never had any follow up training and I've never even used the laser cutter or the 3D printer.

Question: Tell me about a time you used one of these tools with your class.

CT1: I printed heart-shaped cookie cutters for my biology class. They were really cool, the kids frosted the cookies with the patterns, and they loved it. It took me awhile to get a good print, but I didn't design the cookie cutter myself. I downloaded it from the internet and it took about three tries to get a good print. I ended up printing like 5 of them so the kids could share. It was fun.

CT2: I haven't really. Like, I've had some ideas, especially with making a wall graph with the sticky vinyl. I saw a lesson online that was really cute. But, I don't have the time to figure it out. And, really, the lab is so far away from my classroom, it is a five minute walk to get there, so already you're missing ten minutes of class just to get there and back before the bell rings.

Appendix B Stakeholder Power/Interest Grid

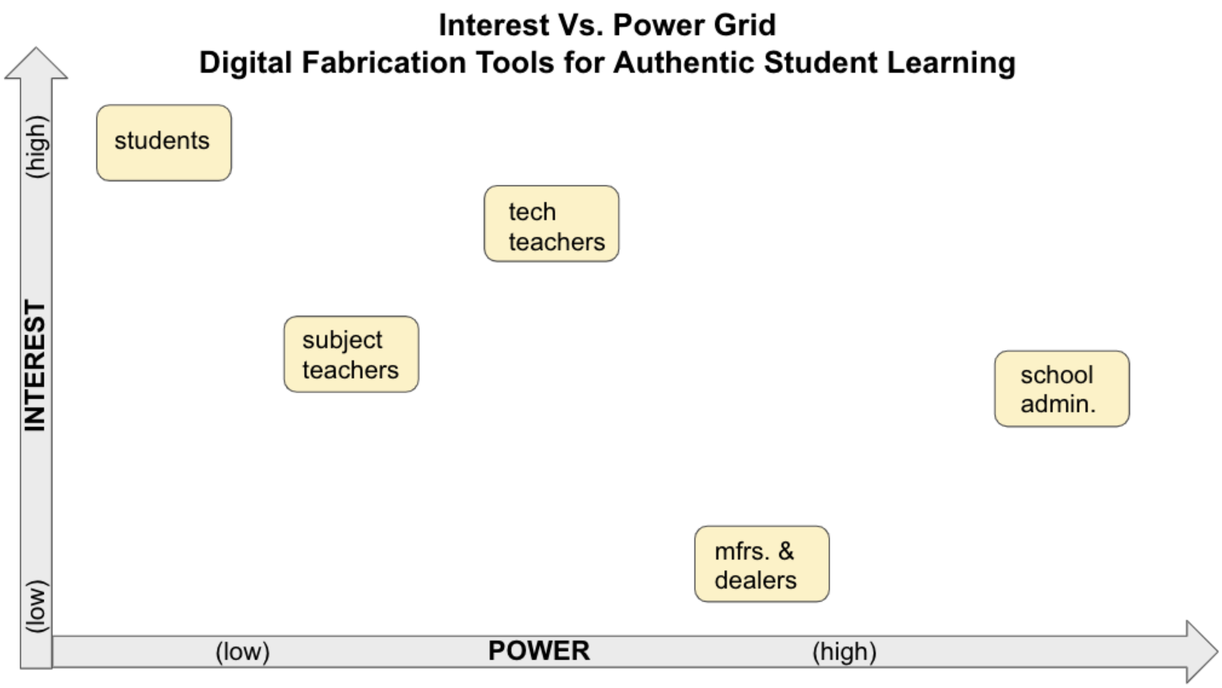

Figure 7. Stakeholder Power/Interest Grid

Appendix C Fishbone Diagram

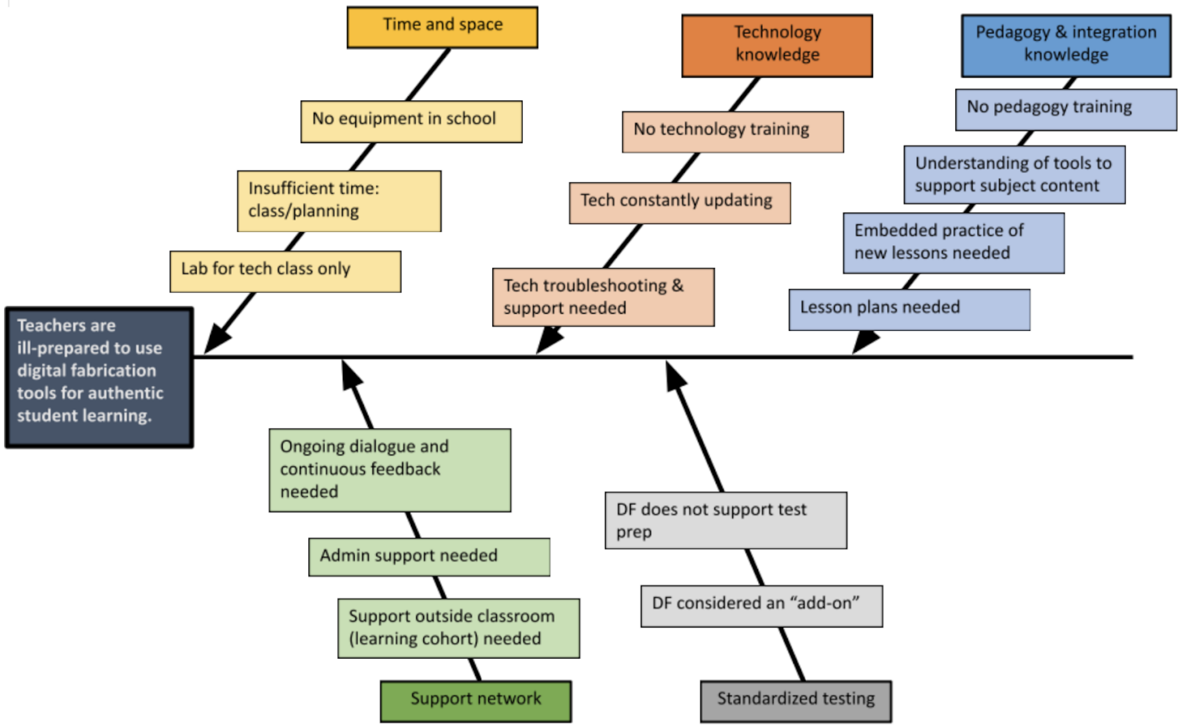

Figure 8. Fishbone Diagram

Appendix D SCOPES-DF Lesson Plan Template

Lesson Plan Builder Template

Use this template to organize all of your resources and prepare your lesson to upload onto the SCOPES-DF lesson sharing website.

Lesson Plan Title

Please provide a brief title that clearly communicates what your lesson is about.

Banner Image

Upload an image that will appear at the top of your lesson. The ideal dimensions for this image are 1024 x 200px. Images outside those dimensions will be automatically cropped to fit.

Featured Image

This image will be shown in previews of your lesson throughout the SCOPES-DF website. It does not otherwise appear on your lesson page.

Lesson Summary

Please provide a summary of the lesson here and any pre-lesson activities or content that would help a teacher planning to integrate this lesson into their curriculum. You can include links and images to be more descriptive.

Additional Contributor

Select an additional contributor to this lesson. They must have a SCOPES-DF profile to be included in the dropdown.

Subject Areas

Select one or more Subject Areas that apply to your lesson. These appear in the Lesson Details box on your lesson page and are also used to find your lesson when searching the SCOPES-DF site.

ArchitectureArtsComputer ProgrammingELAEngineeringHistory Mathematics

Multi-Cultural LearningScienceTechnologyTheatreUnplugged

Age Ranges

Select one or two age ranges for the lesson.

5-8, 8-11, 11-14, 14-18, 18+All ages

Fab Tools

Select one or more Fab Tools that are used in your lesson. These appear in the Lesson Details box on your lesson page and are also used to find your lesson when searching the SCOPES-DF site.

Topic Tags

Select one or more Topic Tags that apply to your lesson. These should be different than Fab Tools. and will appear in the Lesson Details box on your lesson page. If you don't see any tags that apply, leave blank or use the "Add New Choice" option.

Curriculum Standards

Select one or more Curriculum Standards that apply to your lesson. These appear in the Lesson Details box on your lesson page and are also used to find your lesson when searching the SCOPES-DF site.

What You'll Need

This section is very important for teachers prepping for the lesson so be as detailed as possible. Please include a list of all the materials necessary to complete your lesson with links if necessary. If there is a worksheet or file download, include it later in the File Attachments section.

Learning Outcomes

List the learning objectives that students will complete by the end of this lesson. These can be in the content area, technical learning objectives, SEL, or any other learnings that are supported by participating in the lesson.

Step 1, Title

Provide a brief sentence or title for this step. (Once all fields are complete you can add more steps one at a time.)

Step 1, Brief Description

This is an overview of the step and appears on the left-hand side of the lesson next to the more detailed instructions. Be succinct and descriptive in these 3-4 sentences.

Step 1, Instructions

Please provide thorough and detailed instructions for this step of the lesson. Use the text editor to create clarity through the use of numbered lists, bullet points, bold, italics, and underline. Include images, screenshots, and links to outside sources where applicable. The more detail, the better for instructors to utilize your lesson with students.

Add a Step

You can add as many steps as needed, one at a time. Note, you cannot go back and insert an additional step before current steps, so plan ahead for your step order.

Appendix E Survey Questions

Appendix E.1 Pre-Survey Questions

(demographics and screening questions are removed)

1. What grades do you teach?

2. What subject area(s) do you teach?

3. Which of these technologies are available at your school?
   - 3D printer
   - Vinyl cutter
   - Laser cutter
   - None of these technologies
   - I do not know.

4. What level of training have you had for the following technologies?

	none	limited	extensive
3D printer			
Vinyl cutter			
Laser cutter			

5. How comfortable are you with these technologies?

	Extremely uncomfortable	uncomfortable	neutral	comfortable	Extremely comfortable
3D printer					
Vinyl cutter					

Laser cutter					

6. Have you ever used these technologies with your students?

no	none	yes	Don't know
3D printer			
Vinyl cutter			
Laser cutter			

7. How many lessons do you teach that use these technologies per week?

	0	1	2	3 or more
3D printer				
Vinyl cutter				
Laser cutter				

8. How prepared are you to use these technologies with your students?

	Not at all	prepared	Very prepared
3D printer			
Vinyl cutter			
Laser cutter			

9. Please indicate your agreement with the following statements.

	disagree	agree	unsure
I know how to integrate a 3D printer into my lesson plans.			
I know how to integrate a vinyl cutter into my lesson plans.			

I know how to integrate a laser cutter into my lesson plans.			

10. Please describe any barriers you face in using these technologies with your students.

11. Do you think that these technologies (3D printer, vinyl cutter, laser cutter) are relevant to your students' learning? Please describe your answer.

Appendix E.2 Post-Survey Questions

1. Which of the following technologies is incorporated into your lesson plan that you developed during this study?
   - 3D printer
   - Vinyl cutter
   - Laser cutter

2. What are 2-3 things do you hope your students will learn through this lesson plan?

3. How likely are you to implement this lesson plan with your students in the upcoming school year?
   - Definitely will use
   - Likely to use
   - NOT likely to use
   - Definitely will NOT use
   - unsure

4. Did this lesson plan development process change your view of the above technology in classroom use?

5. Please describe how your view of the above technology changed during this lesson plan development.

6. How prepared are you to use these technologies with your students?

	Not at all	prepared	Very prepared
3D printer			

Vinyl cutter			
Laser cutter			

7. Please indicate your agreement with the following statements.

	disagree	agree	unsure
I know how to integrate a 3D printer into my lesson plans.			
I know how to integrate a vinyl cutter into my lesson plans.			
I know how to integrate a laser cutter into my lesson plans.			

8. Did this lesson plan development process help you think of new ways to use the technology in your classroom?

- Yes
- No
- unsure

9. How helpful were the following elements in helping you think of new ways to use the technology with your students?

	Not helpful	neutral	helpful
one to one lesson development meeting(s) with the researcher.			
The lesson plan template itself			
Hearing other teachers share their lessons.			

10. How comfortable are you with these technologies?

	Extremely uncomfortable	uncomfortable	neutral	comfortable	Extremely comfortable
3D printer					
Vinyl cutter					
Laser cutter					

Appendix F Semi-Structured Interview Questions

What are the personal goals of your lesson plan and were they met?

Are you planning on using this lesson plan with your students? Why or why not?

What are the learning outcomes you hope for your students using this lesson?

How comfortable are you with doing this lesson?

What was most helpful in lesson plan development and why?

What improvements could be made to the one to one lesson plan development sessions?

What are the differences in this process with how you usually develop lesson plans?

If we had the time would you want to learn more about the technology or learn how to use it with the kids?

How did developing this lesson plan change your perception of your chosen technology to facilitate learning in your classroom?

In what ways does the technology enhance your classroom learning goals?

What are your biggest learning outcomes personally from this intervention?

Appendix G MS Completed Lesson Plan sample

Lesson Plan Title

The Lost Art of Creativity - A Sketch Journal Project

Banner Image

Featured Image

Lesson Summary

During the four quarters of the school year I have a different group of 6th Graders each time. By the time the quarter has ended each student in the class will have created 3 - 4 different designs for 3D Printing. This Sketch Journal Project will be the initial lesson of the quarter where students create a unique design for their sketch journal based on their own ideas surrounding the concept of creativity. They will sketch out their cover art idea, and then using a scanner, a Cricut, and the Cricut Design Space software, the students will print out a vinyl image to affix to their Sketch Journal.

Additional Contributor

(Select an additional contributor to this lesson. They must have a SCOPES-DF profile to be included in the dropdown.)

Elizabeth Whitewolf

Subject Areas

(Select one or more Subject Areas that apply to your lesson. These appear in the Lesson Details box on your lesson page, and are also used to find your lesson when searching the SCOPES-DF site.)

Architecture<u>Arts</u>Computer ProgrammingELA<u>Engineering</u>History Mathematics

Multi-Cultural LearningScience<u>Technology</u>Theatre<u>Unplugged</u>

Age Ranges

(Select one or two age ranges for the lesson.)

<u>11-14</u>

Fab Tools

(Select one or more Fab Tools that are used in your lesson. These appear in the Lesson Details box on your lesson page, and are also used to find your lesson when searching the SCOPES-DF site.)

<u>Cricut Maker</u>

<u>Scanner</u>

Topic Tags

Select one or more Topic Tags that apply to your lesson. These should be different than Fab Tools. and will appear in the Lesson Details box on your lesson page. If you don't see any tags that apply, leave blank or use the "Add New Choice" option.

#Creativity#Cricut #Design#Expression

Curriculum Standards

ISTE Student Standards:

1.4a - Students know and use a deliberate design process for generating ideas, testing theories, creating innovative artifacts or solving authentic problems.

1.4b - Students select and use digital tools to plan and manage a design process that considers design constraints and calculated risks.

1.6c - Students communicate complex ideas clearly and effectively by creating or using a variety of digital objects such as visualizations, models or simulations.

What You'll Need

The teacher will need access to a Cricut Maker, access to a computer with the Cricut Design Space software, a piece of vinyl for each student, and a tool for weeding…a variety of objects can be used here if there is nothing specific accompanying the Cricut Machine. An Exacto knife is just one example of a tool that works well.

Each student will need a marble composition notebook, and, of course, their personal creativity

(Links are provided in case purchases are going to be made)

Learning Outcomes

Students will be familiar with the Cricut Design Space software platform

Students will be familiar with the correct orientation for loading vinyl onto the Cricut Maker

Students will be familiar with the concept of mirroring images to reach a desired print result

Students will be comfortable and able to “weed” excess vinyl

Students will be able to articulate their images and explain their conceptual relationships to the idea of creativity

Step 1, Teacher-Student Discussion

Teacher will facilitate a discussion with the students about their thoughts on where creativity comes from

Step 1, Brief Description of Teacher-Student Discussion

The purpose of this discussion is to hear from the students about their perceptions on where creativity comes from. The teacher will ask open-ended questions so as not to influence the students on their perceptions.

Step 1, Instructions for Teacher-Student Discussion

The teacher will ask the students “Before watching the video, where do you think creativity comes from?” The teacher will provide wait time and facilitate a discussion through listening and adding follow-up questions as needed

Step 2, Introduction to Creativity Video

Teacher will open this YouTube link ahead of time to be prepared for showing the

Step 2, Brief Description of Introduction to Creativity Video

This video is meant to teach students that there are multiple areas of the brain related to creative thinking. With that said, students will hear about situations where parts of the brain were damaged, yet individuals still managed to show their creativity in their work. The purpose behind this activity is for the students to understand that creativity can be taught, and therefore learned!

Step 2, Instructions for Introduction to Creativity Video

Students will enter the classroom and be seated. The teacher will explain to the students they will be watching a roughly five-minute video on the concept of creativity. They should be instructed to keep their phones away and their computers closed.

Step 3, Teacher-Student Discussion Post Video

Teacher will facilitate a discussion with the students about their thoughts on the video

Step 3, Brief Description of Teacher-Student Discussion Post Video

The purpose of this discussion is to hear from the students about their perceptions on where creativity comes from. The teacher will ask open-ended questions so as not to influence the students on their perceptions.

Step 3, Instructions for Teacher-Student Discussion Post Video

The teacher will ask the students "So after hearing the video, where do you think creativity comes from?" "Did your perception of creativity change following the video? Why or why not?" The teacher will provide wait time and facilitate a discussion through listening and adding follow-up questions as needed

Step 4, Explanation of the Journal

Students will all be given a journal with grid lines on each page for assistance with precise and accurate drawings

Step 4, Brief Description of the Journal

This is a journal that will be used for initial sketches of 3D print designs. The purpose for the journal is to be able to get thoughts from the students' heads onto paper, before then using online software capable of producing their desired results for their 3D designs

Step 4, Instructions for Journaling

Students will be instructed to date every entry to keep a record of their thought progression while develiping their 3D designs, given different constraints for each give assignment. In this lesson the students will sketch out a design that exemplifies creativity to them. They are allowed to make multiple designs before finalizing their option for their vinyl print.

Step 5, Scanning of the Student's Drawings

Students will all be given scissors to neatly cut out their finalized design for their notebook cover.

Step 5, Brief Description of the Scanning Process

Students will learn how to load the scanner in the correct direction and ensure that the scan is saved and named appropriately.

Step 5, Instructions for the Scanning Process

Students will be place their paper drawing side up into the scanner and listen for the scanner to initially pull the paper for scanning purposes. Once the sound is heard, students will press the Scan button, and ensure that the paper goes throught straight to avoid any distortion of images and/or text present in the design. Students will then save the scans directly to the computer desktop since their is a designated computer with the Cricut Maker.

Step 6, Printing of the Student's Scanned Drawings

Students will all be given a tutorial on how to use the Cricut Design Space software

Step 6, Brief Description of the Printing Process

Students will learn how to upload an image into the software, remove any unwanted background from their uploaded image, mirror the image to ensure desired directioning of the image, selecting the given material to use with the Cricut Maker, and finally loading/unloading the material into and out of the Cricut Maker.

Step 6, Instructions for the Printing Process

Students will be given access to the teacher account for Cricut Design Space. Students will click the + symbol to start a new project. Students will then select Upload to import their scanned image. Once students find their image on the Desktop they will select Upload. From there the student will go back to the Canvas and click on Images to select their design and then select Add to Canvas. Students will determine the correct sizing for their project to ensure it fits on the cover of their notebook. Once sizing is confirmed, students will click Make It in the top right corner. Students will toggle on the Mirror option. Students will then click Continue, select Vinyl as the Material, and then load the Mat into to Cricut Maker. When students unload the mat it will be ready for "weeding" and then affixing to their notebook cover!

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