Fabricating Engagement: Benefits and Challenges of Using 3D Printing to Engage Underrepresented Students in STEM Learning

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1. Introduction

In recent years, “maker” culture and 3D printing have become increasingly popular. Member-driven and community-based makerspaces are cropping up across the U.S. offering access to digital fabrication tools such as laser cutters, CNC mills, and 3D printers. Schools are also beginning to take interest, with groups like MakerEd [1] working to promote the educational benefits of maker skills in both formal and informal learning spaces. We have explored the use of 3D printing as a means to engage underrepresented students in STEM learning. 3D printers are becoming more common in learning spaces due to dramatically decreasing costs and steadily improving reliability. Additionally, educators now have access to an array of free and open source 3D modeling tools. A low-cost entry point and the ability to rapidly create tangible artifacts sets up 3D printing as a prime opportunity to promote an interest in engineering sciences in schools.

In our work, we set out to answer three research questions: 1) How can we use 3D printing to engage different underrepresented populations (young adults with intellectual disabilities and underrepresented minorities) in STEM learning? 2) What are the benefits and challenges of teaching 3D modeling and printing as it relates to the technology itself? and 3) What are the benefits and challenges of teaching 3D modeling and printing as it relates to these underrepresented populations?

We present findings from a multisite case study leveraging 3D printing for two underrepresented populations in STEM learning: young adults with intellectual disabilities and minority students from low-income and/or non-native English-speaking families. We found benefits and barriers to learning 3D modeling and 3D printing skills at both sites. In this paper, we offer our lessons learned from our case study (RQ1), identify general issues relevant to teaching 3D modeling and printing (RQ 2), and describe issues that are unique to the underrepresented populations at each of our investigation sites (RQ3). Our findings suggest that while some technical challenges are specific to the medium of 3D printing, teaching these tools offered students opportunities to improve their technical, communication, and collaborative skills. We believe that this medium presents exciting opportunities for students to apply learned skills to real-life situations and that findings from this study are transferable to other types of learners.

2. Related Work

Minorities, women, and individuals with disabilities are historically underrepresented populations in STEM. The STEM workforce, and particularly computer science and engineering, have a disproportionate amount of white, male representation as compared to their peers. Over the past several decades, researchers have studied the disparity of representation in STEM fields [2]. Despite these efforts, the participation levels of individuals with disabilities and minorities remain disproportionate. Recent statistics show that only about 11% of undergraduate students in the US report a disability and that underrepresented minorities are less likely to obtain a degree than their non-minority counterparts [3]. Our study examines STEM-engagement for two underrepresented populations leveraging 3D printing as a topic and teaching medium.

2.1. Making in the Classroom

As the Maker Movement continues to grow, many efforts have been made to integrate making into both formal and informal education settings. Researchers have examined maker culture as it impacts communities, cultures, and educational settings. Among such studies is Paulo Blikstein's [4] work on "Digital Fabrication and 'Making' in Education" in which he discuss the benefits of digital fabrication in educational settings. He looks at the experiences of students in classrooms utilizing making in the curriculum and discusses the advantages of using digital fabrication in an educational setting. In his observations, he found making to be an asset in the classroom when utilizing contextualized learning of STEM topics, by creating meaningful, concrete tasks for a project or concept.

Edward Pines and colleagues [5] explored the possibilities of "Broadening Participation Through Tngagement in the Maker Space Movement" and shared the lessons they learned in using makerspace activities as a partnering component to traditional engineering curriculum. They contribute an interesting discussion on how to balance the interests of the various stakeholders and students' investment of time in their extracurricular Maker activities. Pines, *et al.* suggest that establishing maker curriculum in addition to the traditional curriculum has allowed for the development of broader skillsets which cover knowledge beyond engineering, including teamwork, creativity, innovation, collaboration, critical thinking, project management, and systems engineering. These skills are highly valued in the technical workforce but not always practiced or developed in formal education settings.

Oplinger *et al.*'s "Making and Engineering: Understanding Similarities and Differences" [6] covers a general survey which shows that both making and engineering are perceived to be active, project developing fields. Stronger correlations are shown in the perception of making and engineering, as participants in the making community were also found to relate their work to the work engineers perform and found both fields to be admirable. This correlation may suggest that there could be a smooth transfer of interest and a higher likelihood for students involved in making to self-identify as engineers, thereby building their tenacity in continuing to study the STEM fields in their future educational and career endeavors.

3. Methods

We conducted a multisite case study which explored two underrepresented populations of students and their engagement with 3D printing, a common digital fabrication tool that is widely popular with the maker movement. We provided students at each site with access to 3D printers, filament, and related materials; and we taught the basics of 3D printing and 3D modeling. In this section, we will provide an overview of both case study sites, outline the instructional approach and materials used at each site, and describe our data analysis process.

3.1. Overview of Case Study Sites

At each site, we tailored lessons, activities, and goals to the populations and their environments. Table 1 provides a high-level overview of both case study sites.

Table 1. Overview of Case Study Sites

	Site 1: Integrated Post-Secondary Classroom (IPS)	Site 2: Afterschool Program (AW)
Duration:	2 academic semesters (12 weeks each)	16 sessions per grade
Population:	Young adults with intellectual disabilities (ID)	Minorities from low-income and/or non-native English speaking families
Num. of students:	**Semester 1:** 6 undergrads; 6 ID **Semester 2:** 7 undergrads; 7 ID	**3rd Graders:** Approx. 15 per session **4th Graders:** Approx. 10 per session
Researchers Present:	**Semester 1:** 2 per session **Semester 2:** 3-5 per session	2-3 per session
Setting:	Formal (course taken for credit)	Informal (afterschool workshop)

Site 1: Integrated Postsecondary Course (IPS)

Our first case study site was a university classroom working with students with intellectual disabilities (ID). Our university offers a four-year, postsecondary certificate program for young adults with ID that seeks to promote independence and employability for its students. Intellectual disability is a developmental disorder onset during childhood that affects intellectual functioning and social adaptive behavior [7]. Some individuals may have a more specific diagnosis or condition, such as Down Syndrome or Fragile X Syndrome, but any child that meets the diagnostic criteria of impaired reasoning and social behavior would fall under the higher-level heading of ID. This is distinct from cognitive impairment that results later in life from events such as traumatic brain injury, stroke, or degenerative neurological diseases onset during adulthood. Impaired intellectual function can impact skills such as memory, planning, or abstract problem solving. Social and adaptive behavior impairments can affect one's ability to read social cues, maintain appropriate personal boundaries, and sometimes manifest as a very shy demeanor. Appropriate support mechanisms that scaffold cognitive function and reinforce positive behavior can help students achieve success in secondary and postsecondary education.

For two semesters, we have taught an integrated course in which undergraduate students (UG) without disclosed disabilities work with students with ID from our campus' postsecondary program. The course has many goals, chief among them to promote awareness of students with ID on campus, dispel misconceptions about the abilities of these students, and to promote an interest in STEM fields for all students involved. Persons with disabilities are vastly underrepresented in engineering disciplines and people with ID experience unemployment greater than 60% [8]. With this in mind, we designed this course to both promote an interest in STEM for all students involved, and we also introduced the idea of self-employment by way of entrepreneurship as another avenue toward employment and self-determination.

Undergraduate students in this course came from several different STEM fields including information systems, business technology administration, computer science, computer engineering, and mathematics. Demographic information about undergraduate students at this site are given in Table 2.

Table 2: Demographic information about undergraduate students in the IPS class.

Semester 1			**Semester 2**		
Student ID	***Gender***	***Major***	***Student ID***	***Gender***	***Major***
UG1	Female	Computer Engineering	UG7	Female	Business Technology Administration (BTA)
UG2	Female	Mathematics	UG8	Female	BTA
UG3	Male	Information Systems	UG9	Female	BTA. Minors in Computer Science and Political Science
UG4	Male	Information Systems	UG10	Male	BTA. Minor in Philosophy
UG5	Male	Information Systems	UG11	Male	Information Systems
UG6	Male	Undecided	UG12	Male	Pre-Computer Science/Pre-Engineering
			UG13	Male	Undecided

Our findings from this site are derived from two semesters of teaching this course. During the first semester, class sessions were 50 minutes long and held three times a week. Twelve students were enrolled, half with ID and half undergraduates without disclosed disabilities. This class was held in a single-lab environment where both design and printing activities took place in the same space. During the second semester, class sessions were changed to a 2.5-hour block and held once per week. This change was made in part to accommodate more students as enrollment increased and we found that students needed more space and more computers to work (**Table 1**). Each class block began with a traditional lecture and moved to a longer lab activity. Students worked in teams of two with one student with ID and one UG student working together for the duration of the semester.

Site 2: Afterschool Workshop (AW)

The second case study site was an afterschool workshop held at an elementary school in Baltimore, Maryland. Our workshop was open to 3rd and 4th grade students enrolled in an afterschool program (run by our university) that is designed to help support academically vulnerable students in their studies. Typical activities during this afterschool program (e.g., doing homework, or playing educational games) are designed to help students reinforce fundamental skills such as reading and math. Students also receive enrichment time as another component of this program. Our 3D printing and modeling workshop was offered as a form of enrichment. The goals of our afterschool workshop were to introduce students to a new technology, hopefully engage them, and spark early interest in STEM fields.

Three researchers visited the elementary school once per week to conduct two back-to-back workshop sections (one-hour per grade level). In addition to the three researchers, between one-to-three afterschool program volunteers (e.g., school's teachers or undergraduate volunteers) were present during most sessions. None of the volunteers had experience with 3D modeling or printing technologies and opted to assist mostly with classroom management. We conducted 16 workshop sessions per grade level (32 total). Attendance fluctuated on a weekly basis, but approximately 10 to 15 students were present at each 4th and 3rd grade workshop, respectively. Causes for attendance fluctuations included absences (e.g., students not at school or sent home due to disciplinary action) as well as students joining or leaving the afterschool program entirely (e.g., transferring to or from the school). Near the end of the school year, two teams of students from these workshops applied their newly acquired 3D modeling and printing skills toward participation in a regional competition where they were challenged to solve problems in their city using digital fabrication.

Workshops were project-based and each week, students either worked on a new activity, or towards completing an unfinished activity from the previous week. Some activities that worked well in the IPS class were also used at this site. However, all instructional materials and approaches used were appropriate for the environment and student learning needs.

We tried to maintain a consistent workshop structure on a week-to-week basis to promote positive behavior and learning [9]. Instructions for each activity were introduced at the beginning of each session (announced verbally, displayed on the projector screen, and provided in a Google Doc in each student's folder). After each activity was introduced, students were free to start designing (on paper first and then Tinkercad). Some activities (e.g., brainstorming) required group work. For these activities, students worked in groups of four or five. Afterschool program volunteers helped us form these groups by providing valuable insight into classroom dynamics (e.g., ongoing interpersonal conflicts and work habits/preferences of students). In addition to collaborative group work, we placed an emphasis on peer learning because of previous success in the IPS class and due to the large student-to-researcher ratio at this site. The same agenda and teaching materials were used in both the 3rd and 4th grade workshops.

3.5. Materials

The materials and design activities that we used at each site were similar and based on prior research and fieldwork exploring 3D printing in makerspaces and in informal mainstream education. Materials and their uses are described below.

Writing Utensils/Paper: Used primarily for brainstorming and 2D design. These materials were part of an important first step before moving to CAD software. At the afterschool workshop, notecards were used for independent activities and large drawing paper was used for group activities. In the IPS class, white printer paper was used in place of both due to smaller groups.

Projector/screen: Used at both sites to display instructions for ongoing activities as well as demonstrations (e.g., showing how to change the build plane in Tinkercad). The projector/screen was also used to display lecture content in the IPS.

Computers: The IPS class used Windows desktop computers in a university lab with two students assigned to each computer. During the second iteration of this class, we experimented with adding a second mouse to some desktops to promote sharing and turn-taking practices between partners when working collaboratively. At the afterschool workshop, students used laptop carts provided by the school. Students had access to Windows laptops with 11-inch convertible touchscreens.

Google Drive: Google Drive [10] is a free online office productivity suite. Google Drive was used at both sites to facilitate activities/assignments. Each student had access to their own Google Drive folder that consisted of places for them to (1) access instructions, (2) work on non-modeling activities (3) write reflections, and (4) store files.

Autodesk Tinkercad: Tinkercad [11] is a free cloud-based computer aided design platform provided by Autodesk. Tinkercad is compatible with most modern web browsers and does not require the installation of any additional software. All that is required is an Autodesk account (requires an e-mail address for account creation). Unlike most CAD programs, the designer creates models by dragging basic geometric polygon shapes across a workplane. Shapes can be easily manipulated (e.g., moved, resized, scaled, skewed, turned into a "hole" or negative space) and grouped together when needed. We selected Tinkercad because it is free, has minimal hardware requirements, and is marketed as an easy-to-use tool for beginners. Tinkercad was the primary modeling software used at both sites.

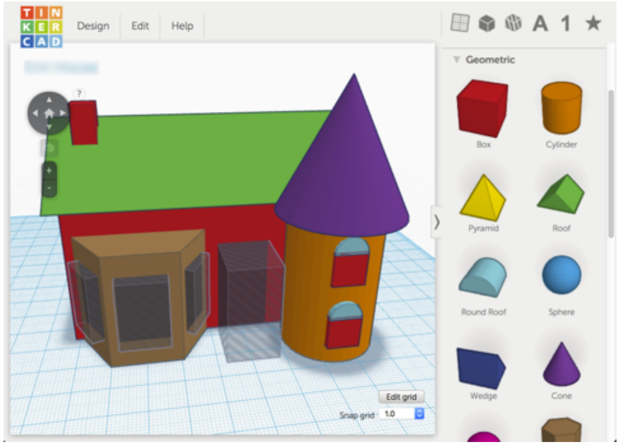

Figure 1. Tinkercad's interface. The image is of a house created during a demonstration in the IPS class.

Autodesk Project Ignite: Project Ignite [12] is a service provided by Autodesk that lets educators select from and assign pre-made projects in an online classroom environment. Instructors then generate and share a unique access code which their students can use to create Audodesk accounts and connect to the online classroom. These accounts can be used to sign directly into other Autodesk services, such as Tinkercad, and are managed by the instructor. Project Ignite was only used during the afterschool workshops. At the time of our studies, Project Ignite was the only way to access Tinkercad without an email address. Since the conclusion of our case studies, Autodesk has folded Project Ignite's features directly in Tinkercad.

Thingiverse: Thingiverse [13] is a popular online repository for 3D models and other digital fabrication files. Designs on Thingiverse have creative commons licensing and can be uploaded, downloaded, and/or modified by any members of the community for free. Students at both sites were introduced to Thingiverse during an activity where they were asked to identify and categorize models that they would be interested in reproducing.

Printrbot Simple Metal: The Printrbot [14] Simple Metal is a relatively low-cost 3D printer with a build volume of 6 cubic inches. At the time of our studies, the Simple Metal was available for $599.99 (without a heated bed). However, this printer has now been phased out by the manufacturer in favor of a newer, more expensive model. The Simple Metal was used at both sites with PLA filament.

Cura: Cura [15] is an open-source software that can be used for both slicing (preparing) 3D models and controlling 3D printers. Cura is also Printrbot's recommended software for use with their printers. Cura was used at both sites.

3.3. Data Collection and Analysis

Data Collection

During the first semester of the integrated postsecondary (IPS) class, we recorded field notes based on our observations and collected student assignments for review. Assignments included written journals, sketches, digital files, and printed objects. In the second semester of this class, we collected the same information and added video recordings of each class session for deeper analysis.

During the afterschool workshop, we recorded field notes based on our observations. To help contextualize these observations we reviewed artifacts created by students including lists of brainstormed ideas, 2D sketches, 3D models, and journal reflections.

Engagement was tracked at both sites through a qualitative measure (observable behaviors). For the purposes of our study, we defined engaged behavior as any time a student followed instructions, remained on-task in their work and discussions, and demonstrated a desire to keep learning (e.g., curiosity).

Analysis

Our analysis started with a within-case analysis where we analyzed data from each site independently. For both sites, we performed a thematic analysis of our collected data to identify emergent themes. To facilitate this process, researchers involved in data collection at each site participated in weekly meetings to discuss observations and themes present in all sources of data. After analyzing each site as a bounded system, we performed a cross-case analysis to identify common themes between occurrences at both sites. This approach is explained in detail in [16].

4. Findings

From our fieldwork, we have collected data and observations on the unique needs and perceptions of our student populations at each site, techniques for engaging and maintaining interest in 3D printing, and our lessons learned for teaching 3D printing in formal and informal learning environments. We have found that despite some challenges, 3D printing can be used to provide students with meaningful forms of engagement with STEM learning. We hope that educators and researchers find our case studies useful when considering 3D printing as a tool for promoting student engagement, and that technology designers will take some of our identified barriers into consideration when creating new tools for these populations. In the following sections, we highlight several themes found during our within-case analyses as well as their implications.

4.1 Observed Benefits of Learning 3D Printing

We observed several types of benefits associated with exposure to 3D printing at both sites. We noted opportunities for students to practice relevant STEM, communication, and collaboration skills that are applicable in other facets of life. We also noted benefits of providing students with opportunities to apply these skills to real-life situations.

Relevant STEM Skills

Like with previous work [4], we found that the 3D modeling and printing process provides many opportunities for students to reinforce skills related to science, technology, engineering, and mathematics.

Working individually and in teams, students had to solve abstract and concrete problems. In addition to replicating designs and following precise instructions, students also had to push their problem solving in more open, free design tasks. Students needed to identify a problem or product, defend the need (either as a solution or a marketable item), design their solution through drawings or low-fidelity prototypes, translate those preliminary designs into three-dimensions, and then test the structural integrity of their designs.

Site 1

UG and ID students learned about digital fabrication and gained experience with 3D modeling software, slicer software, and the 3D printer hardware. Students were also offered resources to seek out alternative design techniques, including script-based rendering (OpenSCAD [17]), 3D scanning, and direct-manipulation of free-form shapes (Sculptris [18]/Mesh Mixer [19]). The tools and hardware specific to 3D printing were novel skills gained by all students. By participating in the class, the students with ID also practiced more generic computer skill proficiencies. This included sending and receiving files, searching for resources online, and writing emails. Practicing spatial reasoning and future planning, such as how to account for overhang, helped students with ID practice some of their abstract reasoning skills.

Site 2

Like in the IPS case, students participating in workshops were able to reinforce basic computer skills while acquiring new ones. Without explicitly realizing it, students completed an entire iterative design cycle and learned how to decompose large, complex objects into a set of smaller, more familiar shapes when designing with Tinkercad. Furthermore, students were introduced to several free online resources that they can re-visit to continue their education if desired. Finally, while very little time was devoted to printing in the classroom, students developed an understanding of some of the basic limitations of modern FDM 3D printers (i.e., size, time, material, overhang).

Communication and Collaboration

Students at both sites regularly practiced their ability to communicate. Collaborating with peers, explaining designs, presentations, and competitions surrounding 3D printing helped students build their oral and written communication skills.

Site 1

Throughout the semester, working in teams and giving product demonstrations, students built up and refined their communication skills. Articulating their designs, planning and dividing up tasks, and asking one-another for help with modeling questions or printer problems helped students with ID practice their social skills. The entire class benefited from presenting their designs and products to the rest of their classmates for critique and discussion. Students would describe their individual or team products in front of the entire class and received feedback on their work. This offered opportunities to practice public speaking and critical listening.

Site 2

Like in the IPS class, students had ample opportunities to practice their communication skills through working collaboratively. Students used communication skills to work together toward common goals, and helped each other reach individual goals. Through interacting with each other and new tools, students had opportunities to improve and expand on their vocabularies. This in turn may lead to improved engagement in learning [20].

Applied STEM Experience

Students at both sites had the opportunity to apply learned skills to real world applications. Previous literature has suggested that certain populations are more engaged in STEM fields when they see applied uses for these skills [4]. By using 3D printing, we can take these applied concepts a step further by offering students tangible outcomes that they can test and take pride in creating. Like with previous research that explored the use of 3D printing in other educational settings [21]–[24], we found that identifying real world problems, creating solutions, and seeing those solutions actualized (even at a prototype level), offered engaging experiences beyond skills acquisition.

Figure 2. Affinity diagramming [25], [26] exercise used to explore potential applications of 3D printing.

Site 1

In the integrated classroom, we discussed several uses for consumer-grade 3D printers, despite their seemingly constrained output (plastics, small build space, mediocre print speed). By exploring what they might want to print and gaining an understanding of how the printers worked, students identified multiple applied uses for 3D printers. Students discussed and designed products for assistive technology, organization, everyday utility (replacing broken or spare parts), customization, games, and art (**Figure 2**). Students were also fascinated with more advanced 3D printing topics such as 3D printing for medical applications and high-level concepts like digital rights management and legislation for digital fabrication.

Site 2

Two teams of students entered a local competition where they were challenged to solve a problem in their city using digital fabrication. They were instructed to address their problem through either building a solution or through redesigning a physical space. All students participating in the workshops took part in initial class-wide brainstorming and design efforts. However, due to team size restrictions, we asked students to self-volunteer to participate in the actual competition. Two 4th graders, and three 3rd graders made up our final teams.

The 4th grade class identified ice on sidewalks as a major problem (influenced by inclement weather). Their solution was to create a set of 3D-printable spikes that could be attached to the bottom of shoes with Velcro.

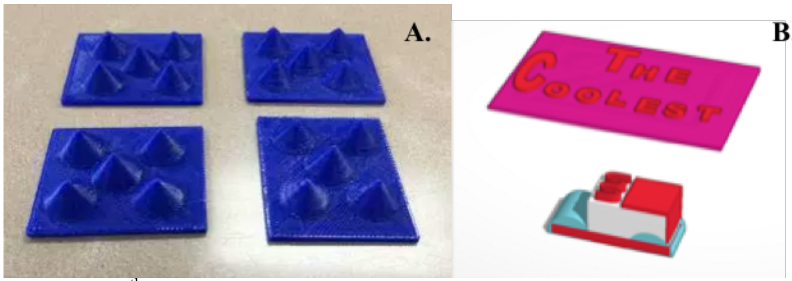

Figure 3. Components of the 4th grade team's project. Image A is the 3D-printed spikes for walking on ice. Image B is a model of a shoe designed to be used as part of the competition display

The 3rd grade class identified homelessness and vacant homes as major problems in their city. To address this problem, students opted to design new spaces for homeless people to live. The final design was a house with a door for people to enter, walls for protection, and storage space. It took several iterations to get this design to a printable state. Both teams selected their primary designs for entry into the competition. Team members with designs that were not selected compromised by creating complimentary designs to be displayed alongside the team's primary entry to the competition. These complimentary designs include a shoe for the 4th grade project, and a trashcan and a house-repairing robot for the 3rd grade project.

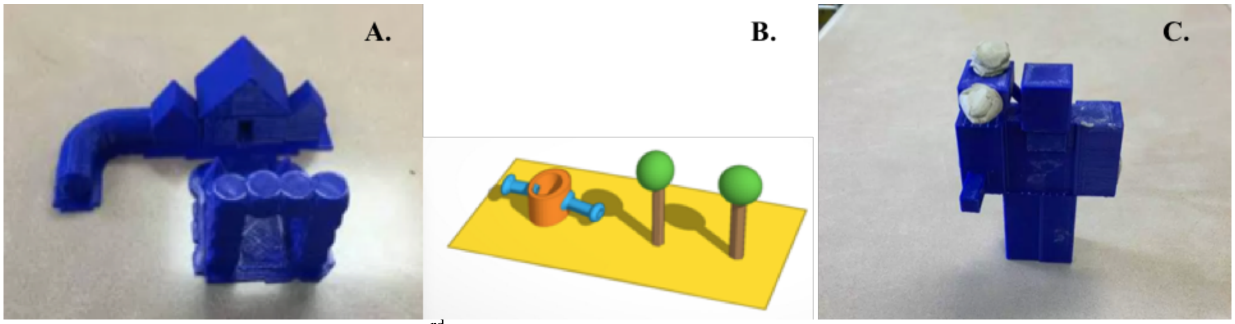

Figure 4. Different components of the 3rd grade team's project. Image A is a futuristic house designed for homeless families. Image B is grass, trees, and a futuristic trashcan designed to go outside of the house. Image C is a futuristic house-repairing robot.

Despite having little time for iterative design, students worked together as a team, tuned out other external distractions, and made compromises to achieve a common goal. Team members were motivated by the opportunity to represent their school and compete against other teams with more time and resources.

4.2 Observed Barriers Leading to Disengagement

We noted several factors that lead to student disengagement. Sometimes these issues were specific to the current limitations of 3D modeling and 3D printing tools, but there are also considerations specific to students with ID and students with mixed-ability working together.

General Limitations of 3D Modeling and 3D Printing Tools

For both of our investigation sites, it was necessary to use free and open-source software whenever possible and to use reasonably priced printers. Our free tools and consumer-grade printers meant that our student populations were susceptible to the same pitfalls of 3D printing as many other learning environments with restricted resources. Modeling tools often present an interesting tradeoff between ease of use (with a drastic learning curve) and features. Novice tools like Tinkercad may limit students as their design skills grow, while more advanced tools may be too difficult to learn initially. While transitioning from novice tools, some users find that more advanced tools have too many options or use entirely different vocabulary.

It is well-documented that modern FDM 3D printers are relatively slow and not free of failure [27]. Moderately small prints such as the house in **Figure 4** can easily take over an hour to print. Because of our time constraints, failed prints would almost always result in students being unable to see the finished product of their work. Our previous work found that failed prints are often discouraging to students [28]. Other problems include the need for extra maintenance and troubleshooting whenever failed prints arise.

Site 1

We found a mix of technology barriers, some specific to ability and others related to the current state of 3D modeling and 3D printing tools. Several publications and case studies exploring 3D modeling and 3D printing have pointed out struggles with inaccessible modeling interfaces, convoluted slicer variables, and the plug-and-*pray* quality of consumer-grade 3D printers (filament clogs, prints not sticking to the build plate, temperature control, etc.). These problems were sometimes exacerbated for students with ID when interfaces were too complex. This made it harder for students to recall or find menu items, widgets, or tools. To work around these issues, we had two to five aides in the classroom that could troubleshoot issues with students. We encouraged students to write their own how-to manuals for reference if they got stuck on a problem they had already learned how to solve in the past.

Site 2

The 3D printers used at this site were shared resources. As outsiders who only spent time in this environment once a week, there was no guarantee that the school's 3D printers would be in usable shape when we visited. It was common for the printers to need some regular maintenance (e.g., calibration or print surface cleaning). Having to perform these maintenance tasks on a regular basis (during a 1-hour workshop) would have been detrimental to our productivity. Because of these factors, we spent a significant amount of time outside of the workshop printing for students.

While the average cost of 3D printers has steadily declined over the last few years, they are still too cost prohibitive for many schools to acquire at scale. We had fewer 3D printers than students, and even fewer people trained to operate them. The high printer-to-student ratio, and the amount of work required to get printers set up meant that we were rarely able to have more than one printer running at a time. Letting students operate 3D printers independently would have potentially placed the safety of both the students and printers at risk.

Taking this into consideration, we opted to place an emphasis on activities that all students could participate in: brainstorming, sketching, modeling, and refining. The majority of our printing was moved off-site to our university, where time was not a factor, and we could be sure that printers were functioning correctly.

Technology Barriers Unique to Each Site

In the case of both populations, students sometimes struggled with everyday technology interfaces and tasks, such as keeping track of login credentials or familiarity with input devices or interfaces. Limited exposure and computing resources may be partially to blame, but there are also problems specific to ability and context.

Site 1

Students with ID struggled with the more ubiquitous components of postsecondary education, such as maintaining multiple sign-in credentials for multiple online accounts, accessing cloud-based storage for assignments or tools, and correctly navigating local file systems for saving and printing design files. These issues could slow down or stop progress on tasks until a peer or a teacher could assist [29].

For more individual problems, like forgetting log-in information for a service, we tried to implement better password management for students (i.e. always keep your password in X location) and made arrangements to sign students on to temporary or guest accounts and transfer their work to their own accounts at a future date. These workarounds were sufficient to get the job done, but bring into question issues of cyber security (i.e., keeping credentials private) and self-determination for the students with ID [29].

Site 2

Like with the IPS class, password management was among the most challenging barriers to overcome at this site and was prevalent in two ways. Few students had developed personal systems to manage passwords and difficulties remembering passwords to log into the school's computers were a common occurrence. Because this was an afterschool setting members of the school's technical support staff were not available to assist with password recovery. To work around this barrier, we asked students to assist their peers (who were unable to sign-in) by logging into multiple computers using their personal credentials. Students also faced difficulties logging into Project Ignite/Tinkercad on a regular basis. Project Ignite does not ask users to verify their passwords when signing up with a classroom code—a contributing factor to failed logins. We observed many instances where students were unable to login because they had made errors in their usernames or passwords when creating accounts. To mitigate this challenge, we designed notecards containing each student's username, password, and URLS's that they would need to access that may be difficult to spell. We found that this additional form of prompting was an efficient way to help students log in and start designing quickly.

Students preferred to use their laptops as a tablet with the touchscreen as a primary source of input. Many students also preferred using the touchscreen keyboard for text input (as opposed to the physical keyboard). This was especially troublesome when using Tinkercad. Tinkercad is not designed to recognize any of the multi-touch gestures that students were already familiar with. Additionally, interface elements are quite small and not designed for touch input (e.g., camera control in **Error! Reference source not found.**). This, in combination with the small laptop screen size lead to many accidental taps and was a source of frustration for students. To address these frustrations, we encouraged students to use their laptop's keyboard and trackpad. These observations suggest that students from this population may find computer-aided design tools to be more intuitive if they supported more than one input modality (e.g., touch).

Limited Practice Time

Time to practice skills in and out of the classroom was very important and often difficult to come by. Students needed additional practice in order to promote retention and mastery of newly acquired skills, but faced obstacles of time, ability, and access resources.

Site 1

During our first semester, we tried having class three days a week for 50-minute sessions. We found that the time needed to log into computers, start up 3D modeling applications, and prepare files for printing was beyond what we could fit into a single, 50-minute session [28]. During the second semester, we moved to the block class format, with class lasting 2.5 hours one day per week. This made it easier for students to make substantial progress on their designs and enabled them to use and observe the 3D printers firsthand more often. However, we found that students stopped thinking about the class in between sessions. Even though students could access their models and the Tinkercad application outside of class, they never sought out extra design practice outside of lab hours. When students came back each week, especially the students with ID, they had to work to reorient themselves to the tools and assignments given.

We tried to address this with more take-home assignments, but found that students would skip or forget these pieces of homework and/or rush to do them during lab time rather than work on the assignments at home.

Site 2

We encountered new students almost every week. Every time a new student attended the workshop, it took time and energy to get them up to speed. The onboarding process for each new student included creating an Autodesk account through Project Ignite, creating a new Google Drive folder, and teaching students how to access Tinkercad, and Google Drive. This led to a less than ideal scenario for everyone involved. New and continuing students had different needs and requirements for assistance. These tensions made the importance of peer learning even more evident.

5. Researcher Reflections From Case Study Sites

5.1 Reflections from Site 1

The integrated classroom was unique in that it served as an introduction to digital fabrication, a crash course in entrepreneurship, and included a community and social good component. We had to use tools and assignments that were flexible enough for the diverse student ability represented by the integrated enrollment. We were also keen to see the impacts of peer learning on the students' experiences and its role in inclusive interactions between students with diverse abilities.

Intrinsic Motivation

Everyone has the occasional bad day, however, for our students with ID having a bad morning or a low energy day could severely impact their participation. A student who was having a difficult day may not be able to mask their feelings in the same way that their neurotypical peers might, due to impaired adaptive behavior. This meant a student may refuse to talk, fail to complete work, and/or remain completely disengaged from the instructor and their design partner. Even though the students worked throughout the semester to build positive peer relationships, these negative engagement days were confusing and frustrating for undergraduate students and sometimes impacted classroom progress for other students.

To combat low intrinsic motivation, we introduced reward structures using the course materials. A student who doesn't want to complete an exercise might be tempted to participate if they are promised unrestricted modeling time. Or to prompt a student through an assignment they don't want to complete, we could offer to print an extra copy of the object for the student to keep. The highest tier of reward was usually picking an existing design or making a special design "for fun" and printing it. Using the materials to motivate the students who were feeling low or no engagement was often successful and still offered ways to work on the intended skills for the lesson.

Failed Inclusion

During the first semester of the integrated classroom, we observed undergraduates dominating modeling interactions [28]. Undergraduates, often well meaning, unaware, or simply suffering from tunnel vision due to concern for their grades, would take mouse and keyboard control away from their peers with ID. The UG student would attempt to guide or point to choices for their partner and after a few minutes, take control of the mouse and complete the task in question with little or no explanation. Sometimes control was returned to their partner, but sometimes not. In turn, students with ID had less practice with modeling and could become disengaged with the activity entirely.

To mitigate this behavior and explore the instinct to dominate the modeling interactions, we implemented a few test conditions in our second semester. We tried adding a second mouse to shared computer stations to encourage both students to contribute to modeling activities. We also tried timed pop-up reminders (**Figure** *5*) that would appear as an alert blocking the entire modeling space. This alert prompted the students to change roles/mouse users.

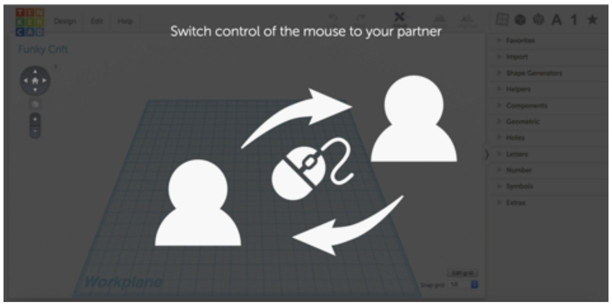
Switch control of the mouse to your partner

Figure 5. Pop-up alert used to prompt students to switch.

Despite our best efforts, the secondary mice and the pop-up alert were both summarily ignored. Undergraduates still dominated the mouse time and would only switch when prompted, in some cases repeatedly, by instructors or aides. Going forward, we are considering other options to mitigate this behavior. We still believe working in teams provides a strong benefit in communication practice and peer learning, but there is still progress to be made with positive, inclusive interactions and students' self-awareness.

5.2. Reflections from Site 2

Site 2's 3D printing and modeling workshop was offered during an afterschool program as enrichment time to students and only conducted once a week. Afterschool programs often provide students with an informal environment where they can learn without many of the restrictions and stresses (e.g., tests and grades) associated with traditional classroom learning. However, because these programs take place at the end of a long school day, these environments don't always provide the structure needed for optimal learning opportunities.

External Factors Leading to Disengagement

There are many external factors that can contribute to a students' level of engagement while learning. These include having access to proper nutrition, positive relationships with family members, levels of stress, self-expectations, and the education level of parents [20]. Educators have little-to-no control over these factors because they are largely external to the learning environment. In this setting, one small disruption would often lead to the derailment of the entire classroom's progress. At site 2, we observed that disruptions were often the result of changing classroom and environmental dynamics. Because we only visited this space once a week, having the support of the program volunteers was an essential component of our ability to work around these dynamics.

The Need for More Engaging Tools

We identified several barriers to engagement associated with the performance of existing software tools. The vast majority of students did not find Tinkercad tutorials or Project Ignite projects to be engaging or interesting in any way. This can largely be attributed to a lack of feedback. We observed that tutorials and projects provide textual instructions and static images in a separate panel from the workspace, but provide no feedback. Actions performed in the workspace have no impact on a user's progress through a tutorial/project. In fact, the only way to proceed through one of these activities is to click "next." Students instead preferred to learn through exploration and trial-and-error until they achieved their desired results. When needed, students were still able to leverage both their peers and us for support. Taking these factors into consideration, we abandoned Project Ignite projects entirely and only used it for account management.

A final source of frustration to both students and us as educators was the search function in Thingiverse. Students often became frustrated when they were unable to find what they were looking for. We as educators found that poor search results (e.g., something inappropriate) can often lead to distractions that draw students off tasks. This was a cause for increased vigilance.

6. Implications and Recommendations

Our case studies revealed that while there are some barriers to leveraging 3D printing as a means of engagement for these populations, there are numerous benefits. We believe 3D printing is a valuable tool that can spark interest in STEM and that our underrepresented populations were able to have applied experiences with technology that they found engaging and validating. We identified several benefits and barriers to using 3D printing to engage underrepresented students in in this context. We offer several suggestions to help support educators looking to implement 3D printing in their classrooms.

Software and Hardware

When selecting modeling software and printers, weigh your needs against your budget. Open-source and free modeling tools can be an excellent resource, but recognize that you may need to provide additional instructional materials and support to make these tools accessible to all students. Regarding software, be attentive to students' personal experiences and expertise with technology and their individual levels of ability, both cognitive and physical. For printers, carefully consider the amount of time you have available for printing, the space where the printer(s) will be kept, and the hazards to the machine and your students.

Class Size and Structure

We recommend smaller class sizes wherever possible and offering students as much extended design time as you can afford. Modeling and printing are both time-intensive tasks that require dynamic environments that support creativity and conversation while still providing spaces that promote concentration. Utilizing peer learning is a good way to redistribute the burden of troubleshooting away from instructors and aides while encouraging students to explore and teach other. In mixed ability classrooms, consider offering scaffolding to small groups to encourage even distribution of work and experience. For example, having students identify with a role (e.g., the artist, the modeler, etc.) may provide students with opportunities to express make contributions based on their strengths and reduce the temptation to cut each other out of assignments.

Projects and Assignments

While 3D printing is still a new and innovative technology in educational spaces, the excitement of printing will not be enough to keep students engaged. Be sure to incorporate a mix of structured and unstructured assignments in lesson plans. Anticipate that some students will struggle with certain modeling tasks and require additional time or practice, while others may excel at modeling. We found that mixing individual assignments for skills building and more complex projects promoted creativity and catered better to different ability.

7. Limitations

A major strength of our multi-site case study approach is our ability to provide rich, thick, descriptions of bounded systems [16]. This strength is also our primary limitation. Because our approach was constrained to two unique sites, our findings may not be entirely generalizable to all underrepresented groups of students. However, we do believe that the overlapping aspects of our findings will be transferrable to other settings [16] (as they were between both of our sites) and may be of interest to educators and researchers working to further integrate these technologies into educational settings. It should also be noted that changes have been made to both Tinkercad and Project Ignite since the conclusion of our case studies. Tinkercad has received significant functional and interface updates [30] while the features of Project Ignite have been folded into Tinkercad entirely [31].

8. Conclusions and Future Work

We have presented findings from two case studies examining how 3D printing can be leveraged to engage underrepresented populations in STEM learning. Our findings reflect several benefits for students learning 3D modeling and printing, including practicing relevant STEM skills, developing communication, and experience with applied STEM problem solving. We also noted struggles with printing and modeling technology, everyday technology barriers for underserved populations, and resource limitations. Finally, we provided a more detailed look at unique challenges faced by our populations and the context at each site.

At Site 1, we found that it was necessary to accommodate students experiencing low-engagement days and that truly inclusive technology education may require additional support from teachers or may need to be baked into the interfaces of digital fabrication tools. At Site 2, we identified several unique external factors that had an adverse impact on student engagement and areas in which existing technologies can be improved to better engage students. We believe that our current findings will be of value to educators and researchers working to increase levels of diversity in STEM fields and to technology designers working to craft new tools to support these populations. In the future, we plan to further explore inclusive education by collaborating with special educators to design more accessible educational tools and to study the impacts of maker education on underrepresented youth populations.

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