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Uncertain Matters: Material to Form Curricula for Digital Design and Fabrication

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ABSTRACT

We review the development of a mobile makerspace platform focused on digital fabrication in particular additive manufacturing (AM) or what is more commonly referred to as 3D printing. We engage in a reflexive analysis of our curriculum development as a part of the iterative process of this design-based research project. We review the component parts of our Material to Form curriculum, reflecting on the events of the makerspace platform as they symbiotically informed and catalyzed the iterative development of the curricular component. Our analysis is focused on thematic curricular ideas stemming from the uncertain material and disciplinary possibilities of digital fabrication. Our reflexive method draws from our own identity as arts education researchers working within STEAM frameworks to analyze researcher-participant knowledge of the mobile makerspace events. We also draw upon a mixed method dataset that offers insight into participant engagement to better understand iterative development of curriculum. In our analysis of this curriculum development, we highlight both implications for engaging interdisciplinarity and connecting across disciplines through culturally responsive teaching. The outcome is a unit of curriculum for using digital fabrication in classrooms that offers theoretical and practical considerations concerning design thinking and digital fabrication for STEAM practitioners.

Keywords: STEAM, making, makerspace, digital fabrication, kinaesthetic learning

INTRODUCTION

Digital design and fabrication create opportunities for new material expression and design innovation for artists and engineers alike. Combining the excitement from the maker movement and the novel creation of deployable makerspaces, we review the development of the Mobile Atelier for Kinaesthetic Education (MAKE) 3D and the Material to Form curriculum resource[1]. MAKE 3D is a mobile makerspace platform that can be deployed anywhere there is electricity to create a curricular spectacle of digital fabrication, in particular additive manufacturing (AM) or what is more commonly referred to as 3D printing. Curricular spectacle is any pedagogical approach involving activities, resources, and instruction common to curricular endeavors that maximizes visibility through highly innovative approaches and nuanced presentations of content (Sinha et al., 2020). Our interdisciplinary design-based research project combines this notion of curricular spectacle and a mobile makerspace platform to develop

[1] The Material to Form curricular resource can be downloaded for free at https://sites.psu.edu/mobilemakerspace/make-with-us/

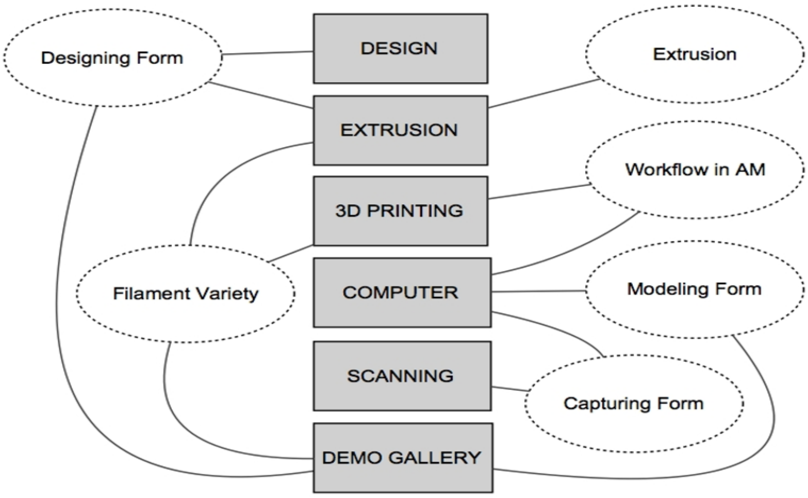

Figure 1. A diagram that connects the physical mobile stations that were housed in the MAKE 3D trailer (gray boxes) and the curriculum modules that utilized the activities at these stations (dotted line ovals)

strategies for how to meet the novice user almost anywhere and entice them into a series of hands-on activities providing a range of knowledge and aptitude for additive techniques in digital fabrication.

In the following, we engage in a reflexive analysis of our curriculum development as a part of the iterative process of this design-based research project (Barab and Squire, 2004; Design Based Research Collective, 2003). We review the component parts of our Material to Form curriculum exploring thematic connections between the maker movement, art education and arts-integrated approaches to curriculum such as science, technology, engineering, art, and math (STEAM) initiatives. Our review includes reflecting on the events of the MAKE 3D platform as they symbiotically informed and catalyzed the iterative development of the curricular component. The purpose of our analysis is to share and discuss the development of a free online instructional resource developed as part of a research study involving a mobile makerspace that introduces digital design and fabrication for interdisciplinary contexts of learning. Our analysis is focused on thematic curricular ideas that came from iteration and an exploration of the uncertain material and disciplinary possibilities of digital fabrication. Our reflexive method draws from our own identity as arts education researchers working within STEAM frameworks to analyze researcher-participant knowledge of the MAKE 3D events. We also draw upon a mixed method dataset that offers insight into participant engagement to better understand iterative development of curriculum. The outcome is a unit of curriculum for using digital fabrication in classrooms that offers theoretical and practical considerations concerning design thinking and digital fabrication to meaningfully inform an interdisciplinary teaching resource designed for STEAM practitioners.

Overview of the MAKE3D Project and Material to Form Curriculum

As a part of our funded research (NSF award #1623494), the research team of MAKE 3D developed a deployable makerspace exploring interdisciplinary making with a particular emphasis on 3D printing technologies. The focus on additive forms of digital fabrication, specifically 3D printing that uses fuse deposition modeling, came about due to its centrality within the research interests of the core research faculty involved in the project. Three core faculty comprised the research team including: Aaron D. Knochel, the principal investigator, an Associate Professor of Art Education whose research included a focus on makerspaces, informal learning, and digital fabrication; Tom Lauerman an Assistant Professor in the School of Visual Arts in sculpture and ceramics whose work in digital fabrication includes designing his own paste extrusion 3D printer that uses clay; and Nicolas Meisel, an Assistant Professor of Engineering in the School of Engineering Design, Technology and Professional Programs with a focus on engineering design and additive manufacturing. The team shared an interdisciplinary approach to design thinking and material science that inspired a curricular approach incorporating a comprehensive spectrum of concepts that we call the Material to Form curriculum. The Material to Form curriculum is structured in six modules. Initially these modules were organized in the following: Designing Form, Modeling Form, Capturing Form, Extrusion, Workflow in Additive Manufacturing (AM), and Filament Variety. The Material to Form curriculum and the MAKE 3D stations were co-constructed symbiotically to maximize informal learning in a deployable makerspace platform (**Figure 1**).

The essence of a mobile makerspace lies in its nature of being accessible, both physically and intellectually (Moorefield-Lang, 2015). The entirety of the deployable MAKE 3D platform is contained within a trailer and different equipment, consumables, and support systems necessary to operate the makerspace were custom designed for mobile deployment. When the MAKE 3D trailer arrives at the desired location, all contents can be

Figure 2. An example of the flexibility of the mobile makerspace installation. We were able to set up in this courtyard using an electrical outlet on a streetlamp post

deployed in a flexible configuration allowing the learning space to cater to the needs of the students and environment (**Figure 2**).

The curriculum for MAKE 3D was developed with the intention of introducing 3D printing in a makerspace platform to evaluate informal learning events. The curriculum was originally conceived as a project with a clear start-to-finish trajectory. However, given the nature of the makerspace as an informal learning space for voluntary learners and the project's mobile platform, it became apparent that the materials and curriculum would need to be accessible from multiple entry points allowing a range of durations of engagement. As such, each learning module required flexibility to address varying expertise, learning styles, time constraints, and levels of interest. Throughout the development of the MAKE 3D project, the Material to Form curriculum has gone through multiple iterations informed by ongoing pilot studies and changing membership within the research team (Jordan et al., 2020; Sinha et al., 2017).

The structure of the curriculum utilizes a backward design approach inspired by the Understanding by Design (UbD) framework (Wiggins and McTighe, 2011). UbD approaches the curricular process first by identifying desired results, that then determine assessment evidence, leading to planning the learning experiences and instruction. Each Material to Form module is organized around this framework by providing module goals, essential questions, and meaning and acquisition statements of learning objectives; followed by formative and summative assessment standards that are based upon the National Core Arts Standards (National Core Arts Standards State Education Agency Directors of Arts Education, 2014); and then a suggested learning activity which includes a material list, key terms, and proposed project. Modules also include additional teaching resources providing case studies and instructional resources in the form of hand-outs and graphic organizers that can be used to assist in guided instruction. Case studies focus on a particular artist or group, offer examples of their work, provide a project description, reflection questions, and references that lead to further resources. As a design-based research project, the research team focused contextual and formative analyses to iterate both the MAKE 3D platform and the Material to Form curriculum throughout the project duration. These modules and the MAKE 3D events that influenced their development will be discussed in more detail in the following.

Designing form

Designing Form focuses on creative prototyping based on the process of design thinking (Doorley et al., 2018; IDEO, 2012). The conceptual foundation for this module is based on the understanding that design is an iterative process, which is cyclical and manifests through multiple modalities of problem posing and solving. Although there are many manifestations of design thinking stages and it has encountered various critiques as a potentially meaningless umbrella term or management fad (Micheli et al., 2019), we focus on its iterative nature and cyclical orientation organized around stages generally identified as: empathize, define, ideate, prototype, test, and implement.

To support participant engagement within this station, nontechnical materials such as cardboard, scissors, and tape are provided for the prototyping process. Printed support materials that indicate the stages of design thinking are also on offer. Facilitating the Designing Form station in MAKE 3D events, it was clear that student engagement was uneven. Due to the open-ended nature of the station, there was little to engage students within a set of challenges or parameters that often motivate problem posing within design thinking initial stages of empathize, define, and ideate. Instead, the station became an entry way to engage with materials through forms of sculptural doodling: a playful practice of manipulating 3D materials without defined purpose that takes on emergent intention. Students would utilize this space to socialize and become more comfortable within the makerspace. After some time, this may or may not have led to experimentation with other stations. The low technical barriers also may have influenced why students chose to start or remain at the Designing Form station.

The written curriculum reflects our experiences with the Designing Form station within MAKE 3D events in that essential questions and the activity are focused on iterative design processes, understanding stages within the design thinking framework, and finding problems through play, free association, and personal interest. The two case studies also reflect some of these foci, but in reviewing all case studies one could easily rearrange certain cases as they exemplify multiple concepts within the curriculum. The first case, Rebecca Strzelec is an artist, designer, and educator whose practice includes the creation of wearable art objects created using computer-aided design (CAD) programs and 3D printing. Rebecca's work combines utilitarian, political, and whimsical themes exemplifying how everyday life can impact product design in unexpected ways. The second case, artist Jonathan Keep works in synthesizing traditional techniques in ceramics with digital fabrication processes. Keep's works are often inspired by patterns and forms from the environment such as icebergs or petrified wood, and his practice reflects upon the aesthetics of the natural world while simultaneously experimenting with process and materiality (Han, 2014). His iterative form creation utilizing parametric design and 3D printing in clay highlights the cyclical nature of design thinking and prototyping processes and is key to why he is included in the Designing Form module.

Modeling form

This module focuses on CAD 3D modeling, available through programs such as Fusion 360 (https://www.autodesk.com/), Tinkercad (https://www.tinkercad.com/), and SketchUp (http://www.sketchup.com/), as an important part of digital fabrication. Understanding and utilizing software resources are often the most intensive aspects of learning to use digital fabrication tools. Like graphic design and 2D printing, the printing process requires an understanding of the basics of the printer and materials that allow it to function, but ultimately it is the use of software to create that differentiates the outcome. Understanding the basics of 3D printing file types and material properties are important, but the ability for software to push the modeling process into formations that are impossible to achieve through handwork are what drives design innovation in this space. An extreme example of this is the innovation taking place in automation and prototyping where artificial intelligence and generative 3D modeling are pushing boundaries of CAD to maximize parametric design possibilities and increase predictive capabilities.

The MAKE 3D platform was always a project space that focused on the novice, introducing additive processes such as 3D printing through short, accessible, high-impact engagements. We knew from the beginning that our mobile platform and emphasis on curricular spectacle would be best applied to opening learners' interests in these technologies and our emphasis was on giving them enough exposure to entice their further exploration. For these reasons, Tinkercad was ultimately chosen for the makerspace because it is free to the public and can be learned quickly. Modeling Form relied heavily on the computer station that was in the MAKE 3D platform, which hosted six desktop computers and several small posters that prompted learners to get started in Tinkercad. Research assistants were also stationed nearby as there was constant need to monitor internet connections and answer questions. The Modeling Form module was setup along with the Workflow module as a grouped station since both required a computer for modeling activities.

The written curriculum extended the in-person events by not only focusing on modes of CAD, but also by providing information and processes that introduced modes of remix into learners' modeling repertoire. In this module, students explore using Tinkercad to both build new digital forms and to employ strategies of remixing pre-existing digital models to create new objects. The role of remix was never a part of the conversation or support material developed for MAKE 3D events, but it became clear that learners were familiar with navigating creative communities online where sharing projects and modifying other users' works is the norm: examples include code blocks in Scratch, fan art in DeviantArt, and 3D models in Thingiverse. Therefore, the curriculum extends focus of CAD modeling to also learn how appropriation and remix as creative strategies can play a part in 3D modeling. The first case study in this module focuses on artist Matthew Plummer-Fernandez's "artbot," developed in collaboration with Julien Deswoef, called Shiv Integer (Hern, 2016). Shiv lnteger randomly selects objects licensed for remixing on Thingiverse before assembling them into dysfunctional sculptures and uploading them once more onto the Internet as new designs (Newitz, 2016). The second case study focuses on developments in parametric design presenting researchers Eduardo Castro e Costa and Jose Duarte's project in mass customization of ceramic tableware using the program Grasshopper (Castro e Costa and Duarte, 2013). The objective of their project is to grant potential designers, businesses, and customers the opportunity to design and model custom products according to their practical needs and personal preferences.

Capturing form

Like Modeling Form, the scanning equipment provided in the Capturing Form module offers participants the opportunity to develop 3D models but using a very different approach through digital scanning. Initially, the MAKE 3D platform employed two 3D scanning set ups: An Occipital Structure Sensor mounted on a mini iPad and a Microsoft Kinect with Skanect software. Over the course of the events, the Occipital Structure Sensor proved to be more user friendly and intuitive for learners in the space. The hands-on engagement introduced participants to 3D scanning, but what was most exciting about the station was the high level of peer-to-peer interaction that the station inspired. Scanning usually involved two or more people as participants scanned each other, making scanning an inherently collaborative event. While both Modeling Form and Capturing Form required research assistant support, at the Capturing Form station there was usually a demo given periodically and then learners would pass on instruction to one another. By contrast, learners at the 3D modeling station tended to be more isolated while using the desktop computers.

The Capturing Form module in the written curriculum extends the possible tools at play by highlighting free-to-use apps that can run on iOS or Android smartphones. The research team was aware that equipment like the Occipital Structure Sensor or Kinect are not cheap or widely available, so the curriculum tries to expand access via the use of applications that employ photogrammetry. Remix is also discussed in this module introducing the idea of scanning the world around you as a course for creative modeling and design evolution. This brings into effect some dramatic outcomes that are highlighted by the case studies in considering acts of 3D modeling as appropriation and body customization. In the first case, Morehshin Allahyari's work Material Speculation: ISIS probes the illusory condition of the recurring copy that challenges concepts of memory, the past, and loss through historically significant sculpture (Karimi and Rabbat, 2016). Allahyari's work explores the complexity of cyber archeology and cultural appropriation through digital scanning, open source culture, and postcolonial theory. The second case focuses on BOOMcast as an example of how digital scanning and 3D printing can be used for customized medical applications. BOOMcast was initially created as a customized cast by Studio Fathom for T.V. personality Mike North of Prototype This! and Outrageous Acts of Science (Holterman, 2015). Despite the BOOMcast being a one-off project, it points to directions other innovators may take 3D printing and scanning to better serve the medical needs of individual bodies.

Extrusion

The Extrusion module and contributing stations within the MAKE 3D platform was another landing area for many participants as they entered the MAKE 3D environment, but one that was much more focused on material play without the underlying concept schema of design thinking present in the Designing Form station. Material extrusion systems in the form of 3D pens and handheld clay extrusion tools were leveraged alongside 3D printers using both clay and plastic filament. These materials and processes highlight additive processes of fabrication both from a computer-aided and hand-building perspective to allow participants to reflect on the complexities of design choices to the capabilities of the manufacturing system.

Within MAKE 3D events, the Extrusion module and the Filament Variety module were often set up together on a table along with the 3D pens and clay extruders. The 3D pens are simple devices that mimic the function of a 3D printer head by heating the filament at the point of contact while also feeding the filament through an extruding nozzle very similar to a glue gun. The 3D pens are good for demonstrating various filament properties, such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS), but also provide an acute contrast to the precision of computer-aided fabrication that you would get from a 3D printer. Due to the varieties of material play and the contrast of low-tech and high-tech fabrication, this station was always lively and full of engaged students exploring material possibilities, mixing media, and generally keeping hands busy.

The Extrusion module in the written curriculum reflects these modalities of compare-and-contrast material exploration that was activated in MAKE 3D events. Essential questions and lesson content focus on analytic and creative processes where materials and processes are explored, tested for limits, and evaluated for their prospective applications. The first case study focuses on Tom Lauerman, a core faculty member of the research team, whose practice integrates traditional techniques such as sculpture, craft, and design, along with contemporary digital processes that aid creative ways of working (Lauerman, n.d.). Beginning in the Fall of 2015, Lauerman became interested in developing and exploring extrusion-based processes for 3-D printing in clay, and his innovations in the field include his progressive development of a dual-color clay 3D printer (Lauerman, 2019). The second case study, unusual in that it focuses on a project as opposed to an individual or group, provided information about filament making itself and its relationship with plastic waste cycles through the Felfil. The Felfil is an open-source desktop filament extruder that makes custom filament from recycled plastic pellets and failed print material (Nelli, 2016). The Felfil project focuses on open-source solutions for recovering and repurposing plastic waste to reduce its environmental impact. Both cases highlight the additive process as independent of the actual material used, but also ask learners to reflect on the implications of their material choices from a design perspective and as part of a material life cycle.

Workflow in AM>>>Process

The Workflow module originally focused on the preparation of 3D prints from importing the STL file to exporting the 3D print-ready file. Vocabulary and essential questions were focused narrowly on print preparation by reviewing the different parameters in the slicing software (*Cura*) that can be varied to create the desired output. Setting these parameters requires consideration of aspects such as designating support material, infill densities, layer thicknesses and object orientation to the print bed.

While this information is important to understanding the design and print aspects of 3D printing, ultimately the MAKE 3D events were not well suited for engaging learners in this production cycle. 3D printing is slow, so to take a participant from idea, to design, to print would take at a minimum several hours. The duration of our events averaged 2-4 hours, and individual participation averaged about an hour. These averages indicate that participants rarely experienced a full prototyping cycle. In actuality, the 3D printers functioning in the space were more for proof of concept as opposed to providing a production environment.

Renamed in the written Material to Form curriculum, the Process module focuses mostly on the design and print workflow, but also expands to examine the notion of process itself in creative practice. In this way, the preparation process becomes a location for experimentation and emergence even while negotiating fixed technical parameters that need to be understood to successfully 3D print. Again, the case study gives some insight into this expanded sense of process. The case study highlights the work of Sophie Kahn, a visual artist whose creative practice plays with digital fabrication processes, misusing advanced 3D laser scanners with the goal of generating glitchy outcomes. Kahn then prints the resulting defective files of failed 3D scans as sculptures.

Filament variety>>>Material variety

Finally, while not a formal curricular module, a Demonstration Gallery (see **Figure 3**) was conceived to add a collection of 3D printed items that would allow participants to see a wide variety of materials and objects constructed through additive processes. The gallery provides a curated collection of engineering and art objects in a range of printed materials that are meant to illustrate the wide variety of potential in 3D printing capabilities.

Originally called the Filament Variety module and later modified to the Material Variety module, the written curriculum reflects a wide array of additive processes, most not represented in the MAKE 3D platform. Due to issues of safety and cost, MAKE 3D presented fuse deposition and paste extrusion 3D printers. Other processes such as selective laser sintering and stereolithography are in the curriculum to present the full array of what is possible. The case study for this section focuses on Alex LeRoux, an engineer and designer who developed a 3D printer known as the Vesta that uses concrete. Le Roux successfully printed what is believed to be America's first livable 3-D-printed shelter (Scott, 2016).

Iterating Curricular Form and Modularity

Over the course of the development of the MAKE 3D curricular resources, we drew upon several conceptual frameworks informed by design thinking (Doorley et al., 2018; IDEO, 2012) and the process-oriented constructionism of Seymour Papert (Harel and Papert, 1991). The later development of the expanded mods drew from the art education concept of transdisciplinary 'big ideas' as conceptualized by Walker (2001) and subsequently elaborated upon by scholars including Bautista et al. (2016), Buffington (2007), and Parsons (2004). In this section,

Figure 3. The Demonstration Gallery at a MAKE 3D event

we will summarize the evolving forms the Material to Form curriculum has taken, the conceptual framings that shaped those forms, and their affordances and constraints.

The six modules of the Material to Form curriculum (Designing Form, Modeling Form, Capturing Form, Extrusion, Process, and Material Variety) are centered on material processes in 3D printing. In addition to its process-oriented framework, design thinking also places an emphasis on naming and solving problems (Schön, 1983), and visualizing and materializing potential solutions to them (DiSalvo and Lukens, 2009; Ejsing-Duun and Skovbjerg, 2019). By emphasizing experimentation with 3D printing, the Material to Form modules aimed to foster student capacity for materialization of solutions to challenging problems.

Reflecting on the conceptual strengths of the Material to Form modules, we also identified constraints they presented as a curricular tool. Despite our efforts to build the modules for freeform navigation, the focus on technical processes and materials do suggest an order, with more complex processes building on earlier concepts. This structure may, for instance, disinvite an educator without access to 3D scanning tools by implying that not only could they not make use of the Capturing Form module, but also subsequent modules. Centering the modules heavily on particular processes also meant that such a teacher, even if they were interested in the artists and concepts discussed in Capturing Form would not be able to use that resource. As the project evolved, we sought to develop resources that could leverage the process-based instruction from the earlier modules, while opening them up structurally and conceptually to invite educators with varied interests and facilities in their places of teaching.

As a result, we introduced two mods[2] to the curriculum structure: Forms and Bodies and Glitching Form. The mod was conceptualized as a different curricular form that could extend learning from the original six modules by introducing more thematic investigations of 'big ideas' (Walker, 2001). A big idea, similar to a key idea (Parsons, 2004) or organizing theme (Bautista et al., 2016), is a concept that extends beyond any single discipline (Walker, 2001). A big idea is a concept that

[2] We chose the term mod, as an abbreviation of modification, as an ode to video game culture when players introduce modifications to a game space that changes its action or appearance.

'does not belong to the art world, though it is something artists have made works about. It suggests many questions, is full of complexities, has many instantiations, and encourages different points of view' (Parsons, 2004, p.788).

Big ideas are transdisciplinary by nature and useful for building curricula that integrate disciplines such as the arts and sciences (Bautista, 2016). Big ideas invite multiple perspectives and ways of working and are useful for accommodating a population of educators with diverse interests and resources (Buffington, 2007).

The mods we built around the big ideas of human bodies and glitching systems could be readily used in spaces with different material affordances, as their conceptual aims could be accomplished via a variety of means. A setting without access to a 3D printer could still meaningfully engage with any of these units, focusing on creating solely digital work such as 3D models, or by eschewing digital media completely and challenging students to fabricate with physical materials like wood or clay. The flexibility afforded teachers is also extended to students, as the thematic framing of the mods aims to create an open-ended problem space for generating varied solutions. This open-endedness was developed to both foster design thinking's generative and iterative approaches to problem-solving (Doorley et al., 2018; Schön, 1983), and to reflect contemporary art practices, which are largely centered on solving material and conceptual problems rather than cleaving to a particular artistic process (Parsons, 2004). Centering a big idea in each mod, rather than centering a technical process, allowed for the inclusion of case studies in the teaching resources featuring artists who engage with the theme using a variety of processes, including entirely non-digital craft processes. STEM fields have historically been exclusionary to both women (Hill et al., 2010; Makarova et al., 2019) and populations of color (Riegle-Crumb et al., 2019), so expanding the case studies to include artists working outside of digital fabrication allowed us to curate a more equitable and representative canon of creators in these curricular mods. The mods are also not dependent on each other, and don't invite a particular order of completion, more overtly enabling teachers to select, omit, or reorder them however they choose.

The first mod developed for the curriculum, Forms and Bodies, challenges students to create an artifact to be worn by a particular body. Students need to collect data on a chosen person in their life, both through physical measurement and interview, to develop an object that is a "good fit" literally and metaphorically for their chosen person. The mod emphasizes the particularity of bodies, and questions ableist generalizations about human bodies and the shapes they take (Hamraie, 2013). The mod is also structured around three categories of body-object relationship: extending bodies (discussing artists such as Rebecca Horn and Stelarc), adorning bodies (discussing artists such as Danit Peleg and Rebecca Strzelec), and connecting bodies (discussing artist Sonya Clark's "Communicatools" series). This tripartite structure is intended to scaffold a variety of potential learner engagements and teacher coordinated emphases with the generative problem space of human bodies.

The Glitching Form mod has a similar tripartite structure, built around three common glitching practices: glitching at the point of capture by interfering with scanning processes, glitching with software by (mis)using 3D modeling tools, and glitching with code by manipulating the underlying data structures of digital forms. This mod examines how glitch artists experiment with technical systems that undergird ubiquitous digital artifacts, breaking rules and pushing boundaries of these systems and structures to make them more visible (Russell, 2020). Ultimately, students are challenged to conduct their own creative exploration, developing a digital or physical artifact that meaningfully explores the potential of glitching forms.

Having summarized the evolution of the Material to Form curriculum modules and the subsequent mods, we turn next to analyzing the implications of the changes made to the curriculum over time, and how they reflect on issues of interdisciplinarity. We will also examine how the above-described curricular choices interface with larger trends of research and practice exploring culturally-responsive teaching across disciplines. We will first discuss issues of interdisciplinarity as they impacted the research and development of the curriculum, and then discuss the culturally responsive teaching within education scholarship both within the arts and engineering, drawing connections between the two throughout.

Theorizing Interdisciplinarity

Over the arch of the MAKE 3D project and through the development of the Material to Form curriculum, there is a trajectory that moves from the technical to the thematic. The initial bond that allowed the core research team to come together was a shared interest in the emergence of digital design and fabrication technologies that were changing manufacturing and production for artists and engineers alike. The role that 3D printing played cannot be overstated in this process: it was a core technology that excited the research team from various disciplinary perspectives; it dovetailed nicely with maker education and informal learning due to its prevalence within the maker community both in makerspaces and online forums; it overlapped with advances in open source cultures through 3D printing initiatives such as RepRap (https://reprap.org/wiki/RepRap) which was important for leveling the playing field for those with limited access to more expensive or technically complex printing procedures; and it captured the high visibility computational event that was at the core of our theorized use of curricular spectacle to harness the potential of short exposure learning experiences that may provide lasting impact to learner's education. As Knochel (2018) has theorized, these high-visibility technologies can perform as curricular boundary shifters: entities that have a high incidence of disciplinary border crossing that transforms cultural, social, and institutional norms in learning spaces and beyond.

However, boundary shifting is not an easy process within radically transdisciplinary spaces of science, technology, engineering, art, and design. Malina et al. (2015) suggest that there is a 50-plus-year history of investigations in science, engineering, art and design that has generated over 40 reports suggesting that the community of interest and practice is healthy and well established while at the same time
'it is clear that many of the opportunities and obstacles now facing the SEAD community were identified and worked on in the past.' (p. 6).[3] Ultimately our project succumbed to many of the issues that are prevalent within the SEAD and STEAM educational communities. Such communities have ongoing challenges sustaining funding, ensuring a deep sense of epistemological variance in knowledge formation, and maintaining methodological rigor to meet the varied demands of very different academic communities. However, the opportunities to impact student learning though arts-integrative initiatives far outweigh these challenges. Integration of arts and humanities to STEM subjects have been associated with positive learning outcomes including increased critical thinking abilities, higher-order thinking and deeper learning, content mastery, problem solving, teamwork and communication skills, improved visuospatial reasoning, and general engagement and enjoyment of learning (National Academies of Sciences, Engineering, and Medicine, 2018). And while these impacts to student learning are important for advocating for STEAM initiatives, there are perhaps even more vital reasons that STEAM initiatives need to be pursued as they are situated within research concerning gender difference in learning and broadening participation for STEM fields. As Marín-Marín et al. (2021) in their bibliographic analysis of the term 'STEAM' within publications within the Web of Science (WoS) database, state

> the topics of study on STEAM-EDU [an abbreviation used by authors to refer to STEAM projects in the educational field] include aspects related to gender differences, the influence of STEAM-EDU on people of different races, the skills developed by students, and teacher training to implement teaching and learning processes with STEAM-EDU (p. 18).

The aligning of STEAM education with integrated knowledge and holistic learning toward equitable access, rather than focusing solely on technical overlaps between disciplines, is significant in our estimation. Our own curricular journey showcases this evolution from technique to theme as we made more careful and intentional shifts in the Material to Form curriculum that reflect efforts in broadening participation and engaging in culturally responsive forms of pedagogy in any discipline. We share more about this aspect in the next section.

Connecting Across Disciplines Through Culturally Responsive Teaching

In shifting our curricular design strategies from the process-oriented modules to the big idea-oriented mods, we drew upon culturally responsive pedagogies in both art and STEM education. We recognized that centering digital fabrication processes as the locus of critical and creative attention to some extent decentered the cultural contexts of digital fabrication as loci of critical attention. In the mods, we aimed for the curriculum to acknowledge that the often assumed-neutral cultural referents in both art and STEM education are neither neutral nor universal, but largely rooted in dominant disciplinary histories centered around White and European cultures and male cultural producers (Acuff et al., 2012; Martin et al., 2018). Ladson-Billings's (1992, 1995) work on culturally-responsive pedagogy critically addresses the implicit cultural norms imposed upon students by curricula and aims for educators to affirm and respond to the varied cultural referents students bring into the place of learning. Responding to the diverse cultural referents of students not only broadly contributes to a 'synergistic relationship between home/community culture and school culture' (Ladson-Billings, 1995, p. 467), but also can pointedly address the systemic exclusion and devaluing of marginalized students that contribute to educational inequity (Hanley and Noblit, 2009; Ladson-Billings, 1992, 1995). As such, culturally-responsive pedagogies have been explored by both art educators and STEM educators as strategies to address inequity in their respective disciplines. In this section, we will discuss applications and theorizations of culturally-responsive pedagogy in art and STEM education, and how our conceptualization of the Material to Form mods attempted to address the issues surfaced in each discipline.

Acuff et al. (2012) noted how, in culturally-responsive art education, critical curation of the canon of thinkers and artists included in curriculum is necessary to avoid perpetuating received (often white-male-centered) histories

[3] Discourses and scholarship in science, engineering, art and design (SEAD) are very similar to those in educational communities of science, technology, engineering, art and math (STEAM). The only difference in our estimation is that STEAM has been taken up more widely in pre-K-16 educational discourses.

of art. In the shift toward centering big ideas in the mods, we were afforded a wider array of potential exemplary artists to draw from, facilitating a critical and considered curation of exemplars. Not tethered to specific digital fabrication processes, the Forms and Bodies mod could bring in artists like Sonya Clark, who works with a wide variety of physical materials, including ones drawn from traditional craft practices of the Black diaspora. Lai (2012) argued that by meaningfully engaging with and affirming creative practices rooted in historically marginalized cultures, culturally-responsive art pedagogy 'resist[s] the cultural deficit paradigm and decontextualized learning that devalues or disconnects students from their ethnicity and culture' (p. 18). In developing the mods, we aimed to include non-digital modes of making, particularly those by women and BIPOC creators, not as an addendum or option for deficient settings without digital fabrication tools. Rather, we aimed to center and legitimize non-digital making practices as valid approaches to addressing the big ideas and critical questions at the center of each unit while still impacting understandings of material and technical processes. Likewise, in the Forms & Bodies mod, disabled bodies are not singled out as deficient and needing assistance, but rather as part of the diversity and particularity of human bodies that artists and designers must attend to when creating objects that interface with human bodies.

Several scholars of art education have noted that culturally responsive practice in the arts not only benefits the marginalized students who may see themselves reflected in the curriculum, but that it may confer benefits upon all participating students. Acuff et al. (2012) argued that culturally-responsive art practice ultimately benefits all students, as all students are impacted by the 'prescribed and oversimplified stories' (p. 10) imposed by the uncritical repetition of dominant norms. Drawing on the psychological research of Amodio and Lieberman (2009), Lee (2012) specifically asserts the necessity of critically-responsive art education for non-marginalized students, as arts practice elicits both embodied experiences and the cognitive creation of meaning which are 'critical to unlearning cultural bias… [which] is considered to be deeply rooted in the emotional processes of the brain' (p. 49). While the Material to Form mods reflect the attitudes of culturally-responsive arts pedagogy in their conceptualization and curated canons more so than the earlier modules, there are still areas for improvement. A minority (28%) of the artists discussed in the mods are white men, however the majority (84%) of artists discussed are white, and all of the included artists work and live in the global North. The shift to a big-idea-centered ethos creates the opportunity for these oversights to be addressed in future iterations or additional mods, which a focus specifically on digital fabrication processes may not.

Scholars in STEM education have likewise articulated the need for, and benefit of, culturally-responsive pedagogy in their discipline. Scott et al. (2015) noted that, while there are numerous technology programs

> 'currently offered to raced-gendered-ethnic minority students … the vast majority focuses exclusively on technical literacy (i.e., programming) and do not mention issues of diversity, community, culture, or identity' (p. 413).

The focus on technical literacy enacts a tacit imposition of the assumed-standard values of (majority white and male) STEM industries and communities onto the targeted students, marginalizing the values and modes of making and thinking these students bring into the learning environment (Scott et al., 2015). To invite the development of more equitable and comprehensive STEAM learning programs, Scott et al. (2015) recommended five tenets of culturally-responsive computing (CRC):

1. All students are capable of digital innovation.
2. The learning context supports transformational use of technology.
3. Learning about one's self along various intersecting sociocultural lines allows for technical innovation.
4. Technology should be a vehicle by which students reflect and demonstrate understanding of their intersectional identities.
5. Barometers for technological success should consider who creates, for whom, and to what ends rather than who endures socially and culturally irrelevant curriculum. (Scott et al., 2015, p. 420-421).

Some STEM education scholars have found maker contexts to be valuable settings for fostering CRC, and particularly for critically questioning what counts as *making* (Martin et al., 2018) and who counts as a *maker* (Fields et al., 2018). Martin et al. (2018) sought to expand what counts as making by affirming and incorporating the repertories of practice students brought into their maker space. A young Black woman with interest and experience in fashion design, for example, was able to bring her repertory of practice into the makerspace and extend it with the tools and skills made available to create attire with programmable lighting (Martin et al., 2018). Fields et al.'s (2018) expanded conception of who counts as a maker recognizes a need for diverse representations of making to affirm and serve all students. To accomplish these goals, Fields et al. (2018) developed an e-textile making project within the context of their equity-focused Exploring Computer Science curriculum. In examining the problem of culturally-responsive STEM pedagogy from a curriculum design perspective, Fields et al. (2018) noted how their design of the e-textiles project not only invited and affirmed diverse participation by students with varied relationships to digital technologies, but also invited and affirmed diverse *implementation* by *teachers* with varied relationships to digital technologies.

In approaching our development of the Material to Form mods, we likewise curated exemplar artists and centered big ideas with the aim of inviting and affirming both students and teachers who may not have the experience or material means to engage in ‘making’ when it is defined strictly as digital fabrication. The centering of interdisciplinary big ideas was chosen to invite students and teachers regardless of their relationship to the arts or technology. For example, the centering of human bodies in Forms and Bodies aims to connect to the fact that every student, teacher, and artist has a body, and the centering of glitches in Glitching Form aims to connect to the fact that every contemporary student, teacher, and artist daily interacts with digital systems which may be critically subverted. Within the mods, other interdisciplinary and endemic global issues are addressed, such as ableist design norms discussed and destabilized in the Forms and Bodies and Glitching Form mods. As discussed above, the curated canon of exemplar artists in the units is designed to de-center white-male-focused histories of art and technology by discussing and affirming the practices of makers using a variety of digital and non-digital media, who occupy a variety of identity positions, and who have varied relationships to established communities and industries around digital technology and art making.

CONCLUSIONS

In this reflexive analysis of our curriculum development, we’ve traced the evolving form of our Material to Form curriculum, exploring thematic connections between the maker movement, art education, and arts-integrated approaches to curriculum. Our review highlights a trajectory of revisions tuned to the MAKE 3D events and learner engagement, but also acknowledges the situated knowledge and researcher identity that informs highly interdisciplinary and design-based research. This reflexive analysis in curriculum design showcases the tenuous bonds of interdisciplinary work from shared intrigue by technological innovation to central pedagogical values commited to expanding access and broadening participation within these disciplines. Next phases of the research include continuing mod development finding intersections and thematic syntheses that can further extend the technical core of the Material to Form curriculum. Additionally, the research team is seeking opportunities for further fieldwork to gather data concerning curriculum effectiveness. Focus on thematic curricular ideas that came from iteration and an exploration of the uncertain material and disciplinary possibilities of digital fabrication offer meaningful and culturally responsive pedagogical strategies impacting interdisciplinary teaching contexts designed for STEAM practitioners.

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