SUPPORTING BROADER PARTICIPATION WITH EMERGENT DIGITAL FABRICATION TECHNOLOGIES ONLINE

A Dissertation

by

ALEXANDER N. BERMAN

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Co-Chairs of Committee,	Francis Quek
	Frank Shipman
Committee Members,	Tracy Hammond
	Sharon Chu
Head of Department,	Scott Schaefer

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ABSTRACT

The emergence of affordable digital fabrication technologies like 3D printing may drastically change how physical goods and created and consumed, shifting the focus of fabrication from distribution of physical goods towards the distribution of digital designs. However, many researchers have shown that there are various technical barriers and challenges that newcomers to these technologies face when designing 3D geometries and operating fabrication machinery. Still, few studies have investigated how people gain motivation and understanding of *what can be printed* separate from this practice of designing and operating machinery. This distinction is important, as while not every digital fabrication workflow requires users to be the sole designers and machine-operators, every workflow requires that users to specify what they want to fabricate.

This required specification of *what to print* manifests through collaborations and negotiations between humans and machines who ascertain *how to print*. These interactions may serve as catalyst for those learning to 3D print *as* a practice (i.e. process) or *for* a desired function (i.e. product). The research presented in this dissertation identifies barriers and challenges to initiating this specification-determining collaboration, and investigates how online computational tools and formalized printing processes may help overcome these impediments. We investigate how printing processes similar to services can serve as a proxy for understanding how newcomers learn to specify printing ideas, and demonstrate how printing processes similar to printing services can generate user-interest and -ability to fabricate in both formal and online settings.

The research presented in this dissertation investigates how printing collaborations are successfully initiated, determining the barriers and challenges newcomers face towards *becoming* someone who can co-participate in both proximal and online printing processes. Online participation is crucial for diversifying printing populations, as many locations (e.g. rural schools) may have printing machinery but a scarcity of experienced printing mentors. For communities distal to experienced practitioners, the ability to constructively communicate with online practitioners can foster initial interest and serve as a gateway towards the adoption of 3D printing in more diverse practices.

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NOMENCLATURE

TAMU	Texas A&M University
HCI	Human-Computer Interaction
CoP	Community of Practice
LPP	Legitimate Peripheral Participation
ZPD	Zone of Proximal Development
WYSIWYG	What you see is what you get
HW	Hardware
SW	Software
FDM	Fused Deposition Modeling
SLA	Stereolithography
SLS	Selective Laser Sintering
PLA	Polylactic Acid
ABS	Acrylonitrile Butadiene Styrene
CAD	Computer-Aided Design
Customizer	A parameterized CAD application
W2V	Word2Vec
TF-IDF	Term Frequency - Inverse Document Frequency
SUS	System Usability Scale
CSI	Creativity Support Index
RS	Recommender System

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1. INTRODUCTION

A new student relates a story of gaining initial interest in 3D printing, where after receiving a tour of campus that featured 3D printing facilities through the glass walls of the engineering design center, he tried to gain access to learn from his 3D printing peers. He was denied access, as the center only admits engineering students. Another student had friends that recommended 3D printing, but because they were skilled CAD designers, the student believed that CAD was a necessity to start leaning 3D printing. While future 3D printing and other versatile digital fabrication methods have the potential to afford anyone to make anything from anywhere, socio-cultural constructs inhibit broader embodied and sense-making processes needed for printing. In a 2020 survey of 3D Printing users by Sculpteo [6], over half of the respondents (n>16,000) said that the *knowledge-gap* and *cost-of-entry* are important factors that would limit the adoption of 3D printing. This dissertation addresses how newcomers to emerging digital fabrication technologies may overcome similar knowledge-gaps by developing users' knowledge of *what* can be fabricated by fabrication services.

Newcomers to 3D printing often fail during initial attempts without mentor guidance, causing many to abandon the technology completely owing to a lack of self-efficacy and social support [7, 8, 9]. Learning and mentorship in this dissertation is viewed through the lens of Lave and Wenger's Legitimate Peripheral Participation (**LPP**), where learning is a phenomenon that occurs through co-participation in a given practice [10]. LPP is the means of how newcomers become experienced in a practice, and how the surrounding practice as a whole changes with the integration of newer members [10]. This learning and integration occurs alongside the changing of identity, and the acquisition of tacit knowledge [11, 10, 12] to ***become*** someone who can perform a practice. In this way, people learn by interacting with a More Knowledgeable Other (**MKO**), who can iteratively exemplify new concepts and processes in a way that is approachable to a specific learner [13, 10]. In summary, we view learning as a collaborative process where the objective is for the participants to *become* practitioners. Barriers and Challenges towards this collaboration, based on the theoretical foundation of LPP and MKO's, are identified in this dissertation through Olson and Olson's framework for successful remote collaborations [14], which generalize beyond remote collaborations [15, 16, 17, 18, 19, 20].

The aforementioned students faced barriers and challenges toward technological-adoption imposed implicitly by their peers and institution, but were both able to learn 3D printing by other means: online resources to find nearby printing experts and YouTube instructors. However, there are many barriers towards learning fabrication concepts online. In addition to those mentioned explicitly by Olson and Olson's framework [14], we identified a paradox of self-guided learning in the modern age of search engines: *you often have to have some prior knowledge to find introductory knowledge*. We deem the students mentioned above as "*former newcomers*", as they were able to overcome this online barrier to find their way towards relevant 3D printing resources, unlike the many who are implicitly filtered from learning printing by an inability to find opportunities for participation. Much HCI literature investigating barriers and challenges to learn 3D printing focus on these "former newcomers", not those who were blocked by this implicit online filter, but those who already have identified and accessed 3D printing facilities [21, 22, 23, 24]. This dissertation identifies factors that inhibit broader participation in 3D printing by true *newcomers* to 3D printing in general, proposing and testing technologies that can broaden participation in 3D printing and potentially other online-learning practices.

The ideal digital fabrication machine would receive any user specifications and output an artifact matching these specifications. Present 3D printing technologies, and other fabrication technologies, are complex to utilize as the process of fabrication is not *what-you-see-is-what-you-get* [25].Unless a digital design has been successfully fabricated in the past, made transparent by testimony of others such as in online platforms, it is unclear how physical objects may be created from digital 3D geometries and a slew of printing settings. Presently, knowing what can be printed (i.e. *printability*) is situated within extensive knowledge and environmental factors within chosen printing facilities [9]. The ideal 3D printer of the future may aid anyone to better understand how it is situated within a internet-facilitated *practice* of 3D printing [26], helping newcomers to specify their ideas. This ideal printer does not exist, and many existing studies of printing newcomers convolute the barriers to learning *what can be printed* with the practice of machine operation and maintenance performed by printing-practitioners that is fraught with the aforementioned barriers [27, 28, 29, 30, 31]. We investigate how present 3D printing services, where clients can pay for the operation of specified fabrication machines [32, 33], may serve as a proxy for these future 3D printing technologies that can intelligently aid users in specification tasks. Services may presently aid in specification by collaboratively and incrementally constructing specifications with their clients [34, 32], helping differentiate knowledge of *what to print* from the detailed technical details of machine operation and maintenance. Understanding how these collaborative specification processes are initiated and may be sustained will unlock a broad range of opportunities in Human-Computer Interaction (HCI) research to broaden participation with digital fabrication technologies. These opportunities echo similarities from previous HCI research that highlights the need for creating meta-design systems [35, 36].

This dissertation covers research starting from studies conducted in formal education settings in Chapters 4 and 5, demonstrating how small interventions can encourage peer-mentorship can develop fluency with a variety of technologies to empower expression.Following these studies, Chapter 6 presents a study capturing newcomers' perspective of 3D printing processes and products to better identify barriers and challenges they face *before* entering 3D printing facilities. Chapters 7 and 8 then outlines how people can presently interact with 3D printers online, demonstrating a novel web application that serves as a gateway for newcomers to gain transparent access to these online printing practices. All chapters aim to better understand how embodied and situated technologies may be designed to support digital fabrication in terms of the process (*where and how to print*), product (*what specification to print*), and person (*development of initial interest and self-efficacy*). Understanding these aspects may inform future technologies that may allow anyone, anywhere, to utilize and express their ideas through digital fabrication technologies.

Table 1.1: Summary of Studies

Study	Participants	Year	Section
"Making" CoP in Elementary Schools	Two Fifth Grade Classes	2016	4.1
Proximal and Distal Mentors	Six High-School Students (Skype)	2018	4.2
Exploring the 3D Printing Process for Young Children	33 Third Grade Students	2018	5
Observations and Interviews of 3D Printing Shops	20 Clients and Staff of TAMU Printing Shops	2019	6
Newcomers' Web-Guided Specification of 3D Printing Ideas	21 3D Prinitng Newcomers	2019	6
Analysis of Thingiverse Users and Metadata	Thingiverse User and Design Metadata	2020	7
Analysis of Online 3D Printing Services	Online 3D Printing Services and Social Media	2020	8.1, 8.2
Design and Evaluation of HowDIY	20 3D Printing newcomers	2020	8.3, 8.4

All studies directly related to this theme are listed in Table 1.1.Please refer to this table to determine which study is located in which section.

Following this chapter, Chapter 2 covers the background and motivation for this dissertation, outlining the existing approaches to broaden participation with 3D printing and highlighting the potential impact of digital fabrication technologies. Chapter 3 provides the theoretical foundation that serves as a lens for all subsequent chapters. Chapter 4 provides insight into how minimal proximal and distal (e.g. online) interventions in formal education settings can help foster student peer-mentorship and literacy with various technologies to sustain technological expression beyond the length of these interventions. Chapter 5 studies how a 3D printing service process may be adapted within similar formal education interventions to help spark 3rd graders initial interest and understanding in 3D printing.

Chapter 6 presents two studies, a ethnographic study observing how people initiate and sustain collaborations in proximal 3D printing services, paired with a more-controlled lab study investigating how newcomers with no prior 3D printing experience may be successfully introduced to 3D printing through a brief intervention. Chapter 7 details a study of online printable design sharing conducted on publicly available data, outlining distinguishable user classifications and presenting machine learning datasets and tools to help facilitate design-reuse through multi-modal (i.e. text, images, and 3D renders) classification, retrieval, and recommendation. Chapter 8 connects these practices to the landscape of online 3D printing services through a qualitative analysis of online printing service interfaces and surrounding social media comments, presenting the design and evaluation of the HowDIY system to help anyone initiate collaboration with 3D printing services. Chapter 9 outlines avenues for future work within a meta-design framework for facilitating the collaborative specification of 3D files, and summarizes contributions of this research.

2. BACKGROUND AND MOTIVATION

Digital Fabrication has the potential to drastically change the way we buy and make physical goods, converting digital designs into physical artifacts [37]. This chapter draws from research relating to 3D printing functions and facilities, 3D printing users, pedagogical experiences surrounding 3D printing, and novel applications from HCI and other domains to situate the findings of the dissertation. As the halcyon days of HCI that broadened participation in *"personal computation"*, from allowing anyone to dynamically represent complex calculations in spreadsheets (e.g. visicalc [38]) to creating *What-You-See-Is-What-You-Get* (WYSIWYG) interfaces to translate bit-mapped graphics to desktop paper printers through postscript [39], understanding how people learn to utilize and communicate with 3D printing machinery may significantly broaden participation with these emergent *"personal fabrication"* technologies.

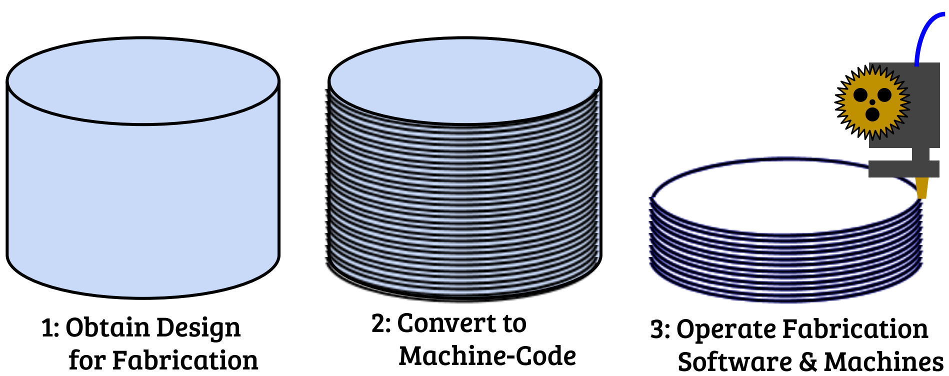

Figure 2.1: All Digital Fabrication Workflows involve 3 steps, converting digital designs into physical objects through translation to machine-specific code. Often this process is not WYSIWYG

2.1 3D Printing and the Future of Manufacturing

Manufacturers of the future need not exist within factories, but can be empowered anywhere by emergent 3D printing technologies to fabricate many personalized and unique applications: from supporting accessibility applications [40] to rapidly producing PPE devices during the COVID-19 pandemic [41]. There is a hope that participation in 3D printing can be broadened to ***anyone*** through membership in an increasing number of supportive "Maker" communities (e.g. Makerspaces and FabLabs), ostensibly *open* to anyone. However, the general population faces challenges and barriers even **before** interacting with technical printing software and hardware in these spaces. One challenge is knowing *what* to fabricate; such knowledge requires an understanding of the capabilities of 3D printers, and the adeptness to combine software and hardware at various stages of 3D printing to produce artifacts with the desired shape, kinematics, statics, and dynamics [25].

3D printing technologies may create the means to effectively distribute design and production [42], profoundly impacting supply-chains [43]. Retailers can benefit from accelerating and distributing flexible manufacturing, while creating toolkits to afford customers better customization and fabrication of their products [44]. In turn, broader sociocultural understanding of introductory 3D printing concepts may further drive, diversify, and democratize fabricated innovations through an increasingly-motivated population. Instead of just one organization iteratively improving products to then distribute from an insular location, products may be developed and documented in a distributed manner all over the world to be produced by anyone, anywhere.

However, 3D printers presently require broader situated and embodied sense-making processes, involving significant tacit skills to operate by oneself [9]. Eventually, 3D printers may be able to embody the domain- and machine-knowledge necessary to be usable in every home [25]. However, there are many challenges with understanding the present domain of 3D printing, namely how to create artifacts with desired shape, kinematics, statics, and dynamics [25]. Advances in how to make 3D printing more interactive (e.g. *WYSIWYG*), such as investigating how humans can better co-design with machines [45, 46], provoke the tension between designer skills and material-fabrication [47]. These tensions can be alleviated through novel CAD applications may better support 3D design with remote mentors [48], design with reusable parts [49, 50], design with better understanding of static forces [51], design to better adapt everyday objects [52], design with code [53], design with better understanding of uncertainties and errors [54], and design with tangible interactions and augmented reality feedback [55, 56, 57]. Translating design intent to machine implementation is another topic of interest, such as automatically optimizing printing products' strength [58, 59, 60], size [61, 62], speed [63, 64], and wasted material [65, 66, 62]. Yet, each application of 3D printing requires different sets of these constantly-evolving tools and processes. Even if these tools and processes were all readily-approachable and available to the general population, it would take a very knowledgeable user to successfully search, interpret, and apply a set of these tools and processes for each unique application of 3D printing. Not all newcomers may be motivated or able to obtain this knowledge *before* planning to print. This dissertation focuses on how to better motivate and facilitate these initial sense-making process so that non-Makers may utilize 3D printing.

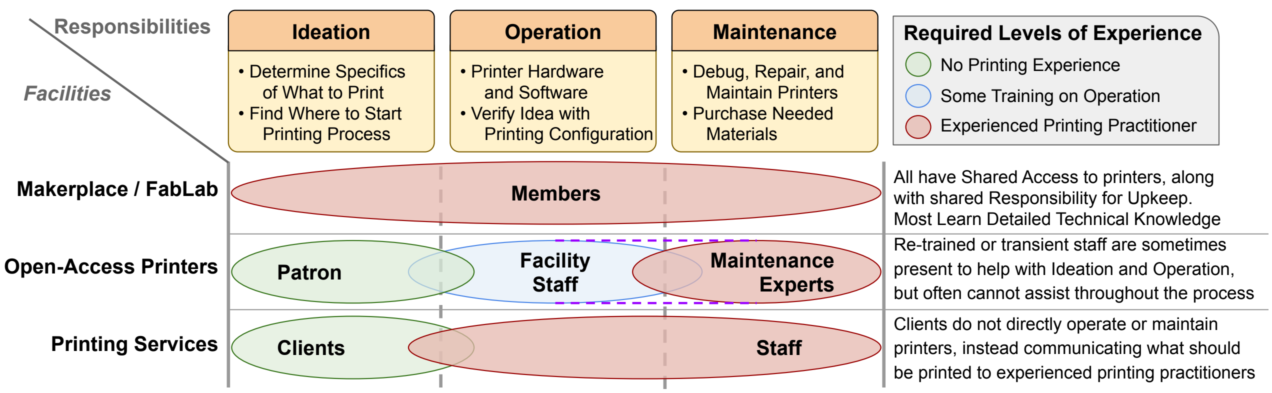

Figure 2.2: Printing Services insulate newcomers from many details of printer operation and maintenance by facilitating interactions with experienced printing practitioners, unlike other facilities that require direct operation of printing machinery with intermittent or inexperienced guidance.

2.2 The Present Landscape of 3D Printing Users

Baudisch and Mueller describe most current 3D printing users as *enthusiasts* who explore the "technological possibilities rather than the applications" [25], early adopters and "*makers*" who hold enthusiasm towards directly operating printing machinery. As the majority of users, 3D printing technologies are often developed with affordances tailored to these enthusiast-audiences, which then impacts who can effectively identify and learn 3D printing technologies.

Sites like *Makerspaces* and *FabLabs* are often run by enthusiasts how collaborate and share work [67, 68], requiring a membership fee (usually $50 to $100 a month [69]) to participate with peers and a range of fabrication equipment including 3D printers. Makers, those who interact in these spaces, participate in informal sharing of expertise [69, 67, 68]) that empowers them to pursue projects that would be less feasible on their own [70]. Easley et al. describe how high-school students may feasible facilitate 3D printing as a service, focusing on the communication hand-offs needed for the student-staff to collaborate amongst each other with the limited guidance of one experienced 3D printing practitioner [7]. While makerspaces-like facilities are inclusive communities that are ostensibly accessible to anyone, membership fees and feelings of not belonging limits many newcomers from joining these spaces [23].

Who prints is dependent on where newcomers can gain awareness and access to printing practitioners, who can help newcomers avoid many initial failures that cause many to abandon the technology completely due to a lack of self-efficacy and social support [8]. This directly limits diversity of who 3D prints [71]. In addition to addressing the prejudices of those who may facilitate 3D printing practices and facilities, awareness and access to 3D printing opportunities must be made available for an egalitarian future of democratized innovation.

2.3 Newcomers' Current Printing Process

There are many avenues to begin learning 3D printing (See Figure 2.2), from Makerspaces where peers proximally learn printing practices from each other [70] to online platforms that may provide iterative feedback and guide learners from a distance [29]. All printing processes entail obtaining a design (e.g. a 3D file and documentation), converting this design into machine code understood by digital fabrication machines, and then operating the machines to create the intended product. Effective methods teaching newcomers to design and print are not sufficient to broaden participation in 3D printing, unless paired with effective methods to motivate newcomers to learn. The motivation to utilize 3D printing may be separate from the motivation to learn 3D printing knowledge and skills. Early failures in learning and conducting printing processes can dissuade newcomers from attempting them again in the future [72].

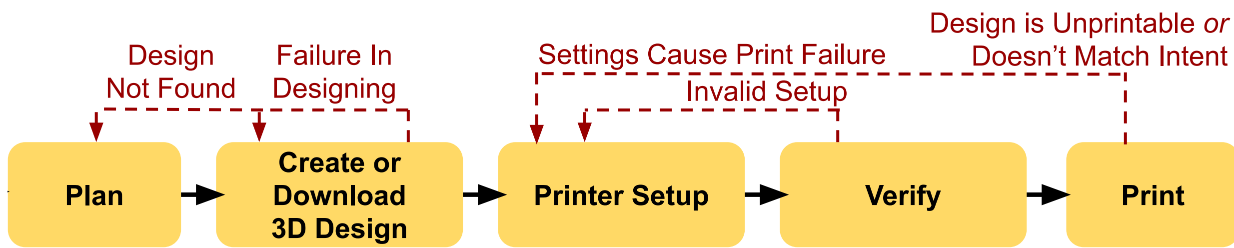

Figure 2.3: Printing Center workflow described by Hudson et al. where a sequence of steps must be followed, with challenges that can force newcomers to redo many efforts

Hudson et al. study how universities, libraries, and schools integrated 3D printing into their existing services, giving insights about how people who are **not** traditional *"Makers"* utilize those printers [72]. These deemed *"casual makers"* are primarily motivated by the product of printing, and face several challenges that are often exacerbated by lack of timely and sufficient support for printing, shown in Figure 2.3. These print centers host 3D printers typically found in Makerspaces, but do not always host proximal printing-enthusiasts to help guide newcomers. Notably, many *casual makers* did not want to visit Makerspaces, because they found it intimidating to approach the 'experts' in these spaces. Additionally, Casual makers often wished they did not have to operate the machines, which most spaces required (e.g. *"I want it to be a black box that's just a service... I'd much rather let somebody else [own the printer], someone whose full time job it is to maintain this device"*). However, 3D printers cannot be presently operated as black boxes, often presenting non-intuitive operational issues, requiring experienced practitioners to successfully maintain and operate [72].

Determining what can be printed (i.e. *"printability"*), a "fluid and provisional attribute of the printing arrangement", requires "artful interactions of heterogeneous media systems" according to Dew et al. [9] Experienced practitioners are constantly negotiating print qualities with cost (e.g.

money, printing time, and post-processing time), and mitigating risks with experience. Printing technologies are nested within broader embodied and collective sense-making processes.

Shewbridge et al. imagined a future where these issues are solves, and 3D printers can be effectively utilized in any household [73]. With an imaginary “faux 3D printer”, they found that households wanted to replicate existing objects, but also wanted to create new objects or modify existing objects. Often the ‘printed’ items could easily be purchased, making 3D printing a utilitarian appliance as much as a creative tool. Many households may not have access to a 3D printing enthusiast, but we can imagine a future where the products of 3D printing can be utilized in every household.

2.4 Learning 3D Printing Online

In order for 3D printing to be accessible within diverse populations, including those in rural locations with access to printers but not experienced proximal mentors, proximal mentor roles may be emulated through interactions with online social resources [27, 74, 75, 76, 77]. Existing online resources provide the information needed for individuals to learn many practices, but finding and utilizing online 3D printing resources is not always trivial [27]. This challenge is especially pertinent when learning practices surrounding emerging technologies [77], where early adopters of these technologies may be more dispersed and have less access to each other as proximal social resources [11].

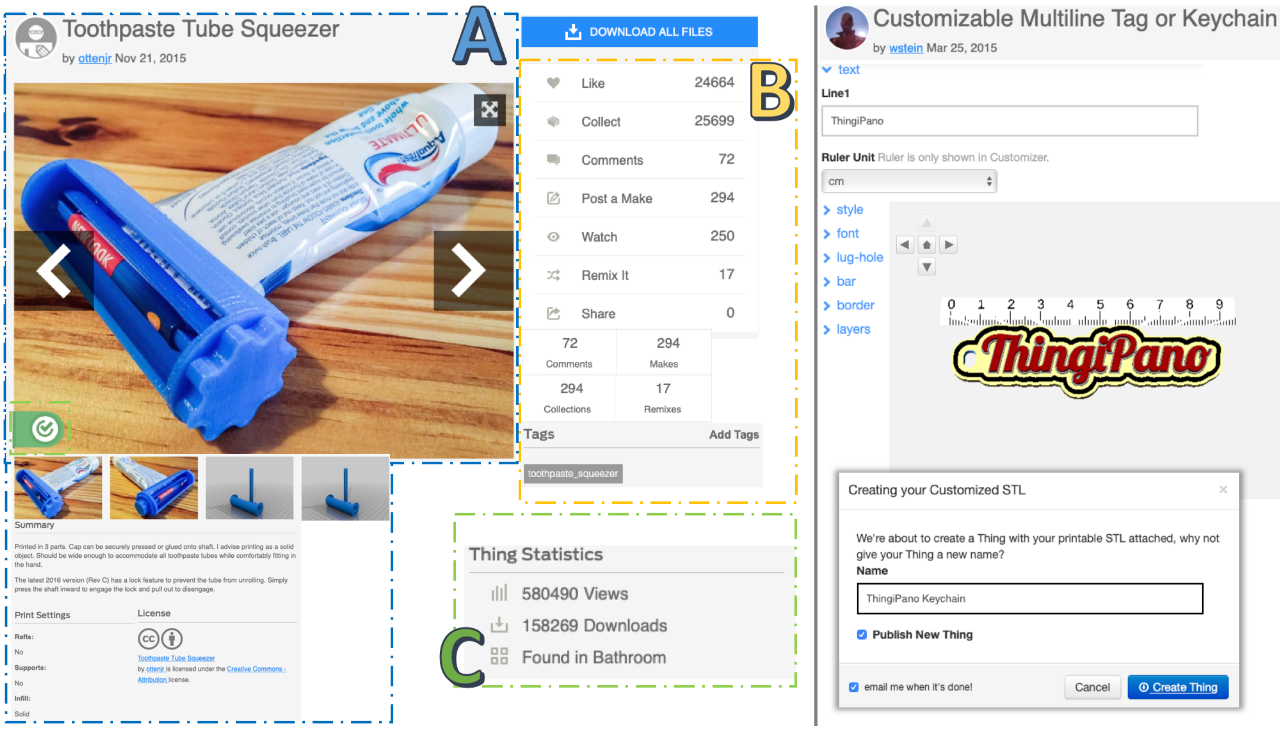

Figure 2.4: Example Design from Thingiverse (*left*) with Designer-Annotations (A), Community-Annotations (B), and Site Information (C). The Thingiverse Customizer affords parameterized 3D designs (*right*). Reprinted with permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1].

2.4.1 3D Printers as Proponents of Reuse

Open source 3D printing projects can provide participants opportunities to reproduce and reuse community resources [78, 29, 30, 31], similar to how a professionals could guide an apprentice. Inspired by prior work on how individuals reuse accessible resources, such as in patents [79, 80, 81] and in open source code [82, 83, 84, 85], Flath et al. explored how individuals reuse open sourced 3D designs on Thingiverse to create new designs (i.e. 'remixing') [78]. They note that over half of the designs on Thingiverse are documented remixes, and claim that the platform itself is of "*paramount importance in the creative process of its users*". Not all categories of design are remixed evenly or symmetrically, with many remixes crossing categories and functionalities. Designs that are well-tagged, featured on the landing page, or were designed as a 'Customizer' received more remixes and were generally more popular. Customizer applications on Thingiverse make designing relatively simple by allowing participants on the site to specify parameters that generate a 3D model (i.e. changing the size and text of a keychain). Flath et al. emphasize that providing affordances for remixing may attract many more users and result in many more published designs on platforms like Thingiverse, illustrating this by plotting the sudden increase in rate of designs published after the introduction of the Customizer application. However, they also note that users who publish with the Customizer tend not to ever publish without the Customizer, indicating many Thingiverse users do not publish or perhaps create designs in traditional CAD applications.

Friesike et al. investigated why people remix through interviews of Thingiverse users that were then validated through quantitative measures of Thingivere design-related sharing activity, identifying that people remix for Inspiration, Play, Learning, Speed, Improvement, and Empowerment [28]. Remixing can broaden designers' creative horizons, pushing the limits of what they can create with processes that are similar to "learning-by-doing" [86, 87] and "reverse engineering" [88]. Analyzing comments on Thingiverse designs, Alcock et al. found that many utilized the platform to learn the basics of 3D printing processes [27]. They observed four main challenges to understanding and utilizing designs from Thingiverse: *1) Understanding Object Functionality* (how the end result should function, as well as how to assemble pieces if necessary), *2) Understanding Design Customizability* (how to obtain a design with minor modifications), *3) Understanding Design Printability* (how to print a given design, including settings such as support structures), *4) Understanding Design Creation* (how qualities of the designs are created by the uploader). However, not all of remixed designs are particularly innovative or useful to other users [31]. Hudson et al.'s research observed that operators would often refer users having trouble with CAD to free online 3D designs to print on Thingiverse, but cautioning that the Thingiverse homepage often featured more complex designs that are not conducive to newcomers' early learning [23]. This makes finding useful files more difficult, because designs of lesser quality or lesser flexibility across practices make finding relevant and applicable designs like finding a needle in a haystack.

Hoffman et al. developed a framework and design-tools to better document design-intent explicitly in 3D CAD design programs, facilitating better easier and more-successful reuse from designer-participants that used their tool [49]. However, design annotations may be difficult to decontextualize to other workflows [89]. Ludwig et al. note that users primarily look for help through Google, that users perceived CAD modeling to be an individual process, and that mistakes in created or downloaded models often only become apparent after printing [90]. While people often try to learn 3D printing on their own, and there is sufficient resources online to teach many aspects about printing, newcomers often need guidance when identifying which resources are necessary for any given 3D printing process.

2.4.2 Teaching 3D Printing with Online Resources

Hudson et al. explored how children can effectively seek and receive help from online resources when 3D designing, including web tutorials, video tutorials, and in-application tutorials [91]. They note that children will often seek and give help from peers and mentors if available, but face several problems when seeking help on their own (e.g. query formulation, evaluating 5 trustworthiness of sources, and understanding text in forums). Children tended to imitate visual elements from tutorials, repeating steps exactly, even if they didn't understand why certain actions were performed. When seeking help via Google, children successfully found help relevant to their intended searches 80% of the time, but rarely successfully recognized or applied that help. Prior impressions of certain online resources led to participants improperly rejecting some sources like forums, one saying "why would I want to use a forum... It's just a bunch of people arguing with each other". Without expert recommendations or better contextualization of online resources, many may not identify and utilize online learning resources.

In addition to Hoffman et al.'s research for making online 3D designs more transparent [92], Chilana et al. investigate how CAD novices can be assisted by remote experts [48]. They first observed how pairs of novices texted experts for help while designing, finding that novices had difficulty formulating questions because of not knowing expert-language and had difficulty conveying visual contextual information. They designed Marmalaid, a CAD and texting hybrid application with affordances for sharing 3D views and for sharing annotations of geometric features. They found that users were able to ask more frequent and more effective questions when they could provide better contextual information. Collaboration in 3D printing is dependent on many situated aspects of newcomers' design-intent and design-process. While there has been significant research to make 3D designs more transparent and CAD more newcomer-friendly, 3D design is only one optional step in the 3D printing process. This dissertation attempts to begin disambiguating printer function (e.g. what to print) from printer operation (e.g. how to design and how to print), so that newcomers can focus more on the former without delving into technical details of the latter.

Ludwig et al. describe how to re-design 3D printers to better afford a *"Internet of Practices"* [90], where they conducted a series of technological probes to investigate how visualizations of data collected from ambient sensors connected to printers may help online mentors better help newcomers learn the practice of operating printers. In this research, instead of continuing investigations on how people may learn to operate and debug printers with remote help, we investigate how people learn *what* can be printed without detailed knowledge of operating machinery.

Nam et al., in collaboration with the author, investigated the perception of 3D printing objects fabricated with consumer-grade printing technologies available in many printing facilities [93]. Participants with no prior printing experience compared mass-produced objects with 3D printed geometrically-identical copies, answering questions about perceived value and writing imagined stories about these objects. The value of 3D printed objects were largely represented by flexibility and participation in production, 3D printed objects have potential to become everyday objects in themes of replicability, representation, and material simulation. Further, as common FDM and SLA products were valued less than their mass-produced clones, emphasis should be placed on supporting print-specifications of customized geometries not financially-feasible through traditional mass-manufacturing (e.g. injection molding). One conclusion is that emphasis should be placed on making a larger variety of materials and printing processes accessible and affordable to everyone, perhaps through fabrication services that can amortize the cost of expensive fabrication machinery.

In this chapter, we have presented an overview of 3D printing's potential societal impact, existing 3D printing practices and facilities, and research surrounding introducing newcomers and novices to 3D printing technologies. This dissertation extends this domain of literature by further explaining how true newcomers to 3D printing, those with virtually no exposure or experience with 3D printing processes, may become "casual makers" or more-experienced printing practitioners. The only work prior to this dissertation and associated publications, to our best knowledge, is that of Sheridan et al. that only investigate what newcomers would produce with printers that could make anything. We investigate how newcomers may utilize 3D printers, peripherally participating to potentially become practitioners.

3. SITUATED LEARNING AND ONLINE COLLABORATIONS

3.1 Situated Learning

Lave and Wengers' situated learning literature present learning as a phenomenon that occurs through co-participation in a given practice [94, 10, 95, 96]. Newcomers may learn about the needed 3D printing technologies with co-participation with experienced printing practitioners and communities. Learning is "an integral and inseparable aspect of social practice", and that all activities and powers of abstraction are thoroughly situated [10].

3.1.1 Legitimate Peripheral Participation

Central to their idea of Situated Learning is the concept of Legitimate Peripheral Participation, and is defined as a "descriptor of engagement in social practice that entails learning as an integral constituent" [10]. In other words, all learners participate in social interactions to 'become' an individual who is capable of fulfilling more challenging and pivotal practices in a community. This process of 'becoming' involves changing locations and perspectives in the social world, gaining learning trajectories, developing identities, and becoming a member of related communities [10, 97, 94]. The peripheral of LPP "suggests an opening, a way of gaining access to sources for understanding through growing involvement" [10], an opportunity to *'become'*. They emphasize the periphality does not imply there is a central role of any community, but that LPP "can be a position at the articulation of related communities" [10], which is supported by recent analysis of online UX communities [10]. LPP is how "identity, knowing, and social membership entail one another"[10], but LPP is not all forms of participation.

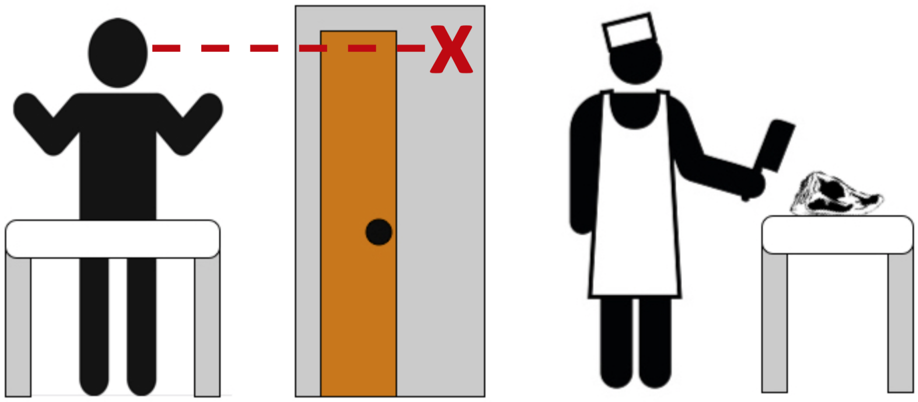

Figure 3.1: Illustration of the butcher example from Lave and Wenger's *Situated Learning*, where a apprentice (left) cannot see experts performing a practice (right), and will not cross the door due to self-enforced constraints

3.1.2 Access and Transparency in Butcher Apprentices

Lave and Wenger explain two concepts needed for LPP to occur: *Access* and *Transparency*. ***Access*** is an individual's ability to interact with "information, resources, and opportunities for participation" [10]. Lave and Wenger demonstrate common issues of *Access* in a butcher apprenticeship program, where people entered hoping to become a butcher, but faced a common problem. Newcomers were tasked with wrapping pre-cut meats prepared by more experienced members in a different room separated by a door, blocking both vision and sound. This door denied the relative newcomers the knowledge, self-efficacy, and identity to '*become*' full-fledged butchers capable of creating the cuts of meat (see Figure 3.1. While they saw the product of the practice, they had no idea how it was made because of a door. This door could be crossed at any point, but the feeling of being an outsider and the lack of awareness about crossing-procedures kept most from opening the door [10].

Figure 3.2: Illustration of Vygotsky's Zone of Proximal Development, where requirements to complete a task can be distinguished into three groups: accomplish alone, accomplish with help, or not able to accomplish

In addition to access, Lave and Wenger describe a need for ***Transparency*** of both actions within the community and of the artifacts that are utilized in these actions [10]. They define transparency as "a way of organizing activities that make their meaning visible". For example, from the butcher-apprentice example, it is not easy to determine how meat was cut if only shown the end product. To better understand transparency, we look through the lens of Vygotsky's social development theory and his Zone of Proximal Development (**ZPD**), which state that knowledge and meaning are socially constructed and acquired through interactions with others with differing levels of expertise [13, 98, 99]. The ZPD can be defined as the "distance between the everyday actions of individuals and the historically new form of the societal activity that can be collectively generated as a solution to the double bind potentially embedded in... everyday actions"[100]. In other words, what people can learn at a given time is dependent on what they know at that time, and what resources are available to assist them. We can view transparency as the visibility of the meaning of an activity or artifact, based on the ZPD of the onlookers. While Situated Learning and LPP approaches learning from a phenomenological perspective, focusing on levels and attributes of participation, Vygotsky's theories provide a lens into how learners' roles result in a learning dynamic between individuals and their environment. Learning and development of one's ZPD occurs through interactions with More Knowledgeable Others (**MKO**) of different levels of expertise [101, 102]. While it can be difficult for online community members to differentiate the levels of experience of their peers [76], the shared multimedia may be able to fulfil certain roles of MKO's [103, 74, 76, 104, 77, 105].

3.1.3 Measures and Principles of "Becoming"

Learners engage by "becoming a participant" [10, 97, 94], so learners online do not just absorb knowledge on demand, but learn through the process of 'becoming' participants of a practice. As Rogoff said in her work on Situated Cognition, "Individuals transform culture as they appropriate its practices, carrying with them forward to the next generation in altered form to fit the needs of their particular generation and circumstances... Creativity builds on the technologies already available, within existing institutions... Individual creativity occurs in the context of a community of thinkers" [106]. Creative processes are indicative of LPP, so measures of creative processes such as design ideation [107, 108] can be employed when evaluating LPP. Bagdy et al. observed how teenagers informally learned practices through LPP with social media, shaping student's perceived future trajectories [74]. LPP should result in the building of self-efficacy, the evaluations of one's own ability in a given domain [109, 110, 111]. Wenger states that the process of 'becoming' involves being acquainted with three principles: *Mutual Engagement* (Social Relationships and Processes), *Joint Enterprise* (Domain and Goals of the Community), and *Shared Repertoire* (Communal Resources) [94]. We can evaluate aspects of 'becoming' as one's increasing familiarity with these three principles within a given domain. By peripherally viewing and interacting with online communities, learners may become part of ever-evolving practices, tacit knowledge and all [74, 105].

3.2 Distance Matters

Hudson et al. notes in their observations of users of Print Centers that they do not have established community expertise like Makerspaces, despite users often relying on facility-staff throughout the printing process [23]. Community expertise was often not established because printing practitioners were transient and only available in the print centers occasionally, or were absent and replaced by re-trained staff from the location (e.g. libraries and museum staff). Even when there are experienced practitioners present, while they do lower the barrier to access for 3D printing technologies, there are several avoidable challenges that newcomers face [23]. In this dissertation, we identify barriers and challenges to establish these collaborations, proximally and at a distance, with Olson and Olson's framework for remote collaboration [14].

3.2.1 Olson and Olson's four concepts for successful collaborations

We present Olson and Olson's four concepts from *"Distance Matters"*[14], which generalize beyond remote collaborations [16, 15, 17, 18, 19, 20], to identify challenges to 3D printing collaborations. There have been presented four concepts requisite to successful collaboration in Olson's framework: *Common Ground, Coupling of Work, Technology Readiness, and Collaboration Readiness* [14]. While Olsons' framework was originally created to compare co-located and remote collaborations, it has been shown in HCI literature to be effective in more general settings [16, 15, 17, 18, 19, 20]. We discuss Olsons' four concepts and how they relate to 3D printing.

1) Collaboration Readiness implies there is information to share and that people are rewarded for sharing. The Olsons' suggest to not introduce communication technologies before establishing a culture of sharing and collaboration. For printing, this implies motivations for users (e.g. printing capabilities) and facilities (e.g. money). This motivation may be depressed if technology does not support the collaboration workflow, described next.

2) Technology Readiness concerns how habits and infrastructure of collaborators may interfere with adoption of technologies necessary for successful collaboration. It is known that first impressions make a big impact when adopting collaboration technologies ("once burned, twice shy")[14], which is observed in 3D printing [72, 7]. The Olsons' recommend that "advanced technologies should be introduced in small steps. It is hard to see far in the future where not only are technologies available, but they fit an entirely new work form". This dissertation helps further identify and order the 'small steps" needed to introduce newcomers to 3D printing collaborations.

3) Common Ground is the knowledge and awareness collaborators share about a task and each other, situated in the cues available within a given moment. There is a tension between asking the right question versus finding the answer in common ground. The Olsons suggested that establishing common ground before beginning a task will lead to greater productivity, but recent work argues that sometimes it is more beneficial to breakdown **content common ground** (*know-that*) while accumulating **process common ground** (*know-how*) in certain tasks [16]. Mao et al. claim "the increasing process common ground, in fact, allows the breaking and updating of content common ground to be possible." Failing to build process common ground may lead collaborators to become "frozen" in their established content common ground, be "seized" by information bias, or settle on a "premature conensus" for the discussed problems and solutions. This is not a new idea, as Rittel states: "you cannot gather information meaningfully unless you have understood the problem but that you cannot understand the problem without information about it" [112]. Users and 3D Printing Facilities must establish processes and workflows for collaboration, in addition to establishing what to print.

4) Coupling of Work is defined by the extent and kind of communication required to collaborate. Tightly-coupled work requires more frequent and higher-bandwidth channels of communications, and where loosely-coupled work has fewer dependencies or is more routine. Coupling is dependent both on the nature of the task and the common ground held between participants. An experienced printing practitioner ordering a tested design would be more loosely coupled than a newcomer ordering a 3D design that has never been tested. More tightly-coupled tasks are more likely to succeed if collaborators are co-located, and if interactions are more formal. To broaden participation of 3D printing, this dissertation investigates how to facilitate and differ the tightly-coupled sub-tasks involved in utilizing 3D printing services.

In this chapter, we have provided theories and frameworks for understanding how people may learn the Practice of 3D printing through collaboration with More Knowledgeable Others. There are two ways to learn 3D printing, through exhaustive trial and error to determine machine-specific incantations and 'printability', or through collaboration with experienced others. As trial-and-error can be costly and demoralizing, this dissertation focuses on the requirements for successful collaborations surrounding 3D printing. This provides a view of future 3D printing processes where collaborative elements are more explicit and formalized (e.g. through printing services), affording broader *access* to experienced printing communities which can *transparently* explain aspects of the printing process to newcomers, so that they can *become* capable of 3D printing. The following chapters explain how to "*open the door*" for 3D printing newcomers, so that future fabrication processes and technologies may be informed by a larger diversity of end-user behavior.

4. TOWARDS SUSTAINABLE HANDS-ON TECHNOLOGY-INFUSED LEARNING THROUGH PROXIMAL AND DISTAL COLLABORATIONS IN FORMAL EDUCATION SETTINGS *

Emerging Technologies are constantly being integrated into everyday practices, demanding that everyone has sufficient technological knowledge to participate within these practices. Hands-On technology-infused learning (e.g. *Making*) often is practiced in informal settings, where learners can explore endless possibilities while collaborating with their peers. However, as mentioned in Section 3.1, More Knowledgeable Others (MKO's) are needed to help guide learners to fulfilling outcomes. While there has been a large body of research of how *Making* is practiced in informal learning settings, this chapter contributes better understanding of how similar forms of collaborative learning may be fostered in formal learning environments (e.g. classrooms).

While the presence of Makerspaces and other informal hands-on technology-infused learning environment are becoming more ubiquitous [113], there are many who still may not have the opportunity to participate because of the cost of entry and because of living in more isolated communities without such facilities (e.g. rural locations). Formal learning environments like classrooms are near-universal, but studied hands-on technology-infused interventions in formal learning environments have been transient and for only short durations. Making, which often values exploration and discovery through informal collaborations [114, 115], is at direct contrast of formal learning environments like schools where students are encouraged to learn through a regiment of curricula to meet accountability standards (e.g. testing). The first section in this chapter, instead, focuses on how students may form collaborations similar to Communities of Practice (*CoP*'s) to sustain their learning beyond short interventions. The first section contributes how short interventions may sustain community-based learning of unfamiliar technologies.

Parts of this chapter are reprinted with permission from: **1)** "Toward a making community of practice: The social aspects of elementary classroom-based making" by Alexander Berman, Brittany Garcia, Beth Nam, Sharon Chu, and Francis Quek in the Proceedings of the 6th Annual Conference on Creativity and Fabrication in Education. 2016. **2)** "Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools" by Alexander Berman, Sharon Lynn Chu, Francis Quek, Osazuwa Okundaye, Leming Yang, Elizabeth Deuermeyer, Enrique Berrios, Skylar Deady, and

The second section extends this knowledge beyond proximal interventions, contributing insight into how mentors may collaborate with students from a distance (e.g. online). With online interventions, mentors could reach more students and reach those who are normally too costly to visit (e.g. rural locations). The second section contributes how online collaborations may facilitate learning of technology-infused practices in classroom communities.

4.1 The Social Aspects of Classroom-Based Making

Studies of informal learning of Making demonstrate how newcomers to these hands-on technologies may learn from their peers to become proficient enough to design artifacts independently. This sections views how similar forms of social learning may be established in shorter, and more-formalized, sessions. The study described in this section investigates how implementing curricula-aligned "*Making*"-sessions in public elementary school classrooms may eventually lead to the class of students becoming independent Makers who can engage with hands-on technologies both in and out of school.

4.1.1 Collaboration in the Making

Few papers in the literature can be found that focus specifically on understanding the social aspects of Making with children. Telhan et. al. [116] conducted a study in which children created an LED mural about social issues that was later displayed for viewing by the community in different libraries. This Making activity drew the Maker participants together with non-Makers into a community appreciating the same products from Making activities. In a study of three child-oriented Makerspaces, Sheridan et al. [70] found that help from more experienced members guided and motivated newer members to take risks and try new creative activities. The newer members harnessed each others' experiences through discussion, discourse and observation, to fuel ideas for their own Making project. Informal Makerspaces thus encourage collaborative learning by providing a common physical area for children to share and combine their products and processes [117]. Through such sharing processes in Making, Naghshbandi [118] argued that children are not only able to achieve creative solutions for a problem, but also develop empathy for one another by listening to each other's ideas.

Bar-El and Zuckerman's [119] work on Maketec is especially pertinent to the study of social aspects of Making. Maketec is a program that brings in teenagers to mentor children in a public drop-in Makerspace in a library. Although their work is still preliminary, they highlighted the significant role of the teen mentors and described briefly how visitors interacted with the mentors: "one visitor perceived some mentors as more helpful than others and another expressed his desire to observe the mentors work on projects, and to serve as the mentor's apprentice". They further argued that the role of the mentors is an important part of the process of 'unstructured learning' that takes place in such a Makerspace.

Previous research that focused on the analysis of learning through Making have highlighted aspects of the process that are also highly social in nature. Bevan et. al. [120] for example, studied children's behaviors in a museum-based tinkering studio program. In a collaboration with STEM practitioners, they articulated the Tinkering Learning Dimensions Framework that presents indicators of Making-centered learning in after-school environments: engagement is the amount of time spent with the Making tools and the display of motivation or affective investment to others; initiative and intentionality are about how children set goals, and seek and respond to feedback from others; social scaffolding indicators relate to children requesting or offering help to solve problems, inspiring new ideas/approaches, and physically connecting to others' work; and, development of understanding indicators were seen in the students expressing realizations, offering explanations, applying learned knowledge and striving to understand.

Similarly, Wardrip and Brahms [114] studied Making by families and children in a Pittsburg museum Makerspace from a sociocultural perspective. They identified seven practices that take place in the Makerspace that appear to support learning: inquiring, tinkering, seeking resources, hacking and repurposing, expressing intention, developing fluency, and 'simplifying to complexify'. The authors then articulated how these processes point to the need for the design of facilitation in informal Makerspaces through *expertise* (facilitators bringing in domain expertise and passion for the activity), *inquiry* (facilitators inviting learners' inquiry to develop choice, intention, interest and personal learning pathways), *scaffolding* (facilitators supporting learners' confidence with tools, materials and processes), *co-learning* (facilitators being colearners in Making pursuits), and *leveraging learning partners* (facilitators leveraging children's adult partners – parents, grandparents, etc. – to extend habits and pathways). We adapt Wardrip and Brahms' framework to ground our formal classroom observations with known learning practices in Making.

4.1.2 Study Description

The analysis that we present in this section drew from a dataset collected during a longitudinal study that engaged two 5th grade classes (ages 10 to 12) at a local public elementary school. The population of the school consists of a large number of students from groups typically underrepresented in STEM fields, specifically from the Latino and African-American communities. The project worked with two classes out of four 5th grade classes in the school. The study incorporated one week of curriculum-based Making class sessions into the classroom for every unit that was covered in the science classes of the 5th graders. The school curriculum consists of a total of three science units over an 18-week semester. Thus, we designed and implemented three different week-long Maker activities in total through a curriculum-matching process with the teachers of the respective classes.

Figure 4.1: Layout of Elementary School '*Making*' Classroom with audio and video recording equipment. Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"* [2].

4.1.2.1 Curriculum-Based Making

Figure 4.1 shows an overview of a curriculum-based Making session in the science class. Each classroom was led collaboratively by the elementary science class teacher and a support person (a technically trained member of our research team). Both were assisted by two helpers who provided logistics support, and mentoring help to students in terms of answering their questions about the Maker activities. The helpers were specifically instructed to not be intrusive in the students' Making process, and to intervene only when asked or when they observe serious difficulty in Making. Each class lasted an average of 65 minutes. The number of students in each class ranged from 16 to 25, with a total of 46 participants in our study in the 5th grade. All students provided verbal assent to participate, and parents signed consent forms prior to video and audio data collection.

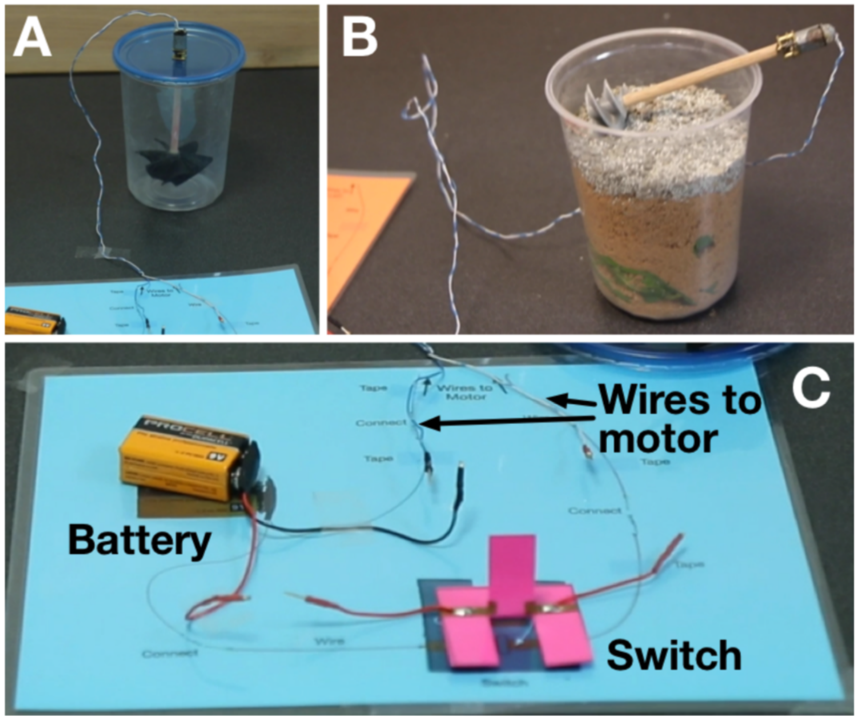

Figure 4.2: Maker Materials consisting of a simple circuit (C) used to power a mixer (A) and a drill (B) to facilitate students' learning of science curricula. Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"*[2].

To be able to investigate the development of a Making-based community of practice among the students, our analysis in this section followed 12 randomly selected child participants (6 males and 6 females) in-depth across the week-long Making interventions as they interacted with the same components (a rotational motor circuit – a rotational motor connected to a battery through a paper switch – see Figure 4.2-C) in two of the science units of the semester of our study.

4.1.2.2 Study Schedule

The first Maker week in our analysis took place in September 2015, and addressed the science unit of 'Matter and Energy: Mixtures and Solutions'. More specifically, the learning goals of the unit were for students to understand that some mixtures maintain physical properties of their ingredients, such as iron filings and sand, while in solutions, such as salt in water or Kool-Aid in water, the process of dissolving makes the constitutions harder to separate. On day 1 of the Maker week, the students built an electronic mixer using a basic circuit with a rotational motor and a 3D-printed mixer-head. All Maker-parts were provided as a kit that our research team assembled. With their electronic mixer, they mixed glitter with water and made observations about the mixture (see Figure 4.2-A). This was the students' first encounter with the rotational motor circuit. On day 5, the last day of the Maker week of the 'Mixtures Solutions' unit, the students built the same electronic mixer again with the rotational motor circuit, and mixed red Kool-Aid powder with water. They recorded observations on the properties of the solution formed.

The second Maker week in our analysis occurred in November 2015, 41 days after the 'Mixtures Solutions' unit. This second unit addressed the topic of 'Earth and Space: Earth Changes and Fossil Fuel Formation'. The learning goals of the unit were that earth contains useful resources and that its surface is constantly changing, as well as the processes that led to the formation of sedimentary rocks and fossil fuels. The students created a model of sediments by layering kitty litter, spinach, and salt inside a transparent cylindrical plastic container. This allowed the students to observe the different layers that simulate the layers of sedimentary rock as they would form naturally over time. The students observed the spinach as it became rancid over the week. On day 4 of the Maker week, they built an electric motorized drill to uncover the 'fossilized' spinach to simulate how fossil fuels would be extracted from beneath the earth. They attached a 3D-printed augur head at the end of a dowel rod onto a geared rotating motor (see Figure 4.2-B). This allowed them to dig through the layers of salt and kitty litter to get at the decaying spinach. The drill is very similar to the electronic mixer that the students made in the 'Mixtures Solutions' unit, with the augur (drill-head) replacing the mixing-head. Moreover, unlike the first unit where the lid of the plastic container could be used to hold the motor in place, no lid was provided in this second unit such that the students had to hold the motor while it spun. The Making activity however was essentially the building of the same rotational motor circuit across both science units.

4.1.3 Data Collection and Analysis

Data was collected in each Making-infused class by the placement of a dedicated video camera and audio recorder at each table in the classroom. A table was typically shared by four students.

Students worked in pairs for all the Maker activities. While the students kept the same pairs within each unit, some students were shuffled by the teacher across tables and pairs in the second unit.

Our analysis in this section pursued the research question of how social practices developed around a focus set of Making components, the rotational motor circuit, as used by 12 students (6 pairs) in the 5th grade class. We looked at three instances during which the students interacted with the focus Making components: **i)** first time use (Day 1 of the 'Mixtures Solutions' unit); **ii)** four days after first time use (Day 5 of the 'Mixtures Solutions' unit); and **iii)** more than a month after first time use ('Fossil Fuels' unit).The compiled video segments of the classes pertaining to these three instances were 26 to 53 minutes long per student, resulting in a total of 121 minutes for each of the 12 students selected for close-up analysis. Video analysis was performed by three coders using a deductive approach to qualitative analysis [121]. The deductive approach is in contrast to the inductive approach (e.g. open coding) where categories and themes are allowed to emerge from the data. In deductive qualitative analysis, a 'categorization matrix' is first developed from prior research or theory. The matrix essentially functions as a framework with which the data are reviewed and coded. Exemplification of the matrix categories noted in the course of the coding. Aspects that do not fit the categorization matrix are coded as well based on the principles of inductive analysis. We made use of two categorization matrices drawn from the literature: **A.** Characteristics of CoP from Lave and Wenger's work (e.g. levels of participation, open dialogue, etc.) and ZPD from Vygotsksy (More Knowledgeable Other, scaffolding); and **B.** Learning Practices as proposed by Wardrip and Brahms [114] (e.g. tinker, inquire, repurpose, etc.).

The three coders familiarized themselves in-depth with the two categorization matrices, and then each coder analyzed the data for 4 students by first creating descriptive codes for any behavior, speech, interaction or event that related to aspects in the matrices. If a significant aspect was observed that did not fit into any of the matrices, a new category was added to the respective matrix. This coding process resulted in a list of descriptive codes for each matrix for each coder. The three coders then synthesized their lists to generate a single list of descriptive codes for each of the two categorization matrices. We also performed quantitative content analysis on some aspects of the categorization matrices (e.g. number of full and peripheral participants), and tracked the following quantitative variables: i) the amount of time when a student gave and received help from mentors (the teacher, Maker instructor or helpers; ii) the amount of time when the student gave and received help from peers (other students in the class); and iii) the amount of time the student spent interacting with the focus Maker materials (the battery, switch, and rotational motor), with interaction being defined as any kind of sustained physical behavior with a focus material, for example, connecting wires, holding the battery for a prolonged period of time, repeatedly pressing the switch, etc.

4.1.4 Qualitative Findings

The goals of our study was to understand how a Making-based CoP may manifest itself within the constraints of a classroom environment among all the agents involved: the students, teachers and helpers, and how scaffolding may occur in the Making activities with participants serving as peer and instructor MKOs. The formal Making-based classroom may be seen as the context of the formation of a Making practice whereby teachers, Maker instructors and helpers function as the 'masters', using Lave and Wenger's term, and the students as the 'apprentices' who are being inducted into the practice. We describe below the main points from the descriptive codes for each of the categorization matrices from our analysis in a generalized integrated narrative.

4.1.4.1 Levels of Participation

Different types of participation can typically be identified in the formation of a CoP, including peripheral participation, full participation, and marginal participation [122]. There were implicit roles in the students' Making engagement that resonated with these roles typically found in a CoP. All the student pairs consisted of a '**full participant**' and a '**peripheral participant**'. In the classroom setting, full participants were students who were actively engaged in the hands-on Making activity, often taking the lead, directing processes, and delegating tasks to others. When they were given instruction, the full participants took the initiative to experiment with the materials. After first time use of the Making materials, full participants would often attempt to directly engage in Making in subsequent sessions without awaiting instruction, relying on their prior experience. When they did request help, they relied heavily on the mentors instead of peers. The engagement in experimentation, tinkering and willingness to take risks of the full participants sometimes led them to give incorrect answers to class-wide Making questions.

Peripheral participants were those who participated in the Maker activity, but at a more passive level, often simply observing and intervening only when directed or necessary. These students listened or observed either a peer, a full participant or a mentor, then acted on the Making. Their greater reliance on peripheral participation did not mean that they were less engaged or learned less. In fact, they participated at similar proportions as full participants, and showed success in project completion. In addition to requesting help from mentors, if necessary, peripheral participants relied heavily as well on peers' help. Their behaviors were more clearly reflective of Lave and Wenger's [10] concept of legitimate peripheral participation.

4.1.4.2 Open Dialogue

A critical aspect in the formation of a CoP is the presence of open dialogue among community members [123]. In the classroom environment, most of the students only interacted minimally with people other than their partner, and especially outside of their table. However, two roles that the students assumed could be distinguished that contributed to the creation of open dialogue in Making: i) '**presenters**' were students who verbally announced steps and milestones of the Making process. These 'announcements' were typically triggered by emotionally charged events, for instance calling for debugging help when frustrated (e.g. "I don't know why mine doesn't work"), excitement at the successful completion of a Making step (e.g. "It worked!". "It's mixing!"), and providing the answer to others' questions. Presenters typically showed great motivation to engage in Making activities; and ii) '**integrative enthusiasts**' were students who took on a more interpersonal role, actively seeking out other students in need, at their table or even across tables, and providing aid whenever possible, even without being prompted to. Although these two roles were not very common, with at most two students engaging in the behaviors in each class session at any one time, they served as a form of social scaffolding for the class, where they dispersed table-specific knowledge to the larger community of the classroom, provided help from the community members themselves, and built up trust in responses and practices, all of which are important indicators of the development of a CoP [124].

4.1.4.3 Socially-Mediated Learning

We found four main collaborative and social ways by which students acquired information and engaged in thinking and reasoning processes in the Making science classes:

Seeking feedback and help: Both full and peripheral participants sought feedback periodically on their work. Full participants sought feedback specifically from mentors (e.g. one student struggled with the circuit and asked a mentor for help), and peripheral participants sought feedback more from their Making-partner (e.g."I don't know why mine doesn't work. How did you do it?"). Seeking help and feedback occurred through both gestural interactions (e.g. pointing to make suggestions if one was having difficulty), and verbal interactions.

Problem-solving: The students frequently debated among themselves on how to troubleshoot and debug problems that arose in Making (e.g. "You have to push it (the switch) harder...No! the other way!"). The problem-solving scenarios were critical to the students creating mutual trust and engagement, and were often catalyzed by the 'integrative enthusiasts' who crossed tables to engage in debates.

Announcements: The behavior of 'presenters' loudly announcing their Making progress provided a channel by which information was shared in an unsolicited manner. The announcements would often draw the attention of other students who would either then reflect on their own Making process, or copy the presenters' activities. For example, one of the students who accidentally reversed the polarity of the wire connectors found that this caused the motor to rotate in reverse. He announced it loudly to no one in particular. The other students at his table turned to look at his project, and imitated reversing the motor.

Question & Answer: In Bevan et al.'s [120] study of learning in a museum Makerspace, the development of understanding was evident through the participants' conversations that showed marks of causal reasoning using the participants' existing technical vocabulary prior to the study.

In the formal learning context of the classroom, technical vocabulary and formal understand was conveyed mainly through mentor-student questioning and answering. The mentors adopted an approach of emphasizing the students' newly-acquired vocabulary in their lesson in this Q&A style of conversations.

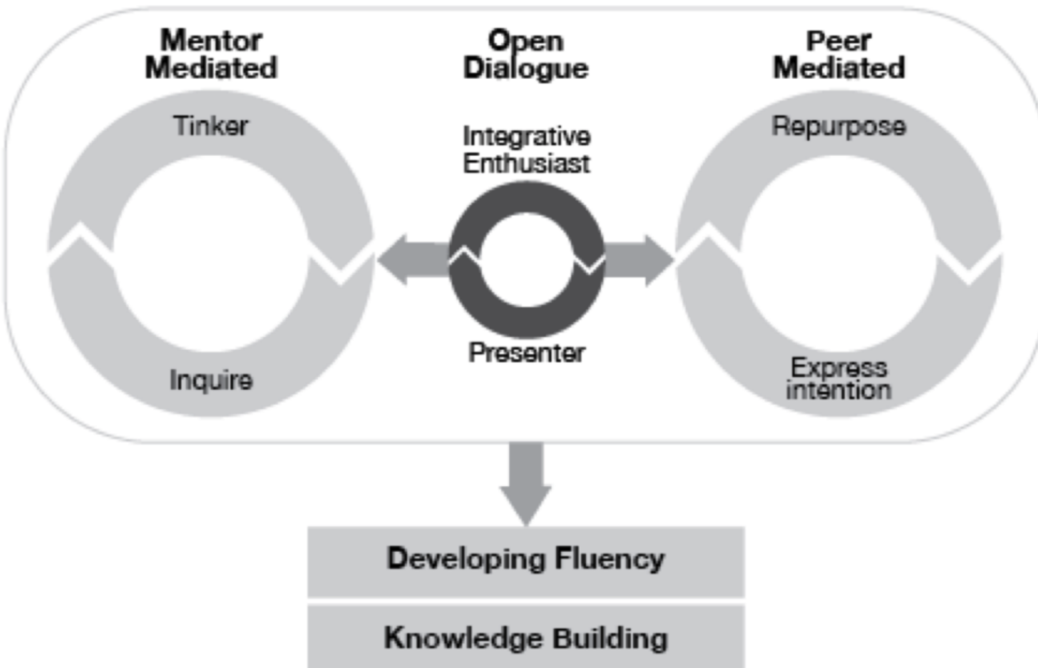

Figure 4.3: Learning Practices in Hands-On Technology-Infused Learning. Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"*[2].

4.1.4.4 Learning Practices

Based on their analysis of activities in a museum family Makerspace, Wardrip and Brahms identified seven socioculturally-based processes that support learning in Making [114]. Our analysis showed that these processes occurred in two distinctive action cycles in the classroom, as shown in Figure 4.3. The left cycle consisted mainly of inquiring and tinkering. Inquiring took place when students explored and questioned the properties of the Making materials in search of unexpected possibilities. Tinkering manifested itself in terms of purposeful play and testing and evaluation of the materials. Students displayed an immense curiosity and excitement when they were first handed the Making materials, by asking the mentors what each part did and actively participating in the lecture when the mentors asked them questions. They consistently picked up the parts and explored. For instance, students used a spindle to make a spinning movement on their body parts or in the cup. This cycle was generally mediated by the mentors who intervened when help was required.

The right cycle consists of repurposing and expressing intention. Through repurposing, students utilized the materials by often disassociating the object properties from familiar, instructed or given uses to create modified, enhanced, or new artifacts or processes. As students learn to express intention, they foster their personal identities and interest areas by pursuing goals independently and collectively through the Making experience. When the students were given a task to make the mixer, they found how to make a whirlpool when they lifted up the moving spindle to the surface of the water. They articulated their intentions and provided instruction to other students on how to replicate the phenomenon. This cycle was most often mediated by peers instead of mentors. The two action cycles were often brought together and catalyzed by the 'presenters' and the 'integrative enthusiasts', with these students for example sharing a repurposive act of a particular pair (that may not include either the presenter or integrative enthusiast) to other tables in the classroom. Together, the inquire-tinker, express intention-repurpose, and presentation-integrative enthusiast cycles construct new classroom practices, and contribute the joint building of knowledge and development of fluency in the use of Making materials and processes of Making and exploration.

In the mentor-mediated and peer-mediated loops, we see again the roles of the mentor and peer MKO's. The inquire-tinker loop typically happens early in the class session before any student has developed sufficient expertise to become a 'knowledgeable other' and so the mentors serve the role of the MKO. The express intention-repurpose cycle is typically driven by student curiosity and exploration, and the roles of the MKO are played by the students who develop early expertise. In each case, we see the dynamic of Vygotsky's social development theory resulting in propagation of knowledge within the classroom.

4.1.5 Quantitative Findings

4.1.5.1 Taking on Roles

Based on our qualitative findings on levels of participation, we reviewed the videos again and assigned each student a role of being either a full or a peripheral participant at any one point in time. We found that while the roles sometimes changed across class sessions, they stayed consistent within a class session, i.e. if a student was a peripheral participant in a class session, she remained at peripheral participation level throughout the whole of that class session. She could however become a full participant in the subsequent class session. During full or peripheral participation in the class, students could further assume an additional role as either 'presenters' (i.e. engaging in unsolicited and untargeted announcements about the Making activity at least once throughout the class session) or 'integrative enthusiasts' (i.e. having intertable interactions at least once throughout the class session). Among the 12 students we tracked, two of them adopted a 'presenter' role in Session 1, two in Session 2, and none in Session 3. There was one student who took on an 'integrative enthusiast' role in each of the three sessions. Although the 'presenter' and 'integrative enthusiast' roles were not uptaken by many, we saw that those who did take on these roles did so with intensity and persistence throughout the class session.

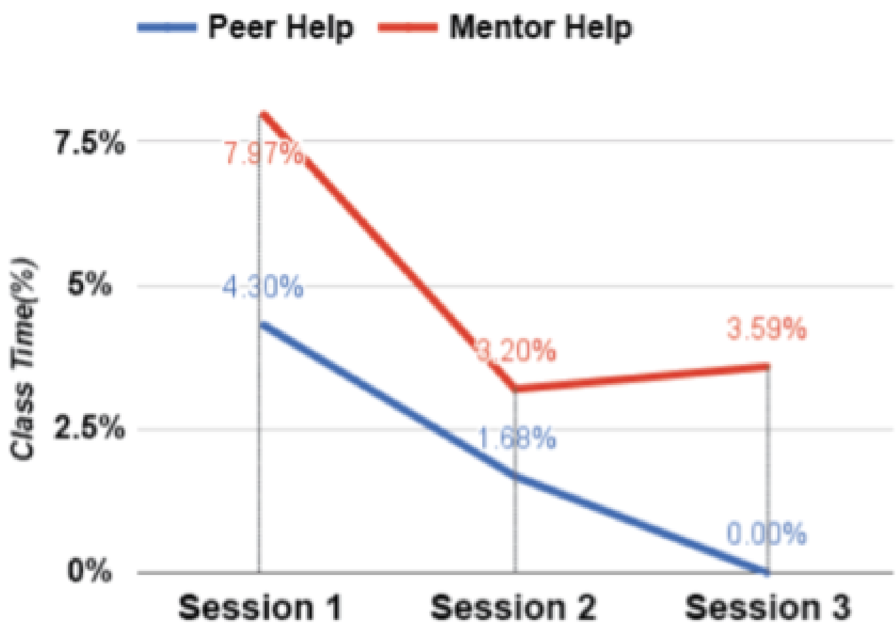

Figure 4.4: Help received by students from their peers and adult-mentors across all sessions. Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"*[2].

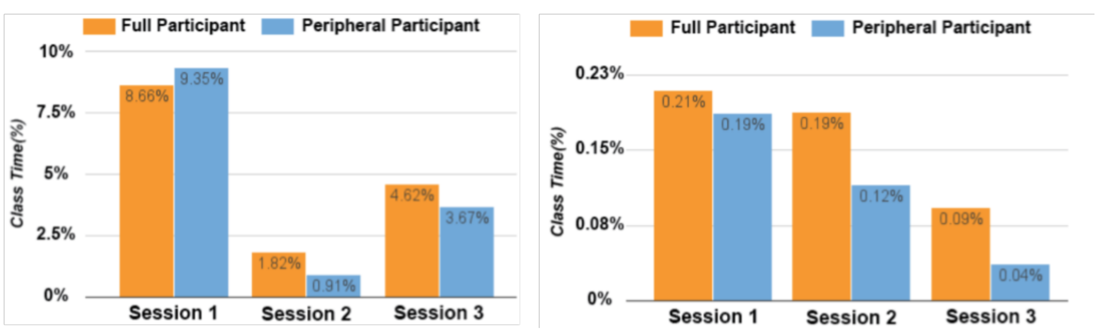

Figure 4.5: Help given from all students normalized by the overall class duration (*left*) and the time spent interacting with Making materials normalized by class duration (*right*). Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"*[2].

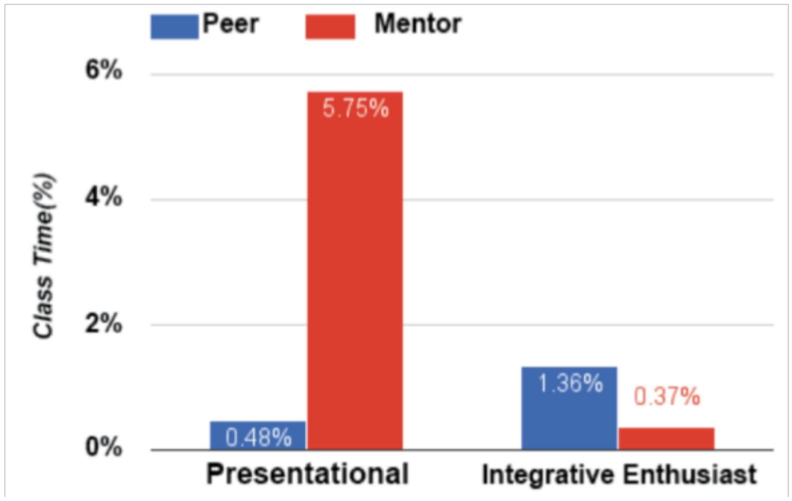

Figure 4.6: Help to 'presenters' and 'integrative enthusiasts' as proportion of class duration. Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"*[2].

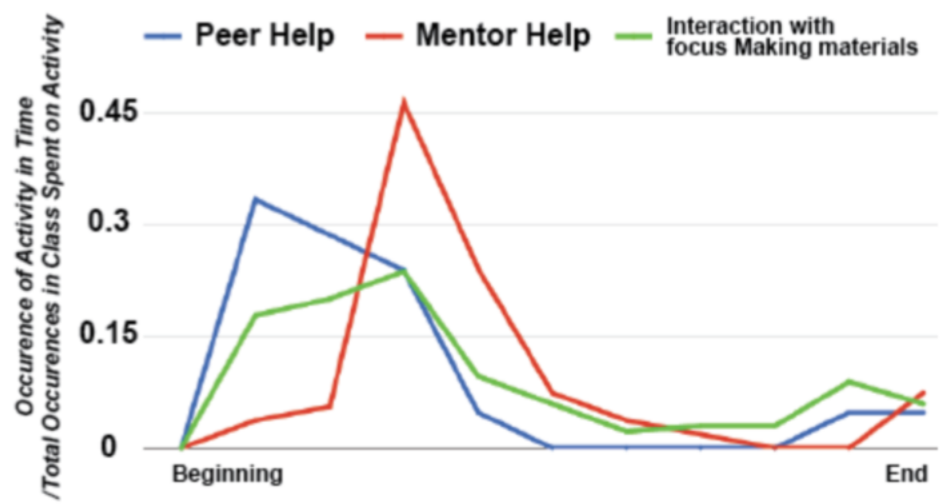

Figure 4.7: Proportion of Average Help received by students and Interaction with Materials normalized by Class Duration Totals across bins of the class duration. Reprinted with permission from *"Toward a making community of practice: The social aspects of elementary classroom-based making"*[2].

4.1.5.2 Peer and Mentor Help

The amount of assistance received by newcomers to a CoP is a key indicator of their successful induction into the practice. As they transition from a 'follower' to more of a 'master' role, the newcomers typically gain and showcase greater independence in the conduct of tasks [125]. We observed a decline in the proportion of help students generally received over the three sessions, as shown in Figure 4.5. Students tended to receive more help from mentors than from peers for every session. Students received less help after the first session, but then required a similar amount of attention in the third class, which occurred more than a month after the first session. We note however that the help in Session 3 related more to performing the specific science activity (drilling into the tough soil with a small motor) than with the construction of the motor circuit itself. Thus, the complete absence of peer help in Session 3 indicates that students did not help each other for problems regarding the science activity, but referred more to the mentors for that purpose. This suggests that peer help was typically received more in relation to the Making process of the motor circuit itself.

A closer analysis of peer help showed that full participants are the ones who consistently gave more help than peripheral participants (see Figure 4.5). It appeared that peripheral participants only helped when full participants did not step in to help. Moreover, students who further assumed a 'presenter' role during the class seemed to receive much more help from mentors than peers (see Figure 4.6). It appeared that the oral announcements of those students brought not only the students' but also the mentors' attention to them. The 'integrative enthusiasts' on the other hand received more attention from their peers. This seemed to be because when the 'integrative enthusiasts' jumped between tables and built networks of conversation, not only did they share information but they also obtained additional help from students across the broader classroom.

Figure 4.7 shows that help given and received in each class session (y-axis shows the normalized number of occurrences across all the class sessions, and x-axis show the progression of time in a typical class session) tended to happen mostly in the first half of the session. It is clear as well from the graph that engagement in peer help occurred before full engagement with mentor help.

4.1.5.3 *Interaction with Materials*

Our analysis of the amount of time that the students interacted with the focus Maker materials in Figure 4.5 showed that there was an overall drop in the amount of interaction in Session 2, with an increase in Session 3. This was because while Session 1 saw exploratory and playful behaviors with the materials, interaction with the materials in Session 2 was more purposeful and direct to the task. With Session 3 being more than a month apart from Sessions 1 and 2, the students somewhat engaged again in exploration of the qualities of the materials in Session 3. It was interesting however that the amount of time interacting with the Making materials for the full participants and the peripheral participants was mostly equivalent in all the sessions. This is explained by the fact that even though peripheral participants were characterized by a more passive behavior with respect to the hands-on Making activity, they still interacted with the Materials in other indirect ways, such as handing materials over to the full participants, feeling the materials, playing with the materials when the full participants were not using them, etc.

From Figure 4.7, similarly to the trend of help received over time, interaction with the Making materials occurred mostly in the first half of a class session. It is interesting as well that the students' interaction with the Making materials followed a similar pattern as peer help and not mentor help. This suggests that their interaction with the focus Making materials triggered peer help in a more unstructured rather than structured or ordered manner.

4.1.6 Discussion: Collaboration Roles and Participation within Classroom Constraints

Both structured (formal) and unstructured social exchanges are necessary for supporting learning the observed Making activity. To broaden participation with associated hands-on technologies, understanding the required structure for collaborative learning becomes necessary.

4.1.6.1 *Classroom Roles and Participation*

Our study showed that students quickly adopted roles within their pairing assignments for the Making-activities and across the classroom. First, they assumed roles of full and peripheral-participants in their work within the pairing assignments, with the former student taking on the more active role in the Making activity and the latter assuming more of a ‘follower’ or ‘helper’ role. Interestingly, our results showed that these self-assigned roles are stable within each class session, but can be fluid across sessions. Eight students in our data switched roles across classroom sessions. This indicates that peripherality does not mean that the student is not somehow engaged and learning. We saw that both the full and peripheral participants appeared equally invested in the success of their joint enterprise of Making in the class.

Interestingly, we observed that a subset of students adopted roles that support a more open dialog within the classroom across assigned pairings, and so facilitate the development of the classroom CoP. Furthermore, the roles of ‘presenter’ and ‘integrative enthusiasts’ seemed to be persistent within class periods with the same students continuing in those roles as the Making activity progressed. Both of these roles appeared to have been predominantly taken up by the students who functioned as peripheral participants in their assigned project pairings (3 out of 4 ‘presenters’, and all of the ‘integrative enthusiasts; were peripheral participants). It appeared that these students self-selected to support open dialog and to take a less active role within their assigned project pairs. This further supports our assessment that peripheral participants were engaged as well as full participants, but participating in alternate ways that not necessarily seem central to the Making process. Finally, the roles adopted by the students facilitated the identification of MKOs and their function to scaffold learning within the classroom.

4.1.6.2 Collaboration Structure within the Classroom

Our results showed that both structured (formal) and unstructured social exchanges support learning in the Making activity. First, we saw students seeking feedback and help, and engaging in question and answer exchanges with the instructor and formal Making mentors in the Making activity. These typically happened within the flow of the planned instructional/learning activity, such as when the activity is introduced, and the students are ‘on-task’ with the assigned activity. We also observed interactions among students beyond the planned activities. These happened when the students engaged each other in seeking feedback and help and in question and answer exchanges. Interestingly, such requests were almost always directed at the full participant of the activity pairs, even though we saw that in a given Making session, the same individual can change across class sessions. This suggests that individuals identify consistently as MKOs within each activity and provide peer scaffolding for the activity. Unstructured exchanges also occurred among students for problem solving in their Making activities and in the 'presenter'-'integrative enthusiast' interactions with the class. Such interactions occurred outside the planned sequence of activities of the formal class schedule, and helped to further thicken a Making practice within the class structure.

Figure 4.3 calls out the three cycles of interaction that contributed to the formation of the classroom Making CoP. Of these, only the Inquiry-Tinker cycle reside within the formal lesson plan where the formal instructor/mentor serves as the predominant MKO for the students. The Intention expression-Repurposing cycle represents student-initiated activities that are sometimes frowned on by the teacher as being 'off-task' with respect to the lesson plan. However, this cycle of interaction can serve to broaden the students' understanding of the Making materials and processes, and to thicken the student's engagement in the Making practice. It also provides the opportunity for peer teaching/learning about Making materials and processes. The presenter-integrative enthusiast cycles further extend the informal student-initiated inquiry across student pairings to the scale of the classroom. This suggests that such informal dynamics can serve positive purposes in learning and need to be encouraged/tolerated in the classroom

Finally, we observed that all three interactive cycles decreased in incidence as the students became more familiar with the rotating motor circuit. This suggests that new Making materials and processes should be introduced periodically within the classroom curriculum to encourage persistent active inquiry among the students.

4.1.7 Contributions and Limitations

Our project was conducted within the purview of a real functioning school system. As such, we had been constantly aware of the needs of the school system with regard to time, curriculum coverage, and classroom discipline requirements. The study reported in this section occurred in just the first year of a three-year longitudinal study. Hence we had to balance the degree of complexity of the Making activity and the degree of free exploration within each class session. Even with these constraints, our results have uncovered indicators of CoP formation around Making practices within the classroom. With careful planning and the curriculum matched Making activity, we argue that multi-level mentoring can take place that involve both peer and instructor-supported learning.

When this study was conducted, there was very little understanding of the social aspects of Making in the classroom. Our work provides some initial insights and observations into this topic, but it is necessary to acknowledge that it is limited by the scarcity of prior literature directly in the area that we could base our work on, the design of the Maker kits used by the children, some of the decisions that we took in the implementation of the Making projects in the school due to logistical and practical constraints, the particularities of the school and classes that we worked with, and the method that we chose for analysis of the dataset. More specifically, we highlight the fact that we only tracked 12 students in this analysis, and relied only on student behaviors in the classroom setting itself. Thus, neither do we claim generalizability nor do we affirm evidence of a Making community of practice. Our findings do provide insights however into aspects of Making that may lead to the possible formation of a CoP in the school.

4.2 Peer-Sustained Technology-Infused Learning with Online Assistance

This section explores how online mentors may foster classroom Communities of Practice facilitated through Hands-On Technology-Infused Learning to support life-long learning and expressive-application with various technologies. While Learning Hands-On Technology-Infused lessons may foster situated learning practices, these technology lessons are not always accessible in locations where mentors can not easily frequent, such as rural locations. Additionally, the often-explored intervention method of facilitating hands-on lessons with proximal researcher-associated mentors [4, 2] may not be feasibly scale to a larger number of questions. This section explores how to facilitate the growth of remote communities of practice through *distal* online instruction methods, eventually removing the needed presence of researchers as *proximal* mentors develop. In this dissertation, this establishes that STEM interventions that do *not* comprehensively cover a topic for every student can be sufficient to establishing knowledge-sharing and mentorship communities in otherwise isolated locations. These communities, in turn, may help facilitate learning with hands-on technologies to sustainably broaden participation these technologies beyond those who directly received interventions from STEM researchers.

4.2.1 Making as Micro-Manufacture (M^2)

Previous work demonstrates how high school students can learn and develop self-efficacy around Making-skills via a novel model of Micro-Manufacture (M^2) [126, 127, 128]. This model extends from formal definitions of Making, such as Halverson and Sheridan's definition of engaging "in the creative production of artifacts in their daily lives and who find physical and digital forums to share their processes and products with others" [129]. M^2 augments Making practices with production or manufacture at small scales for real-world problems. We demonstrated that this model developed high school students' self-efficacy toward Making-skills and STEM careers.

4.2.2 Setting: Rural High School Career & Technical Education Classroom

This section analyzes data from a longitudinal study, that at the time of analysis, was in its third year. This study was conducted in collaboration a rural school district along the Texas-Mexico border. The school district is around 43 miles (around 51 minute driving distance) from the nearest larger town. Six students, in their 2^{nd} or 3^{rd} year of high-school, were recruited to participate in the first two years of the study. Looking for students with diverse interests and capabilities, we received 13 applications. We interviewed those 13 via teleconferencing, and selected six students with a diverse set of interests, backgrounds, and career goals. Two more students were recruited to participate after the 2^{nd} year.

4.2.3 Elementary School Science Hands-On Technology Kits

The end product from students in this M^2 program was to create and deploy science instructional kits to aid in 5^{th} grade elementary school science lessons. These Making-kits were designed to align with and augment specific science topic learning standards taken from state-mandated curriculum. The elementary school class they served consisted of 15 students, with most students working in pairs using the Making-kits. As technology in the hands of elementary students showed to be prone to breakages, the high school students were instructed to produce at least 10 kits for

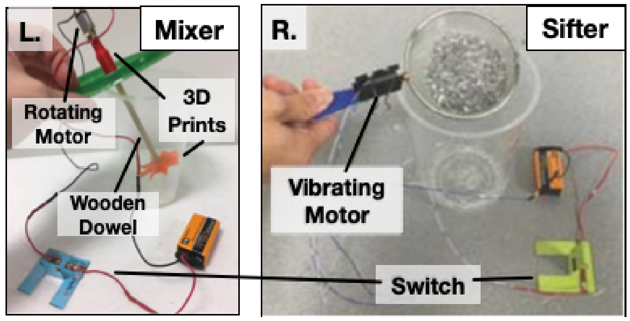

Figure 4.8: Maker-kit for 'Mixtures and Solutions' topic. Reprinted with permission from *"Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools"*[3]

each science lesson.

All designs and details about the kits were developed by the research team, same as the previous sub-section (Section 3.1), and then delivered to the high school students. The kits combined arts and crafts with Making, aiming to be usable by children as young as 8 years old. For example, one unit aimed to teach students the difference between mixtures and solutions, having them assemble a mixer and a sifter (shown in Figure 4.8) to experiment with the combination and separation of different materials (e.g gravel, metal clips, toothpicks, water, salt, etc.). The mixer consisted of a geared rotating motor that drove a 3D printed mixer head via a quarter-inch wooden dowel rod. The sifter consisted of a vibrating motor attached to a small sieve. Students would connect these two devices to a custom-made paper-based switch and a 9V battery. High school students were encouraged to modify and add to the kits, with approval from the research team. For example, students could not find a good local supplier of the 0.25" dowel rods, so they utilized pencils to accomplish to same task.

4.2.4 Study Description and Methodology

This longitudinal study has been ongoing for over 3 years. The entirety of the first year was dedicated to training the classroom to learn Making and M^2 skills for the purpose of deploying Making-kits. Years two and three involved high school students manufacturing and deploying their kits in the elementary school classroom. Between the second and third year, two students graduated and two students left because of class scheduling conflicts and testing-preparations, leading them to be replaced by two new students by similar recruitment. The first and second years had three female and three male students of the same seniority in the program, while the third year consisted of four male students where half are new and the remaining have two years of experience in the program.

As local high school teachers are not fully familiar with the skills and instruction needed for Micro-Manufacture, the classroom was taught via a distance apprenticeship approach by the research team that consisted of experienced members in Making, computer science, engineering, industrial distribution, educational technology, and interaction design. In this section, we refer to those who teach apprentices as “mentors", and those who conduct distance-apprenticeship as “distance-mentors". Over teleconferencing calls, these researcher-instructors would teach about various Making skills (soldering, connecting basic electronics, programming, 3D printing, etc.) and M^2 skills (supply chain, inventory management, batch processing, production line, etc.).

Year 1 was dedicated to training the high school class, students and teachers, to produce and deploy Making-kits. To help encourage interactions like in a Makerspace, we augmented a high school classroom with the needed equipment and layout to resemble a Makerspace. Equipment such as hand-tools, electronic components, and a 3D printer was provided. Students were given the freedom and responsibility to organize themselves and the equipment in the classroom. The initial team of six high school students were taught Making and manufacturing skills by the research team. To facilitate this distance apprenticeship approach, a large television and teleconferencing web-camera was installed in the classroom.

To help start initial communication, students starting the program in this first year attended an in-person workshop at the researchers' laboratory. Here, Micro-Manufacture was explained to the students as consisting of: i) understanding and deconstructing a given kit design and specifications; ii) adapting kit design to local conditions; iii) producing one kit; iv) planning the manufacturing process; v) engaging in the production pipeline; vi) quality testing; vii) deploying kits in the classroom; viii) conducting a post-assessment of the deployed kits. After this workshop, where they saw example Making-kits and were guided in an abbreviated process to manufacture these kits, they were tasked with creating many sample kits as a Making-Production Team(MPT) in their classroom. These sample kits were their objective for the rest of year one, where a teleconferencing researcher would aid them in this process. Each class started with a recap of the previous class, and a review for what needed to be done in the planned manufacturing process to produce the sample kits. The teleconferencing instructor would give students high-level tasks if the prior-assigned tasks were completed. Finally, students would complete these tasks. During the classes, student would learn by participating in this shared practice with the teleconferencing researchers. This first year started in the second semester, covering 18 weeks and 6 sample science kits that varied in Making materials and Manufacturing processes. This year largely served as an introductory lessons and practice kits to train the groups' making and micro-manufacturing abilities.

Year 2 for the MPT consisted of them applying the knowledge they gained producing sample kits to actually manufacture and deploy kits in the real elementary school. This year covered both semesters, totaling to 36 weeks. The MPT were given the target to manufacture 10 kits and deploy them every six weeks, corresponding to the cycle where the elementary school science classroom covered a given curriculum theme in the Texas school year. In addition, students were assigned formal roles to aid in their Making and Manufacturing process: 'Project Manager', 'Production Manager', 'Sourcing Manager', 'Administrator', 'Continuous Improvement Specialist', and 'External Relations Manager'. These roles were developed to give more structure to how the community received input (e.g. Sourcing Manager purchasing materials), processed information (e.g. Production Manager on developing a pipeline for the manufacturing process), and developed output (e.g External Relations Manager). The high school students traveled to the elementary school on the day of deployment (i.e. the science lesson), helping the 5^{th} grade students interact with the Making-kits.

Year 3, consists of similar tasks to Year 2. However, there are three notable differences. One, two students in the program have graduated, leading to them being replaced via a recruitment process similar to Year 1. Two, the two retained students (RS) in the program are now experienced in the actual manufacturing and deployment process for the elementary school. Lastly, the first six-week unit of this year is a practice unit with no real deployment. This will give the MPT, with new members and social dynamics, an introductory period to establish their practice before making and deploying elementary school Making-kits for the remainder of the school year. This section focuses on the 3rd school year's first 8-weeks, the first practice unit plus two weeks, comparing how the mentor-roles and knowledge-needed in the classroom differs from the first two years of the program.

4.2.5 Data Analysis

In this section we analyzed recordings of several classroom sessions to investigate the following research questions: **1)** Are Learning Practices similar to that of a Makerspace taking place in the M^2 classroom? **2)** How do Experienced Students and Teachers retain and utilize expertise gained from previous years in the program to mentor less-experienced members? **3)** How can a distance-mentor effectively train members in a Maker-program that sustains expertise similar to a Makerspace CoP?

To approach these research questions, we analyzed a sample of classroom sessions over the last three school-years of the program. Each class session, averaging about 40 minutes, was captured with two strategically placed video and two high-quality audio recordings. Figure 4.1 shows one camera view of a 3rd grade classroom. The audio recordings were captured using production-quality field recorders [130], and these recordings were remastered onto video streams to ensure audibility for coding. A team of seven coders analyzed data from 8 sessions for year 1, 24 sessions for year 2, and 25 sessions for year 3. For each session a coder wrote memos describing the process of each class, noting in detail events related to the lenses of ZPD and CoP.

The team then engaged in a deductive qualitative analysis approach [131]. The deductive approach relies on the development of a 'categorization matrix', derived from prior research or theory. This matrix serves as a framework to categorize aspects of the qualitative data. Aspects that did not fit in this matrix were also noted based on principles on inductive analysis. We made use of a categorization matrix related to Lave and Wenger's theories (e.g. open dialog, levels of participation, etc.), ZPD from Vygotsky (e.g. More Knowledgeable Other, Scaffolding, etc.), and Learning Practices proposed by Wardrip and Brahms (e.g. Tinker, Inquire, Repurpose, etc.). Following these

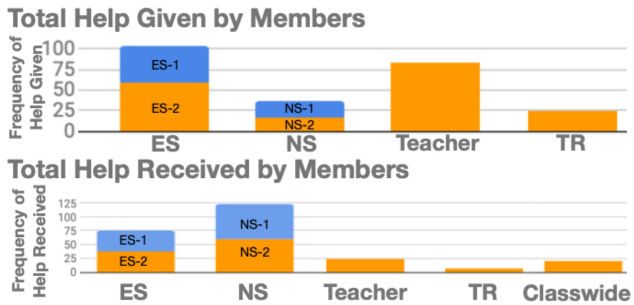

Figure 4.9: Instances of Help Given and Received in Classroom. Reprinted with permission from *"Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools"*[3]

theories, our analysis focused on how learning was facilitated through social actions. For a random sample of 25 of 34 total days of recordings in year 3, coders identified every instance of help given or received in the classroom.

Following Wardrip and Brahm's Makerspace Learning Practices, similar to Section 4.1, we highlight instances of social learning as facilitated by the different classroom agents. These practices serve as a scheme to observe and evaluate instances of learning in our classroom, verifying that it operates similarly to a Makerspace, and gives us a framework to further analyze how Learning Practices are supported through its members. Our coders focused on instances where any individual gave help to other individuals in the classroom. More categories were added to the categorization matrix as new significant aspects emerged in the coding process. Coders noted who gave help to which others, whether the help was asked for by a student, whether the help was needed or successful, if the help was related to their shared project, and whether the help was announced to the class or aimed towards individuals. Each instance of help was described by a brief summary of what help was given and for which reasons. Coders then met to review these instances of help, and identified common themes. One of the coders met with all of the other coders to discuss and resolve codes and themes in all observations.

In year 1 of the program, researchers served the functions as 'masters', using Lave and Wenger's term, and the students and teachers as 'apprentices' to be inducted into the M^2 practice. In year 2, the team moved into a production mode where they became directly engaged in the M^2 practice.

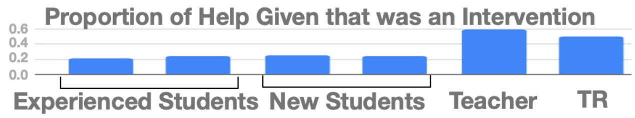

Figure 4.10: Proportion of Help Instances Given as Intervention. Reprinted with permission from *"Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools"* [3]

There was significant turnover in students in year 3, with four students leaving the program (two seniors through graduation and two rising seniors who decided that they needed to focus on their upcoming SATs), and two new juniors were added to the team. This affords us the opportunity to observe the evolving roles of the participants by analyzing the dynamics of how help is given and received.

4.2.6 Study Findings

The goals of this study was to understand how CoP may manifest itself within the M^2 high-school program, and how unstructured learning may be scaffolded by social interactions between peer and instructor MKO's. We observed that help given by the Experienced Students (ES) was largely greater than New Students (NS), indicating that they took on mentor roles to help train the new students. First, we present evidence that the observed classroom facilitates learning practices similar to that of a Makerspace (RQ1). Then we explain how the group addresses gaps in knowledge between years, conveying knowledge retained in the classroom (RQ2), and how effectively the Teleconferencing Researcher (**TR**) could fill these gaps and further facilitate the retention of this expertise (RQ3). Finally, we present our observations that indicate the development and assumption of roles in the classroom. These roles indicate how mentorship may take place in the classroom (RQ2), and how effectively distance-mentors may be at providing mentorship compared to the classroom-proximal members (RQ3).

4.2.6.1 Learning Practices

Based on analysis of a museum family Makerspace, Wardrip and Brahms [132] identified seven socio-cultural processes that support learning in Making. Our analysis found instances of each process, but facilitated by different members in the community-classroom: ES, NS, TR, and the Teacher.

Tinkering took place solely by students, often experimenting with how new circuits connect and learning about near materials and properties. The students were also the sole individuals to *Hack and Repurpose*, although only ES were observed doing this. For example, since wooden dowel rods were difficult to obtain in the rural setting of their school, one student proposed the repurposing of wooden pencils to perform the same function in their Maker-kit. Students familiar with 3D printing would occasionally modify designs to fit school needs, such as modifying a part that attaches to markers to match markers they had on site. Also, students would often create and participate in Making processes of their own choosing, as discussed further in the section 4.2.6.3. Students occasionally *Inquired* about how their Making-kits and acquired skills could be applied to make familiar technologies. In the second year, one student briefly asked about and researched how to make a portable USB battery charger. These instances signify that students may seek to apply their Making knowledge and skills in the future.

All members participated in the practice of *Seeking and Sharing Resources*, which required them to identify, pursue and/or recruit expertise of another to complete a given activity. Figure 4.9 illustrates the total number of help instances given and received by different members in the classroom in our Year 3 analysis. Students gave the majority of help received by their peers. The Teacher gave comparable amount of help to the ES, and the TR gave comparable help in comparison to the NS. However, the TR was only present on about three out of five days of the school week. In the third year, over three-fourths of the help that was given by each of the students was sought by other students, and the majority of help received by each member was sought as well. The Teacher would often ask students about their current tasks, which served to create a more Open Dialogue about what all members were completing, so that students could share their expertise to work better as a whole to complete their Making-kits. The TR would often facilitate the students' seeking of help from each other, by delegating students to work together and by employing Socratic Method during longer lectures. In a lesson covering the use of breadboards in prototyping circuits, the TR asked “Ok - Let me just - let’s start out with the seniors for our group. Based on what you know, what can you tell me about breadboards?”, “What exactly is a breadboard?”, “What is it used for?”, etc. In another early lesson in the third year, the TR would encourage the NS to seek help from the ES, saying “<ES-1>, I’ll have you kind of watch over <NS-1>, but for detail but <NS-1> I want you to primarily do it by yourself.” By encouraging cooperation, discussion, and establishing the ES as sources of knowledge as part of the lessons, the TR further facilitated the Seeking and Sharing of classroom resources. In the second year, we saw less instances of the TR employing these methods, and less TR help related to Making skills requested from students, indicating that students who have established Shared Expertise in their community do not require as much help from the TR. A community that can effectively seek and share resources encourages learning and sustainability of the groups shared expertise.

New students would often *Develop Fluency* by asking their peers how to complete tasks and learn the needed language to communicate about these tasks. For example, when writing daily reports on what they completed that week, the new students asked ES-1 about what they did: “I put – I made switches... Is that ok?”, prompting the ES-1 to respond “You soldered switches”, which then NS-1 repeated that phrase while writing. Similarly, both the TR and Teacher would serve as the mentor to develop fluency in certain cases where students either were not confident in helping each other. While the teacher was able to function similarly to the ES in the classroom in the Development of Fluency, the TR often ran into challenges communicating more complex Making-processes and concepts. To overcome this gap, a common strategy was to encourage students to *Simplify to Complexify*. In this process, students were encouraged to start with simple representations of a more complex subject, and then connecting and combining simpler component elements to make new meaning. One such instance happened where the TR assigned the two NS to work together on a circuit. They met a challenge during this task, leading them to ask an ES for help. The ES was unable to help, resulting in the students showing the TR the problem circuit on the web camera. The TR suggested breaking up the more complex parallel circuit into a single circuit, then expanding it after that simple circuit was constructed properly. The students were able to succeed at this task with this guidance, and without further explanation of the circuit itself. The Teacher also encouraged this simplification process at times, particularly asking students to test smaller components when larger constructions were not functioning properly.

In this 3rd year, the students and teachers were solely responsible for how the students' *Express Intention*, the discovery and development of identity and interests areas through determination of short and long term goals. The teacher served as a reminder for long-term goals, reminding students throughout many of the classes about qualities of the elementary school. He would make sure students guaranteed that "every kit has everything it's supposed to". Students would often assign short terms goals for each other, with the seniors often leading the execution of those goals.

In this classroom, with varying student levels of expertise, Wardrip and Brahm's Learning Practices are largely supported by students. The TR and the Teacher serve primarily to introduce new concepts and intervene when needed. NS often do not have the needed experience to serve as a 'more knowledgable other' (see Figure 4.9), so other students often fill in knowledge when able. The Teacher serves as a proximal resource, intervening when students may lose sight of long-term goals and quality control of their products. The TR serves to address gaps in knowledge, encouraging students to leverage each other's expertise, while injecting strategies of problem-solving and Making, such as *Simplify to Complexify*. Through this process, we see how the dynamics of Vygotsky's social development theory result in the propagation of knowledge in this classroom CoP.

4.2.6.2 Addressing Gaps in Knowledge

In a CoP, members are expected to have varying levels of expertise that they employ to drive their practice. The loss of multiple members may cause enough of a gap in knowledge to suspend the practice of the group. With the exit of four students at the end of the second year, the class in the third year had to account for any knowledge that may have solely belonged to those members. In one instance, the class discussed the loss of the person who usually performed the breadboard prototyping, with ES-2 saying "He was the only one who knew how to do it". ES-1 then chimed in "Well, I know how to do it, but I forgot. Well, I didn't forget, I just...", prompting NS-1 to say "You

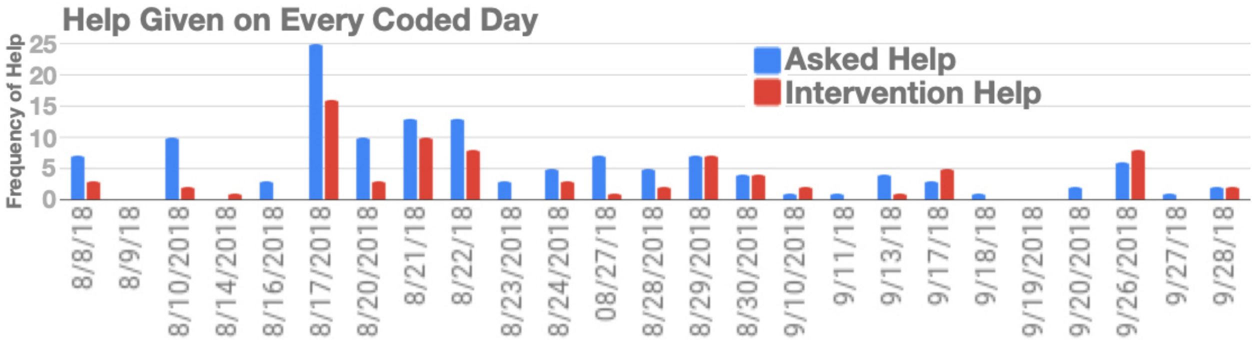

Figure 4.11: Help Given over Time (249 Total Coded Instances). Reprinted with permission from *"Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools"* [3]

didn't forget?". ES-1 responded "Más o menos (English: more or less)". The Teacher, who had participated in prototyping and testing circuits with the breadboard in past years, then intervened and helped guide the students. In other cases, students attempted to help each other while heat shrinking wires and students were learning how to use box cutters, but the Teacher intervened to make sure proper protocol was followed.

Generally less help was given as time progressed in the third year (see Figure 4.11). Most days saw more help asked for than not, although about half the days saw a close balance with intervention-based help. Help was largely received by the NS, while all students received intervention help a little under half of the total instances (see Figure 4.10). These observations indicate that both intervention and self-driven knowledge seeking both play a crucial role in this Making classroom. To facilitate a successful Making CoP, experienced members must be present to intervene with students' Making-processes, aiding the development of Making-fluency.

4.2.6.3 Development of Roles

For a CoP to develop and sustain, members with greater expertise (i.e. MKO's) are needed to take on central roles that facilitate Legitimate Peripheral Participation. Members with less experience learn through observing and engaging incrementally in more central roles on the team. This Legitimate Peripheral Participation was observed in several instances in the third year of this project. That took place often through students' evaluating each others' work (e.g. "Oh my

God... you're going to have to desolder it"), or by observing others (e.g. watching ES construct a flow chart). Over time, members' ability to engage and mentor different skills and processes led students to develop roles in the classroom CoP.

Between the NS, even in the relatively short time we observed them, one of them developed a keen interest in the design and assembling of circuits for the Maker-kits (NS-1). When NS-2 poked fun at his football ability, he joked back "I can make better switches than you". This difference in ability did effect the self-efficacy of NS-2, who said "I will pretend I can build" after the other student made a circuit. We observed this also effected students' eagerness to participate in circuit-building proportionately, which may continue to affect the students' self-efficacy and ability into the future.

The ES had existing roles before the third year, where both frequently: worked with the 3D printer, helped assemble circuits, and helped plan the elementary school lessons and kits. In this new year, one assumed more of a leadership role. In one instance, NS-2 was working at a table, and the Teacher came to ask what that student was doing, saying that each kit needs a battery for each light. ES-2 quickly jumped in, saying "he's just making sure all the LED's work". The Teacher left, and NS-2 signaled thanks to ES-2. Later when the teacher briefly left the classroom, ES-2 spread out his arms horizontally and said "I've got leadership qualities" a few times while pacing back and forth next to the new student. ES-1, at a later date when he was alone with the two NS, mockingly mimicked the absent ES-2: "You did this all wrong. You're not supposed to do it like that... I bet anything he is going to say that". This particular interaction reflects interactions in year two, where all students had the same seniority and were not afraid to criticize each other.

A hierarchy of authority emerged as this community evolved. Throughout the program, the TR was granted supreme delegation ability by all members, likely resulting from being the initial source of knowledge. The Teacher often would coordinate and follow instructions from the TR, while ensuring all students were engaged. However, the ES would sometimes disregard the Teacher's delegations. ES often would negotiate tasks amongst themselves, but more assertively delegate to the NS. The NS sometimes attempted at delegating roles. For example, the circuitminded NS-1 once tried to recruit NS-2 to help solder. ES-1 overrode that delegation, saying "he is helping me with this [emailing]". This hierarchy also often applied to the order in which help was given. In one particular case, the TR assigned circuitry tasks to the NS. When one NS failed, their peer helped them, then a ES, then the Teacher, and finally the TR. The supreme and final authority of the TR is not always beneficial, as in one case where he tasked the students with completing status reports. This interrupted their tasks, and when the Teacher asked why they were doing the reports so early, the students replied variations of "He [the TR] told us to". However, as time progressed the TR gave less and less help to the students (see Figure 4.11). Coders explicitly noted that in later classes, the TR conversed very little. As the TR rarely participated after the first three weeks we observed in the third year, the TR did not interfere or interrupt the flow of the classroom in a similar manner. The Teacher was more successful at negotiating tasks and roles with the students, where the TR was a more external influence to the CoP. Lave and Wenger state that members in a CoP must join with experience in the shared practice, so the TR helps introduce students with initial experiences. After these experiences have been introduced, the TR's relative mentorship effectiveness appears to be less than those in the classroom. From our above observations, we believe that self-sustaining Making expertise through socially-mediated learning in a CoP can be initiated via teleconferencing MKO's experienced in Making.

4.2.7 Summary of Study Results and Contributions

This study identifies how learning practices similar to Makerspaces and the studied elementary school classrooms can take place with only remote interventions of experienced STEM practitioners, allowing adults and students in proximal location to each other to more-effectively grow a technology-oriented community practice through a 'distance apprenticeship' model.

Students were often forgetful of the long-term goals (i.e. the *Joint Enterprise*). The proximal teacher often had to be the one to remind students of their overarching goal and intermediary milestones. While the TR could remotely support the development of *Shared Repertoire* of Skills and Knowledge needed, proximal guidance was necessary to apply this repertoire to their joint task. While situated aspects of the classroom made it difficult for TR to intervene and aid in smaller actions of the class activities, frequent formalized discussions afforded for a negotiation of tasks between the TR and the classroom to accomplish their goals (i.e. *Mutual Engagement*). Remote formation of communities of practice may benefit from these frequent formal interactions.

We observed in this work that the remote mentor did not need to interact as frequently with students as time progressed. Through the successful formation of CoP learning practices in schools, classrooms that were previously inexperienced with technological expression may not only utilize technologies more effectively, but learn more independently. Teachers willing to learn the needed technologies play a crucial role in retaining expertise and moderating classroom social dynamics. However, students in this study demonstrated the ability to transfer knowledge between each other without significant interventions from teachers or researchers. While not studied, this developed peer-mentorship ability may be retained and utilized later in the students lives, facilitating broader learning and expression with technological tools.

4.3 Chapter Contributions

This chapter contains two studies from a collection of publications by the author, involving studying social interactions in classroom technology-infused hands-on lessons and practices. These studies do not focus purely on learning technology-oriented practices, but learning how individuals may gain enough expertise to disseminate knowledge amongst their peers. We show that makerspace-like collaborations can occur in formal learning environments, not primarily focused to teach the technology, but to learn science curricula and collaboration skills. This chapter lays a groundwork explored in the next chapters, showing that introducing and cultivating collaborations is sufficient to foster technology communities of practice.

We have multiple other publications relating to this general subject. In "*Becoming Makers*", we investigated how elementary students develop and express "*Making Literacy*" (i.e. *Shared Repertoire* [97]) that is similar to the concept of "*Digital Literacy*" [133]. This "Making Literacy" can allow greater potential of expression with technology, the same way the same students express ideas through craft-materials (e.g. "*Making as the New Colored Pencil*"[134]). In other works [127, 135], we further analyze the high-school students progression into self-sustaining "makers" by demonstrating increasing self-efficacy scores as time progressed. This chapter demonstrates that initiating hands-on technology-oriented collaborations can be sufficient to inculcate distal Communities of Practice, empowering many to learn various subjects with hands-on technologies. In other words, this section encourages that initiating successful 3D printing collaborations with various newcomers may in turn introduce 3D printing technologies to more diverse clientele and practices.

The relevant contributions of this chapter are as follows:

- Students learn regardless of level of participation with Hands-On Technologies
- Peer interactions can broaden Shared-Understanding of technology beyond curricula-goals
- Peer interactions decrease as familiarity with Hands-On Technology materials increases
- ‘Making Literacy’ affords more Opportunities for Expression through Technology
- Experienced Students in Peer-Mentorship may require External Interventions to maintain a consistent Joint Enterprise

5. INTRODUCING YOUNG STUDENTS TO EMERGING TECHNOLOGIES: PROXIMITY OF EQUIPMENT IS NOT ALWAYS NECESSARY FOR UTILIZATION AND TECHNOLOGY-INFUSED LEARNING*

This chapter focuses on one particular study, exploring how many pedagogical challenges to introducing 3D printing processes and capabilities may be temporarily lessened by requiring collaborations through printing service-inspired "simplified" printing processes. This simplified process may scaffold students learning of digital fabrication processes, better-encapsulating the requisite knowledge to answer the unavoidable question of "*what can I fabricate?*" in any fabrication-process.

5.1 A Simplified Process for Introducing Young Children to 3D Printing

The ability to 3D print can help people achieve utilitarian needs, promote social good, and provide everyday rapid-interventions [136]. At this time, however, operating 3D printings and 3D modeling are challenging for new users [137, 138, 139], with many points of failure that can influence self-efficacy and decrease individual interest toward 3D printing [138]. Rather than burdening children with learning how to 3D design from scratch in the classroom, they could be initiated to 3D printing by appropriating curricula-relevant designs from online sharing platforms.

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* Parts of this chapter are reprinted with permission from "Exploring the 3D printing process for young children in curriculum-aligned making in the classroom" by Alexander Berman, Elizabeth Deuermeyer, Beth Nam, Sharon Lynn Chu, and Francis Quek in the Proceedings of the 17th ACM Conference on Interaction Design and Children, pp. 681-686. 2018.

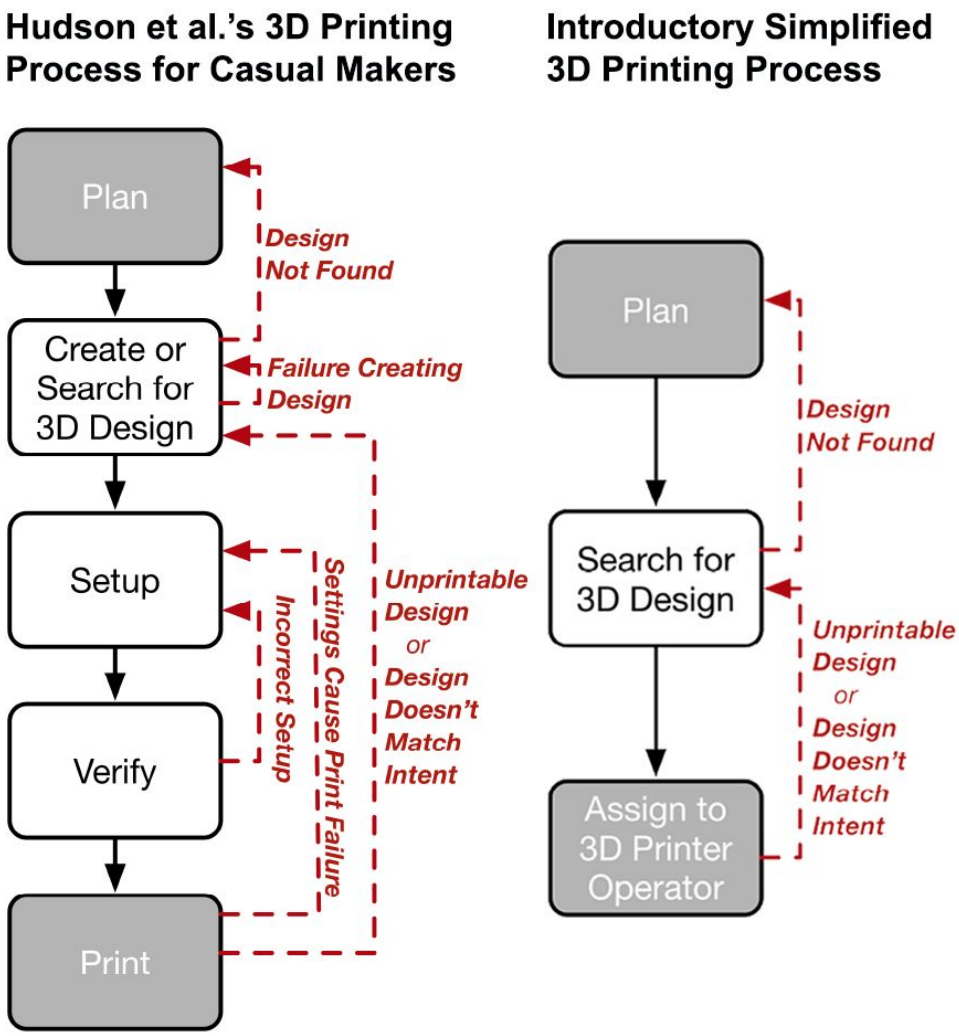

Figure 5.1: 3D Printing process for *Casual Makers* (*left*) simplified for 3rd grade classrooms (*right*). Reprinted with permission from *"Exploring the 3D printing process for young children in curriculum-aligned making in the classroom"*[4]

We simplify Hudson et al.'s "*causal maker*" printing process [23], which explains how novice 3D printing users in public printing centers obtain a 3D file, setup a printer software configuration (e.g. slicing), verify that their print preview matches their intent, and then operate the printer machinery. Many download and print designs, rather than creating design from scratch in CAD applications. We explore how a printing process inspired by these downloading-only "*casual makers*" may be adopted to classrooms to better instill lasting 3D printing interest in students (see

Figure 5.1).

5.2 Study Design and Methodology

We conducted a study in a third grade classroom with 33 students, ages 8-10. At the time of the study, the students had been engaged in Making-based science learning employing basic electronics kits for over a semester. The study is the first time the students employed 3D printing in class. The study took place over four days, each lasting 45 minutes.

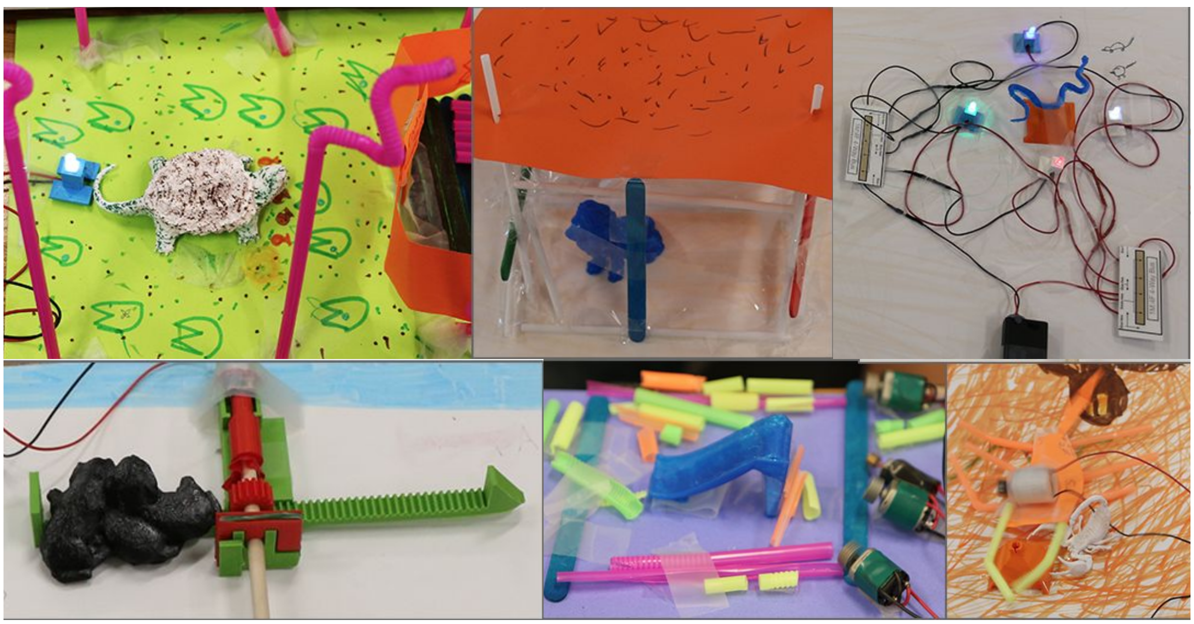

Figure 5.2: Students' 3D Printed Items and Organisms situated in their crafted environments. Reprinted with permission from *"Exploring the 3D printing process for young children in curriculum-aligned making in the classroom"*[4]

For the study, the topic of the science class was *Organisms and Environments*. The aim of this lesson was for students to observe and describe physical characteristics of environments and how they support populations within that environment. The students, working in pairs, were randomly assigned one of three environments; park, aquarium, or desert. Students worked towards creating a presentation to describe an assigned environment. They were asked to 3D print an object that could be found in their environment, and incorporate these objects into their presentations. To create their presentation, they could include any of the Making materials they had utilized in past Making activities (e.g. LEDs, vibrating motors, rotating motors, batteries, switches, a push/pull machine, and other arts and craft type materials). Data collected from the study was of four types: observation notes, questionnaire results, transcripts of semi-structures interviews conducted with students, and audio-video recordings.

Day 1. Following a short lecture about organisms and their environments, the students were introduced to the 3D printing process and a website to search and download 3D design to print (Thingiverse.com). They were shown an actual demonstration of printing using the 3D printer in classroom and also talked about some of the constraints in printing, such as size, material, and complexity of printed objects.

Next, groups of students were assigned an environment, and visited Thingiverse to search for relevant keywords. They were given a worksheet that reminded them that they couldn't print anything too large, too complex, or that didn't relate to their presentation. Once they found the model that they wanted, they approached the 3D printing operator, a researcher experienced in 3D printing, to order a print. They discussed with the operator about their decision to print a model and if the model did not meet the printing criteria, they were asked to search for different 3D design files.

Day 2 & Day 3. Students received the 3D printed objects which were printed by the 3D printing operator on Day 2. On Days 2 and 3, the students worked to complete their presentations. Adult helpers were present to assist the children and did not intervene unless asked by the students. At the end of Day 3, the students presented their projects to the class (e.g. Figure 5.2).

Day 4. Students completed a questionnaire about their interests, elements of that week's 3D printing activity, and elements of that week's presentation activity as a whole. Some students participated in a semi-structured interview with a member of the research team.

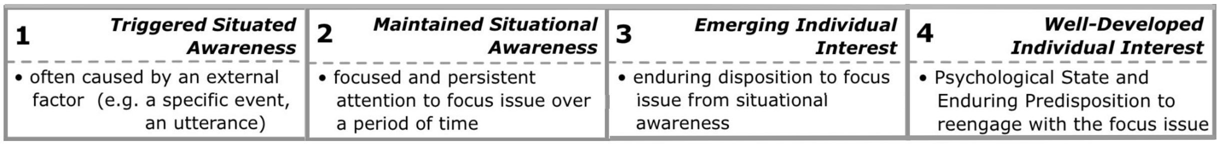

Figure 5.3: Four Levels from Hidi and Renniger's Model of Interest Development. Reprinted with permission from *"Exploring the 3D printing process for young children in curriculum-aligned making in the classroom"*[4]

5.3 Findings: Increased 3D Printing Interest and Observed Challenges

A qualitative open coding analysis was performed on the observation notes and interview responses to generate themes of interest with respect to students' interest in 3D printing and challenges faced engaging in the simplified 3D printing process. We utilized Hidi and Renniger's Four-Phase Model of Interest Development [140] as a framework to analyze students' interest in 3D printing, shown in Figure 5.3. The span of four days of our study does not allow us to infer whether students engaging in the simplified 3D printing process can eventually develop individual interest in 3D printing.

5.3.1 Students' Interest in 3D Printing

Many of the students had heard of 3D printers, but had not seen one. *Situational awareness* of 3D printing was *Triggered* (Figure 5.3, level 1) in the students when the researcher printer-operator compared 3D printers to a hot glue gun. One student exclaimed how she and her mother worked with hot glue guns often, saying it would be fun to also have 3D printers.

Throughout the week of the study, about half of the students moved slowly to *maintained situational awareness* (Figure 5.3, level 2). E.g., one pair of students immediately searched '3D Printers' on their browser before environment assignment. They were self-driven and eager to learn more about printers. Another group didn't act as quickly, instead spending more time researching their environment, but one member repeatedly said "we should go to the page (Thingiverse)".

By the end of the four days, there were indications that most of the students in the *maintained situational awareness* group progressed to *emerging individual interest* (Figure 5.3, level 3) in 3D printing. Many students asked curiosity questions about 3D printer operation not mentioned in the first day's introduction. Some students, seeing support material in the printing process, asked about why the print would need that extra plastic. There were many questions about the price of printers and parts. Some students were curious about different constraints of existing printers, such as the range of size and materials of existing 3D-printed artifacts outside the class.

Other indicators of the students' emerging individual interest in 3D printing are their questionnaire (Figure 5.4 and interview responses. In 5-point Likert scale questions, students responded overwhelmingly that they understood and had fun participating in the activity. The results of the questions are shown in Figure 5. When asked what they would print if they had a printer at home, students in the interviews responded with variations of "I would do everything" and "every day I do something". One student said that he wanted to print and build a robot because he "want[s] to be an engineer when [he] grow[s] up".

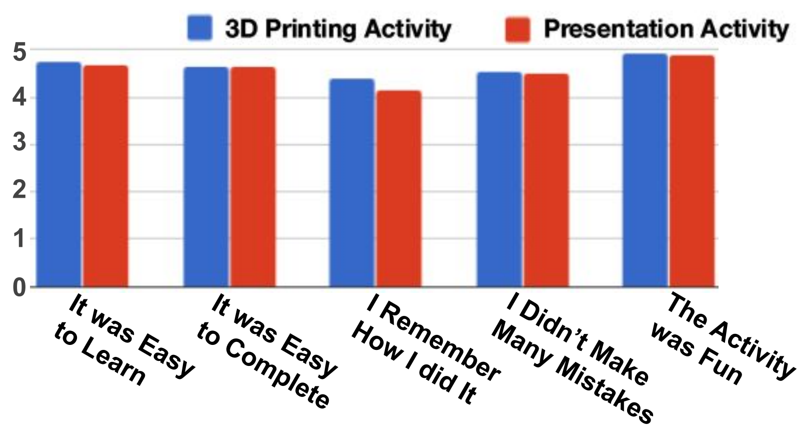

Figure 5.4: Likert-Scale Questionnaire Results from Day 4 on 3D Printing Experiences and on the Presentation Activity as a whole. Reprinted with permission from *"Exploring the 3D printing process for young children in curriculum-aligned making in the classroom"*[4]

5.3.2 Challenges in the Simplified 3D Printing Process

Students faced several roadblocks in the simplified 3D printing process. Challenges occurred at all three steps of the process. We found four main themes of challenges that the students faced:

I. Problems in Identifying Object to 3D Print

Some students had difficulty brainstorming what to print for their environment, reducing the time they had to complete the rest of the 3D printing process. Students that succeeded in planning often relied on past experiences. One group wrote down tigers, because they remember seeing tigers in a desert during a music video. Another wrote down playset equipment for their environment, saying they saw those in "every park".

II. Spelling and Semantics When Searching

Many students were able to find 3D designs on Thingiverse without much help, but searching online produced some confusion and frustration. One issue was that the 3rd graders had difficulty with spelling, and searches did not offer spelling correction. Hence the queries that would normally yield many results with correct spelling produced no results. Some students would give up on a particular query if a helper did not immediately intervene, and some would find a helper to spell out the desired query. E.g., one group searched for whales by searching 'wheels', and needed help to find whale designs. Some query results did not match students intentions. One pair searched for 'slide', and when Thingiverse returned many different slides without playground slides in the top results, they revised their query to 'park slide'. Many students searching animals did not face this issue. E.g., "lion" had fewer semantic meanings than "slide".

III. Mismatched Expectations

Students often chose 3D designs based on certain key attributes, e.g. degree of shininess, color, etc. Thus, when initially ordering their designs, students would often imagine the printed artifacts based on their presentation on Thingiverse. E.g., a pair of students searching for rabbits for their park chose a model because of complex coloring in the preview image. Students were previously instructed that prints would be a random solid color, but many still expected colors shown online. Another pair chose a fish model to be printed since it appeared large online. The operator clarified that the fish could be made smaller by rescaling. To help attenuate students' disappointments, the operator always asked questions about why the students chose a particular design, and communicated any differences between students' expectations, curricula expectations, and 3D printer capabilities with respect to the students' desired print.

IV. Focus on Visuals than Semantics

Students were more interested in printing designs for their visual qualities rather than semantic relevance for their presentations. This highlights that given its strong visual attraction, 3D printing in educational usage faces the challenge of relevance for it to be a tool to support learning. E.g., some students selected designs because "we thought it was cute. We liked it" and "it looked like Mufasa... from the Lion King". When asked how it related to their assigned environment, many students simply said it belonged in the environment, but did not explain how they would incorporate it in a presentation.

5.4 Limitations and Discussion of Study Findings

Through the simplified "*casual maker*" 3D printing process, some students appeared to have gained an emergent interest in 3D printing. Growing self-efficacy was also apparent in students' claims that they liked and were good at 3D printing. However, further studies would be needed to determine if emergent interest persists to become a *well-developed* interest after this one classroom intervention.

Some students presentations were stand-alone, and more decorative than integrated into their science presentations. This result may indicate *triggered situational awareness*, but does not guarantee further progression of interest. Instead, this could lead students to develop Blikstein's "*Keychain Syndrome*"[141], where students recreate items with a near-identical simple fabrication process, not wishing to explore new concepts. In Blikstein's work, he describes this syndrome with a story about students learning how to laser-cut keychains. They would quickly make keychains from image-files, receiving much social praise from friends and family. So much, in fact, that they did not want to learn anything beyond fabricating keychains because they were satisfied with the end-product of the present process they had mastered. To combat keychain syndrome, incentive or formal interventions must be provided for students to learn new or more-complex fabrication processes. We recommend involving students in more complex 3D printing processes as time progresses to avoid this syndrome.

Overall, the simplified 3D printing process was successful in producing students' first prints and developing their emerging interest in 3D printing. Students did face many challenges even in this very-simplified process, that requires students to ask "*What can I print?*" without requiring them to know the technical machine-operational details of "*How can I print?*". The creation of more *WYSIWYG* interfaces could help aid students manage expectations of how a chosen design matches a printed product [37], but students faced many barriers before even choosing a design. Difficulty crafting search queries and identifying items from those query results prevented many from identifying printable items for their classroom task. The next chapter explores how all (adult) newcomers to 3D printing may face similar challenges.

5.4.1 Children Learning "*Making*" Online

While not explored in the above study, this simplified process may afford future opportunities for exploring how people learn fabrication technologies online. Simplified and more-formalized communication processes become more feasible through online collaborations [14]. Early research we conducted demonstrated that "*Making*", and potentially other forms of hands-on technology-infused learning, may be partly facilitated by many online presences [142]. Through content-analysis and Amazon Mechanical Turk analysis of many "Maker" websites, design recommendations for "Maker websites" were developed: **1)** Draw out learning content that isn't purely technological; **2)** Illustrate the risks inherent in Making (i.e. it is not always successful); **3)** Shift the focus of the website to the student as a Maker, not the brand of the Making-facility or product; **4)** Provide avenues for users with low technology understanding to use the website; **5)** Consider linking or associating websites that serve online users with real physical spaces; and **6)** Include interactive features in websites regardless of physical local or transience of the Making-facilities. Additionally, many existing websites are perceived to be targeted for those in higher Socioeconomic Status (SES). Note that interventions in public school classrooms, like the Title 1 school classes described in this chapter, may help students overcome some of these socioeconomic barriers to participate with hands-on technology-infused learning. While the inherent physicality of Making and hands-on learning complicates distant (online) collaborative learning practices, the final chapters of this dissertation begin to reveal how the ethos of “Making”, “Do it Yourself”, and “Personal Fabrication” may be fostered online through simplified and more-formalized collaborations.

The relevant contributions of this chapter are as follows:

- Students’ interest towards fabrication can be triggered by simplified fabrication processes
- Challenges to how young students may search and identify 3D files to download and print
- Challenges between expectations and reality of young students’ 3D prints
- Design Recommendations and Perceived Audience for Online Maker Websites

This ends the portion of the dissertation directly studying hands-on technology-infused learning in formal education settings. All following chapters more generally investigate how interest in similar hands-on technology-infused learning practices may be triggered by proximal and online accessible printing resources.

6. ANYONE CAN PRINT: INVESTIGATING BARRIERS AND CHALLENGES PRESENT IN ALL 3D PRINTING PROCESSES BY OBSERVING NEWCOMERS TO PRINTING SERVICES*

This chapter investigates how anyone may learn how to print, specifically through services. All 3D printing processes require specification of ***what*** to print, determined through collaboration and negotiation between humans and machines to ascertain ***how*** to print. Specifying printable ideas is not trivial but is necessary for anyone to print, affording broader populations the ability to identify and fabricate a large variety of printing applications to affordably deliver large societal impact: protecting many during the COVID-19 pandemic [41], supporting accessibility for the blind [143], and many other unique applications [25, 144, 145]. While previous work has investigated barriers newcomers encounter ***when*** operating and maintaining machinery within 3D printing facilities, this chapters identifies barriers and challenges any newcomer may face when learning to specify and communicate their ideas with 3D printing services ***before*** seeing or interacting with 3D printing machinery within 3D printing facilities.

While previous research has focused on how digital fabrication may be appropriated by printing–enthusiasts [146, 29, 30, 31] or how proximal printing centers have empowered many to directly utilize these technologies [72, 7, 24, 22], the main focus has been on the *practice* of 3D printing through the direct operation of printers. This practice is learned through trial-and-error, often in co-location with experienced practitioners [7, 72]. However, experienced printing practitioners are not accessible to everyone, but we can imagine a future where anyone can utilize 3D printed products. These products may be made by users with encapsulated knowledge of what can be fabricated through printing services, avoiding the demotivating trial-and-error accrued through directly operating diverse fabrication technologies. Ideally, such services would only require specifications on *what* clients want to print, insulating clients from the technical details of printer operation and

Parts of this chapter are reprinted with permission from "Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication" by Alexander Berman, Osazuwa Okundaye, Jay Woodward, Francis Quek, and Jeeeun Kim in the Proceedings of NordiCHI 2020 maintenance. Similar to a poster-printing shop, a client could just design a poster and list specifications like material type and resolution. However, many constraints to what can be effectively and consistently produced with 3D printers necessitate collaboration between clients and services to establish *what* can be printed (i.e. the client's role) and *how* to print the client's order (i.e. the operator's role). Even as these constraints are broken by technological advances in 3D printing, barriers and challenges to establish this collaboration will remain.

Olson and Olson's *four requirements* for successful collaboration, presented in *"Distance Matters"* [14], inform the analysis of our two studies: **1)** observations and interviews of "*familiar users*" (n=20) of 3D printing services and **2)** a controlled lab study introducing *newcomers* to printing collaborations (n=21). *Familiar Users* may possess various levels of familiarity and expertise with printing processes, but all possess introductory knowledge of printing opportunities (e.g. where to print) not yet obtained by *newcomers*. **Collaboration Readiness** refers to newcomers' awareness and motivation to begin interacting with printing services, irrespective of prior related experiences [147, 148]. **Coupling of Work** refers to workflow dependencies between clients and service-operators, where co-location and formalizing of printing processes can aid in these collaborations but are not always necessary. **Technology Readiness** refers to clients' awareness of printing processes, and their ability to effectively begin the printing service process. **Common Ground** must be established between clients and services to establish *what* to print (*content*), as a function of *how* to print (*process*) with combinations of software, hardware, and materials that require experience to master [25, 9].

This chapter reveals that newcomers are motivated, gain confidence, and obtain the capability to 3D print after a short intervention introducing them to basic 3D printing concepts and helping them practice initial collaborations similar to those in print shops. Newcomers to 3D printing have difficultly identifying introductory 3D printing resources and opportunities on their own (*i.e. collaboration readiness*), which makes it difficult to establish the *common ground* and *technological readiness* necessary to collaborate. Even with introductory resources, newcomers often still face challenges establishing *common ground* about what they wish to print, creating ineffective *coupling of work* and damaged trust when printed products that do not match clients' expectations.

6.1 Methodology

We adopted Olsons' framework as an analytic lens to guide the below studies and the presentation of results. Specifically, the overarching research question is: **What are the challenges in initiating successful collaborations between layperson clients and operators of 3D printing services?** First, we describe observations and interviews in two university printing services, gaining perspectives of "*familiar users*" who are within a print shop and thus have already overcome challenges and barriers to initiate print shop collaborations. Then, we describe a lab study investigating how people with *no* prior 3D printing experience (i.e. *newcomers*) may be challenged when starting collaborations with 3D printing services. Together, these two studies capture what challenges are identified in hindsight by populations that are already printing (*familiar users*), and what additional challenges anyone may encounter before printing.

6.1.1 3D Print Shop Observations and Interviews: Barriers Encountered by "Familiar Users"

To gain insight into how "familiar users" perceive and overcome barriers to collaborate with 3D printing services, we observed and interviewed stakeholders in two local university printing shops. We observed two printing shops and conducted semi-structured interviews with 20 people: 4 managers, 8 staff members, and 8 clients. Following inductive analysis techniques and a grounded theory approach [149, 150], we iteratively reviewed the researchers' observation notes, semi-structured interview recordings, and associated transcripts to align them with Olsons' framework.

6.1.1.1 Print Shops are Not Makerspaces

The setting of this study are print shops, which operate differently than makerspaces or purely online printing services (Figure 2.2); clients can consult the staff and/or have them print out 3D files for a nominal fee based on the material cost and duration of each print (see Figure 6.4), where the cost of labor is implicitly integrated. The two printing shops are located within a half-mile of each other at the authors' university in a rural location, and are the only print shops nearby. These shops include clients that are not only students and faculty, but external community members. Managers with significant prior 3D printing and fabrication experiences train staff and oversee the shop. The staff, supervised by the manager, help facilitate the service to a variety of clients. Both shops mainly utilize Ultimaker fused deposition modeling (FDM) machines and Formlabs sterolithography (SLA) machines. Both also have high-end printers (e.g. Stratasys Dimension-SST), which can be employed for much higher fees. Equipment and staff are largely funded by their respective colleges: Engineering (**E-Shop**) and Architecture (**A-Shop**). Below we denote shop-stakeholders as *A* for A-Shop or *E* for E-Shop, followed by *M* for Manager, *S* for Staff, and *C* for Client. For example, ES1 denotes the first engineering staff interviewed. One limitation of this study is that only "familiar users" of university print shops were observed, not including clients of purely-online services.

6.1.1.2 Identifying Prevalent Barriers

Researchers recorded notes of client-staff interactions in these two print shops, approaching clients, staff, and managers to participate in semi-structured interviews. Interviews were focused towards understanding how clients discover the shop and related 3D printing resources; what may prevent clients from discovering or utilizing the shop; and how clients establish collaborations with the shops. While analysis of these observations and interviews revealed many barriers to newcomers, all data was from the perspective of "*familiar users*" who all now have experience in 3D printing. The following lab study captures the perspectives of those who have never 3D printed, and may never have entered a print shop due to similar barriers.

6.1.2 Study 2: Focused Lab Study

To gain better understanding of how people with no prior 3D printing experience (i.e. newcomers) perceive printing processes, and how these processes may change after their first time collaborating with a print shop, we conducted a controlled lab study intervention emulating participants' (n=21, Figure 6.2 - *left*) first interactions with a print shop. Participants were recruited

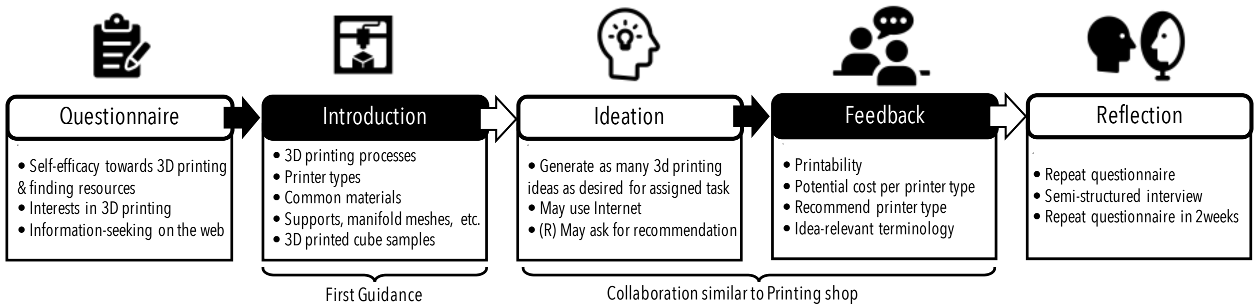

Figure 6.1: Newcomers, after an introduction to 3D printing derived from the observational study, completed a design-ideation exercise and received feedback emulating print shop collaborations. Some could ask for web recommendations (R) during the Ideation stage. Reprinted with Permission from *"Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication"*[5]

via email, based on willingness to learn about 3D printing and absence of previous printing experiences. Participants were asked to complete questionnaires before the intervention, immediately following the intervention, and then two weeks after the intervention. The lab study tested the following hypotheses:

Hypothesis 1: Newcomers to 3D printing will develop self-efficacy and understanding towards collaborating with printing practitioners, if given opportunity to experience similar interactions

Hypothesis 2: Newcomers to 3D printing who can receive practitioner-guidance for searching online will be better able to generate *'printable'* ideas, and to communicate these ideas to printing practitioners

6.1.2.1 Procedure

The intervention (see Figure 6.1) was informed from the observational study analysis, where awareness and introductory knowledge motivated and transformed newcomers into clients of 3D printing services. Participants received a brief introduction to 3D printing similar to the introductions that print shop staff give to new customers (~20 min.). Participants were informed about generic 3D printing process, typically involving (i) obtaining a 3D file, (ii) using slicing software to generate printer-specific code (e.g. G-Code), and then (iii) uploading this to the specified printer.

Then, participants were introduced to FDM and SLA printing; common printing material options and their properties and costs; approximate size constraints of these printers; and explanations on support material and manifold meshes. Participants were given two sample rounded-cubes printed from high-resolution FDM- and SLA-printers to closely examine, as examination can inform newcomers' perceptions towards material aspects of potential 3D printed products of these print shop technologies [93]. This introduction concluded with description of the two university print shops' locations, contact methods, and a histogram of all print prices for Spring 2019 in the A-Shop. Participants could ask questions at any time and take notes to assure their comprehension. The presentation did not contain any examples of 3D printed products besides the examined cubes, to avoid biasing the participants' ideas of what is printable.

After the presentation, the participants were given 20 minutes for the following task: *"Describe and/or Sketch something to be 3D printed that will interact with your phone in a way that can assist with your work or hobbies"*. This task encouraged participants to be creative on how 3D printing could function in their lives, but also be comparable around a similar set of functions. As this ideation stage was often not observed in the printing shop, observing the ideation stage in lab environment gave us unique perspectives into initial design influences and decisions made by newcomers. Participants were encouraged to search online (e.g. on a provided laptop). Afterwards, to provide experiences to participants similar to print shops, the facilitator provided (1) feedback on each of their generated ideas; (2) how to obtain or design a 3D printable file (e.g. online resources and CAD programs); (3) how to identify common problems commonly associated with printing similar meshes (e.g. overhang, orientation strength, etc.); and (4) an estimate of each ideas' shop cost.

6.1.2.2 Independent Variable: Web Recommendations vs. No Recommendation

Some participants could ask for guidance during the 20-minute ideation session. One of authors, assuming a *facilitator* role as someone experienced in 3D printing, recommended search terms and websites based on their questions without additional commentary (**R**: Recommendations provided, **R#**: denotes participants) to 11 of the participants. In the other condition, 10

Condition	Participant	Age	Gender	Education	Major	CAD Level*
No Recommendation (N)	N1	48	M	4-year College	Computer Science	1
	N2	20	M	Highschool Equivalent	Renewable Resources	1
	N3	27	F	Doctoral Degree	Civil and Petroleum Engineering	1
	N4	39	F	4-year College	Education	0
	N5	28	M	Master's Degree	Geology	0
	N6	19	F	Highschool Equivalent	General Studies	0
	N7	46	F	Master's Degree	Bioengieering, Saftey Engineering	1
	N8	35	M	Doctoral Degree	Chemistry	0
	N9	27	M	Doctoral Degree	Water Resources Engineering	1
	N10	60	M	Master's Degree	Finance and Management	0
With Recommendation (R)	R1	24	M	Master's Degree	Plant Breeding	0
	R2	50	F	Highschool Equivalent	Applied Science- Veterinary Technology	0
	R3	23	M	4-year College	Industrial and Systems Engineering	2
	R4	26	M	Master's Degree	Geology	0
	R5	37	M	Master's Degree	Hospitality, Land and Property Development	2
	R6	28	M	Master's Degree	Aerospace Engineering	1
	R7	31	M	Doctoral Degree	Animal Science	1
	R8	24	M	4-year College	Physics	1
	R9	37	M	Doctoral Degree	Mechanical Engineering	1
	R10	23	M	Highschool Equivalent	Computer Engineering	0
	R11	41	F	Doctoral Degree	Psychology	0

* 0: No Experience, 1: Little Experience, 2: Working Expereince

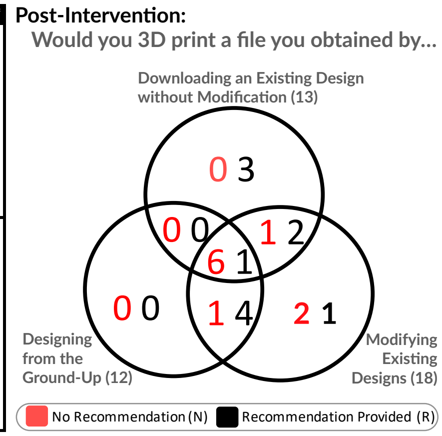

Figure 6.2: Participants in the lab study were generally well-educated, but did not have 3D Printing experience *(left)*. Participants post-intervention considered if they would print files Downloaded from online, Modified, or Designed without modification *(right)*. Reprinted with Permission from *"Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication"*[5]

participants were given no recommendations from the facilitator (**N**: No recommendations, **N#**: denotes participants). All mentions of *recommendation* below refer to these web recommendations. The distinction between the intervention-types tested *Hypothesis 2*, informing the type and extent of web recommendations that help motivate and initiate printing collaborations.

6.1.2.3 Questionnaires

The participants first completed questionnaires containing demographic information, open-ended questions regarding what they think 3D printing can accomplish, their imagined 3D printing steps, how they would find 3D printing resources, and inquiring about their prior experiences with 3D printing, with physical design, and with web browsing (see Figure 6.2). Participants then completed several Likert-scale measures relating to participants' perceptions towards 3D printing and browsing behavior online: self-assessment on the **1)** attitude and behavior toward careful information seeking on the web [151], **2)** individual interest adapted for both 3D printing and information seeking online [152], and **3)** self-efficacy for finding resources to successfully identify and solve problems in 3D printing, and to successfully print for their work and hobbies [153]. All non-demographic questions were repeated in person after the intervention, and again two weeks following the study via email to help measure participants' changing perceptions towards utilizing 3D printing, finding resources online, and collaborating with print services. The Shapiro-Wilk test showed deviations from the normal distribution, so we ran a Wilcoxon Sign-Ranked (WSR) Test between these before– and after–intervention measures. A grounded theory approach was utilized to analyze the interactions and questionnaire data [149]. A set of common axial codes emerged from open coding of videos, audio, questionnaires, and transcripts.

6.2 Findings in Four Concepts

To understand how to motivate and facilitate successful 3D printing collaborations, we organize the findings by the following concepts from Olsons' framework: common ground, coupling of work, collaboration readiness, and technology readiness [14]. Each section below describes one concept within the context of our print shop observations and interviews, then presents the relevant results from the lab study.

Figure 6.3: Some Printing Service Users enlist design-help from the Operators, collaboratively creating simple novel designs quickly in CAD. Reprinted with Permission from *"Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication"*[5]

6.2.1 The Coupling of Work: A little help goes a long way

"If you print something stupid, the service is not going to do it" (AC3)

6.2.1.1 Observational Study: Coupling in Consultation and Validation

Collaborations with services can alleviate the needed experience to begin printing, but the extent and type of collaborations vary (see Figure 6.4). The coupling of work is associated with the nature of the task, requiring differing levels of common ground [14]. Loosely-coupled collaborations require very few interactions, where a client specifies a 3D file and the shop prints it out perfectly to expectations without any iterations of feedback. Tightly-coupled collaborations require many rounds of feedback and advice, requiring higher-bandwidth channels or co-location for success [14]. This section identifies how coupling varies within print shop workflows, and how misidentifications of the workflow result in wasted effort and damaged trust.

Some workflows involve next to no interaction, where clients order a uploaded design and the staff print it, primarily exhibited by those who had prior experience with the shop. However, staff *validate* files before printing to ensure that files are printable and matches clients' expectations (e.g the client's quote at the beginning of this section). Sometimes this validation is loosely-coupled, where files are obviously missing geometries during export from CAD programs (called the "*Double-Blink Test*" by AM1), and a re-upload passes validation. Sometimes validation becomes more tightly-coupled, where the staff will have to explain to the user why something is not printable. Staff often *consult* with clients when they seek advice, and when they encounter non-trivial validation-failures. All managers mentioned guiding users towards not ordering designs that are too thin to print, too large, or too complex (e.g. too many overhangs). Also, staff frequently helped clients understand how to fix common issues like non-manifold meshes. Failures in validation and consultation occurred if the client insisted on printing setting that were risky (e.g. printing faster for a deadline) or if common ground of design function was not established (e.g. parts breaking under extreme forces). Sometimes consultation involved collaborative design, like one A-Shop client that wanted to print a desktop ornament derived from a one-stroke fox drawing image that they quickly extruded in TinkerCAD and printed, shown in Figure 6.3. When we refer to print shop collaborations in this chapter, we refer to these validation and consultation interactions. In summary, tasks surrounding newcomers' design-workflows and unsuccessful printability-validations often require tightly-coupled collaborations.

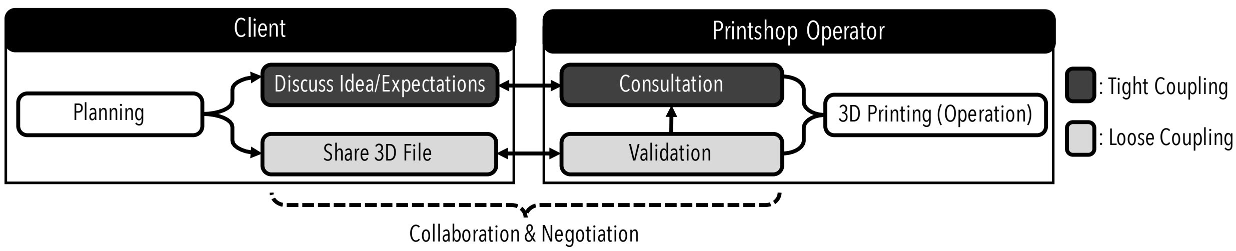

Figure 6.4: The workflows in *Print Shops* help newcomers learn 3D Printing basics while preventing mistakes. Newcomers' first interactions may be tightly-coupled, but this loosens as newcomers learn 3D printing basics. Sometimes failed validation leads to consultation. Reprinted with Permission from *"Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication"*[5]

6.2.1.2 Lab Study: Fostering Collaboration through Formalization and Web-Recommendations

The intervention-design formalizes the aforementioned printing workflows into three steps: **1)** a tightly-coupled introduction based on common consultation content, **2)** a loosely-coupled design-ideation exercise, followed by **3)** tightly-coupled feedback on designs. We investigated the effectiveness of formalizing the workflow on familiarizing people with printing processes, while exploring the coupling during ideation by providing web recommendations.

Beginning with Tightly-Coupled Introduction: Those who were allowed to ask questions (**R**) inquired 1-3 questions to the facilitator (median=1), and received 1 to 5 web recommendations (median=2). Questions asked by all R-condition participants include example projects (e.g. "What are some examples of things I can 3D print?"(R3)), printing feasibility of a design idea (e.g. "how do I know which ideas are feasible to print?"(R9)). Participants often informed online queries and ideas based on previous queries. For example, a Veterinary Technology Supervisor (R2) was rec-

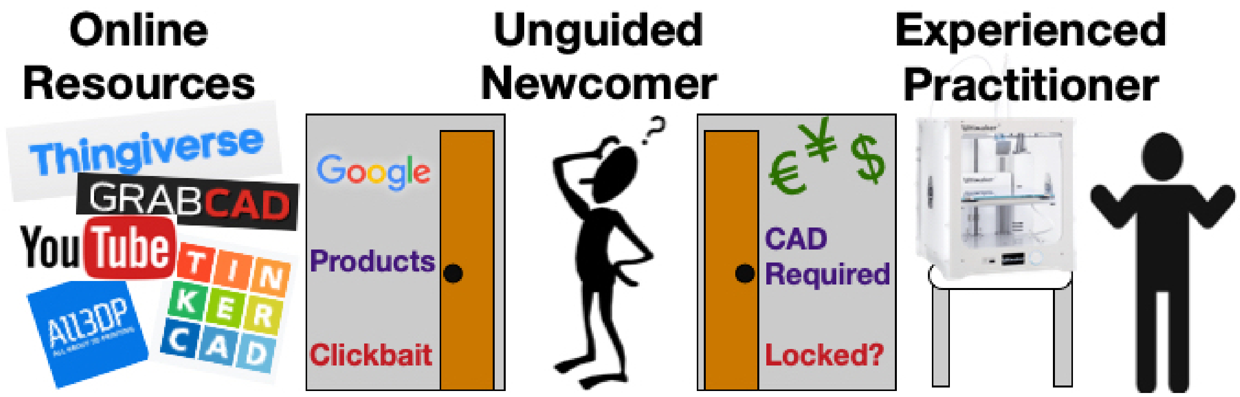

Figure 6.5: Gaining access to the functionality of 3D printing technologies requires newcomers to understand why and how they may open doors to printing resources. Guiding newcomers across these doors may broaden participation with 3D Printing through increased Collaboration Readiness and Technology Readiness.

ommended to search 'otoscope' on Thingiverse, which she found and recorded as an idea (Figure 6.6). This inspired her to search for a "cell phone ophalmoscope", but realizing that ophalmoscopes are complex to purely 3D print due to the need for an expensive lens, instead focused on other ideas.

Changing of Coupling After Initial Guidance: After they received one recommendation, coupling with the human facilitator loosens while coupling with online search resources and services tightens. Participants who received recommendations left with desire to know more 3D printing websites, saying "If I can find a useful website, I could do 3D printing by myself from the beginning"(R9). Additionally, those in the R-Condition often required less feedback (i.e. loose-coupling) on how to print their ideas, as the answers could be embedded in existing 3D printing designs.

The formalizing of initial collaborations succeeded in encouraging newcomers to find and interact with 3D printing resources, represented through significant increases across: enlisting 3D printing help from others (W=22.5, p=0.0035) (e.g. *Get help when stuck on a 3D printing problem*), self-efficacy for the ideation of 3D printing ideas (e.g. *Think of an interesting idea for a 3D printing project*) (W=31.0, p=0.010), self-efficacy for achieving 3D printing goals (e.g. *Finish a 3D printing project*) (W=27.0, p=0.0036), credulity towards online resources (e.g. *How likely* *are you to believe the information contained in the web pages returned by a Web search engine?*) (W=10.0, p=0.00024), and general trust (e.g. *I believe in trusting my hunches*) (W=7.0, p=0.037). Overall, the intervention had a *significant* effect in improving self-efficacy and improving belief in online information-seeking towards 3D printing. Participants in the R-Condition saw significant increase in self-efficacy of Enlisting Help for 3D printing (W=0.0, p=.008) and self-efficacy for thinking of 3D printing ideas (W=5.0, p=.038). For the N-Condition, we saw significant increase in self-efficacy of 3D printing achievement (W=2.0, p=.0090), but not for enlisting help and thinking of ideas. Recommendations to web resources generally helped participants gain confidence in help-seeking for 3D printing, associated with a loosening-coupling of work.

6.2.2 Collaboration Readiness: Doors to Access

> *"[They don't] know the process of how we do things. They don't know whether they can come in or not. When people do come in, they take the time to learn how to do this. It's not that it's hard at all, but people don't come in and ask"* (ES1)

6.2.2.1 Observational Study: Doors to Collaboration

As the Olsons' prescribe, newcomers develop readiness to collaborate through developed awareness and familiarity with collaboration-cultures [14]. Lave and Wenger illustrate how this awareness and familiarity are not trivial in their Situated Learning literature about *Access*: an individual's ability to interact with "information, resources, and opportunities for participation" [10]. In this work, common issues in *Access* are depicted in a butcher apprenticeship program, where a door separated butcher-apprentices from the experts cutting the meat, and were effectively relegated to only wrapping the meats. This door denied the relative newcomers access to the knowledge, self-efficacy, and identity to 'become' full-fledged butchers. While they saw the product of the practice, they had no idea how it was made because of a door. This door could be crossed at any point, but the feeling of being an outsider and the lack of awareness about crossing-procedures kept most from opening the door [10]. Similarly, newcomers to 3D printing encounter a metaphorical door even *before* they interact with printing services.

"Familiar Users" interviewed were surprised that 3D print shops existed. Managers mentioned that "word-of-mouth" and required coursework are what drove many people to visit the shops. One interviewee tried the E-Shop first because it was more visible, being located in a high-traffic area and being highly visible behind glass walls. However, many are not aware about how to talk to E-Shop staff or gain access as they are all located behind the glass-walls with limited physical access. One staff member did admit "there would be a lot more people coming in"(ES1) if the E-Shop had open doors to anyone. A manager of the E-Shop commented "Some of the students never find out about our facility, especially those who don't have projects that require use of the 3D printers or machine shops in class"(EM2). It reveals that newcomers must be aware that a printing service exists, and is accessible to them, to open the door to Collaboration Readiness. The door may be self-opened like AC1, who searched online for available shops, but this can be challenging.

While managers and staff say "[Clients] need to know how to use google [to find 3D printing resources]"(AS2), they admit it's not as easy as it sounds. Many A-Store staff members and managers mentioned something similar to "you have to know what you are looking for"(AM2) when searching online. Newcomers' Collaboration Readiness may benefit from knowledge of where and how others utilize printing services.

6.2.2.2 Lab Study: Google is often a Dead-End

The lab study thus closely examined the door from the perspectives of newcomers who have not opened it yet. We investigated how newcomers found web resources that would aid in collaborations, and found that many newcomers can not find helpful resources for 3D printing without help. Three out of ten participants in the N-condition (n=10) did not look up anything online. Out of the other seven who did search online, only four participants search with terms similar to "3D print", instead often searching for phone products without including 3D printing terms. For example, N9 decided not to use the internet after searching "phone support bike", where he did not go to any of the search result links. Two just scrolled through Google Image search results, but unfortunately, ended up not visiting the 3D print source websites. Three of the four that searches included "3D print" clicked on blog posts that did not contain much information, usually following a format similar to "11 most useful phone accessories for making your phone into anything" (page visited by N3), again not visiting other 3D printing related websites from the blog scrolling. Design-sharing platforms were only discovered if recommended. Twice as many participants with recommendations (6) visited 3D printing informational websites (e.g. blogs and news sites) than without (3). Participants did not visit many links to 3D printing webpages, despite seeing them in their search results. Newcomers may have challenges finding and potentially utilizing websites that inform their printing processes and ideas, and motivate them to print. This presents a paradox of self-guided learning in the modern age of search engines: *you often have to have some prior knowledge to find introductory knowledge*.

Even when asking the right questions, the right search queries, newcomers often did not trust search results from unfamiliar domains. Those who received recommendations recollected: "When I first opened google, I didn't know if I could trust Thingiverse"(R4) and assumed "[Thingiverse] was paid advertisements"(R5). Without recommendations and knowledge of printing-terminology, participants mentioned they "feel more confident talking to people than talking [to people] online... because I want to feel confident I'm using the right words to talk to somebody online about what I'm doing"(N8). As printing practices involve articulation of many online tools and resources [9], newcomers should be familiarized with some of these resources *before* collaboration.

6.2.3 Technology Readiness: Choosing a Printing Process is Difficult

> *"I looked for a playing card holder online, but didn't find one that I liked. I decided to make my own using TinkerCAD and print it... [I went] several times to get feedback from the technicians on my card case design. The help was very useful in getting my design oriented to reduce supports" (N1 two weeks after the intervention)*

6.2.3.1 Observational Study: Knowing Unattended Gaps between Modeling and Printing

3D Printing seems daunting to many from a distance. We found that many clients view 3D printing as primarily an engineers' practice (e.g. *"if you're not engineers, [3D printing] can be difficult"*), even while many were highly-educated STEM practitioners. This is partly due to an assumption that to learn how to print, one has to learn how to 3D model. In reality, there are more options than assumed by newcomers to create a 3D file: 1) download a design from online, 2) modify downloaded design(s) using common CAD tools, 3) design without downloading online designs. Newcomers are often only aware of the last option, which makes them hesitant to even consult the print shops. In one extreme case, AC2 learned about shops from friends but spent over a month learning CAD on YouTube before even visiting the shop to consult staff about printing processes. On the other hand, some students chose not to bridge the gap between modeling and printing, printing purely from online designs. Two clients in particular learned about "model-shopping" online from print shop staff, and frequently ordered figurines (e.g. a Pikachu statue) to print. They trust popular designs on model-sharing websites, as their printability is assured by online users' successful prints. 3D modeling is a useful skill, as AC1 eventually became an inventor of several inexpensive physics instruments (e.g. a $40 spectrometer), but modeling from scratch can be daunting to many newcomers and is not always necessary to 3D print.

6.2.3.2 Lab Study: Exposure to Online Designs Affects Modeling Processes

While all participants were informed about the general printing process, including that shared 3D files may be downloaded, newcomers without recommendations barely imagine it is possible to download and 3D print a obtained design file without modifications. Participants were asked after the intervention to explain if they would model with each of the aforementioned options. Shown in Figure 6.2 (*right*), participants without recommendations were more agnostic to different modeling processes. Those in the R-condition imagined more specific modeling processes than potentially utilizing all 3 options. Three imagined only downloading designs. *"Starting off would be easier"*(N4) to print pre-made designs, especially if *"I thought something was cool... provided a use"*(N2). A few did not want to print online files because of issues of trust and ownership, saying *"I don't know if that [online] stuff works"*(N7), *"It's from someone... his idea of purpose is not mine"*(R7), and *"I want to make it myself"*(R1). N3 did not want to download designs because she felt like it was stealing. Modifying designs was good with all but 3 overall (R2-3, R11), making *"something more useful to me or someone I know"*(R10), to *"tailor to my needs"*(R5) *"which is* *more efficient"*(R9) *"instead of creating [files] from the ground–up"*(R5). While many wish to learn 3D modeling, some comment that they are busy and *"don't have much mental capacity [to learn new skills]"*. R11 mentioned having no desire to learn or use CAD , but *"would get someone to design"* if she couldn't readily find a 3D file.

Not every person wants to learn advanced CAD skills, but many view this as a prerequisite to printing. When explicitly asked "How would you obtain a 3D file to print" before the intervention, 13 mentioned having to design something in a CAD-like application (N1-3,N6-8,R3,R5-8) like "through 3D Paint"(N6). Seven said they had "no earthly idea"(R11) how to get a 3D file for printing (N4,N9-10,R4,R9-11). All participants could see themselves either downloading or modifying downloads to print, but not necessarily designing without downloading. To support print shop collaborations, newcomers should be able to distinguish requirements for printing from requirements for modeling: *3D printing does not always require one to be able to model by themselves in advanced CAD programs*. In fact, many participants viewed 3D printing as a form of shopping, saying "if printing is pricier, then buy it... but if printing is cheaper, then print it" (R10).

6.2.4 Common Ground: Newcomer Know-What is Dependant on Know-How

> *"I've never searched for things that could be 3D printed, so that's cool... it's something we could make... my next step would be to 3D print this, see where problems lie, and adapt it to my usage." (R5)*

6.2.4.1 Observational Study: Specifying a File and Material Does Not Establish Common Ground

All interviewed clients had successfully collaborated with the shop, and had learned more about 3D printing during the process. Many clients mentioned that anyone can "*print like you would at any print shop*", and *"I learned with the people who were working here"*(AC3). However, not all collaborations were successful. Often some details of a final print did not match the clients' expectations because common ground was not established. *Process common ground* with printing services is how clients and services exchange information to establish *Content common ground* of *what* to print, not necessarily *how* the printers are operated. Clients are responsible to explain their printing ideas, but need to rely on service-operators to guide the designing process and set expectations on the final product. Similar to Mao et al. [16], establishing elements of process common ground affords collaborators greater ability to establish the needed content common ground sufficient for collaboration. Without process common ground, collaborators may not be able to establish content common ground, because they did not share information pertinent to the particular 3D printing application.

6.2.4.2 Lab Study: Forming and Communicating Ideas of What to Print

Forming ideas of what to print is not trivial to newcomers. Participants claimed it was difficult to "*discover the launch point to put an idea into motion*"(N5) and was difficult to explain ideas to others, commenting "*complexity of drawing it so others can understand*"(N8) as potential reason. Before the intervention, five participants were not even able to answer to the question "What steps are involved in 3D printing?". Participants before the intervention could not identify where to find printing information, with 12 saying they would use Google, and 6 mentioned having "*no idea*"(R7) where to look. Three (N3,N6,R4) explicitly mentioned turning to social media, like looking for "*guidance through videos on YouTube [and] online communities*"(N6).

Conveying Ideas for Collaboration Participants generated between 1 to 11 ideas during 20 minutes of the ideation task (sum=62, median=2), only 1 to 7 of which followed the assigned task of interacting with a phone to assist with work or hobbies (sum=49, median=1). Participants in the N-condition produced more ideas (38 to 24), but more ideas made by those in the R-condition were relevant to the task (92% to 71%). A large diversity of ideas were generated, from a pointe shoe shaped charging phone stand to multi-functioned phone cases for holding test tubes and for aiding in measurements (R1: Figure 6.6). Only 7 ideas included measurements useful for their design-ideas (e.g. N10: anti pick-pocket phone-attachments). Five ideas in the Recommendation condition wrote website references to YouTube (R4), Thingiverse (R2,R5), and Amazon (R7). Ideas from six participants (N1-2,N5,N8,N10,R7) included details on how to Customize the designs (e.g. earbud inserts made by 3D scanning people's ears – N10: Figure 6.6).

Establishing Common Ground after the Intervention Many ideas required additional dis-

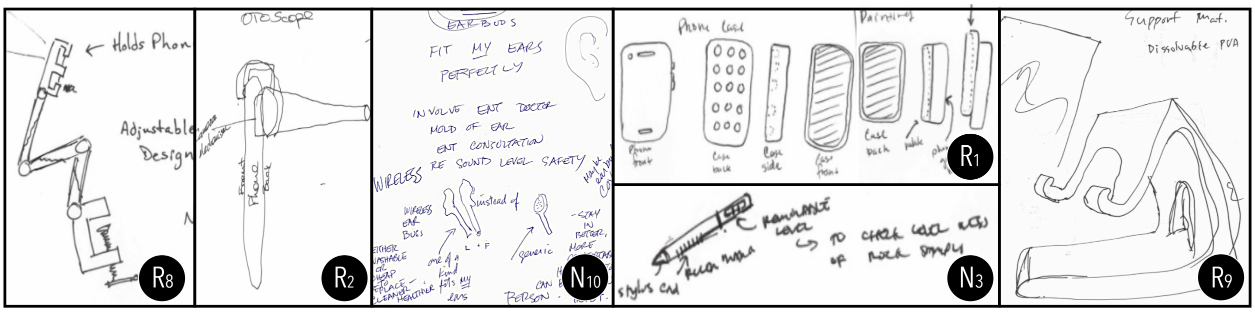

Figure 6.6: 3D Printing Ideas Generated During the Lab Study. Most participants created drawings of their ideas, some directly referencing how they could adapt existing products (R8) or previously printed designs (R9), to help support collaboration with the facilitator. Reprinted with Permission from *"Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication"*[5]

cussion during the Feedback phase of the intervention to explain their design intent (e.g. R1 sketched multiple views of a phone case that has indents to hold test tubes – Figure 6.6). Participants discussed with the facilitator, which is similar to the consultation in print shops, about all of their ideas, around 4–30 minutes. Drawn designs tended to be more detailed than text descriptions, which aided the facilitator in providing more specific feedback. While visual media better-established content common ground, the written word was the most common way to quickly explain what the drafted ideas represented (44 of 50 ideas). The intervention encouraged newcomers to collaborate with printing practitioners, with 18 participants saying they would visit the print shop in the future. 10 participants mentioned that they'd find someone more knowledgeable in 3D printing. Others highlighted that they would not want to own 3D printers– "*owning would require higher education*"(R11), even when R11 has a PhD in Psychology and could imagine printing a physical visualization of "*Maslow's Hierarchy of Needs*". Two weeks following the intervention, 8 noted they had seen printers since the intervention. One teacher was looking to buy a printer for her school based on print shop advice, two were actively planning a printing project, and one had completed a printing project (first quote in Section 6.2.3). Out of the twelve participants who responded, there were significant ($p<.05$) increases in *all* measures via the WSR test compared against before the intervention. The intervention led to many printing within a short time-period, indicating that practice helped foster successful collaborations and sufficient common ground.

6.3 Introducing Anyone to 3D Printing Collaborations

Our results revealed many unknown barriers and challenges to initiating successful 3D printing collaborations, hidden from prior work that investigates newcomers' direct operation of printers *after* interacting with printing practitioners. Formalizing of printing service collaborations can aid newcomers communicate *what* they wish to print easily and effectively, and thus help printing services refine and print design-specifications to clients' expectations. Below we discuss how the HCI community can develop technologies that may motivate and support these printing collaborations.

6.3.1 Motivating New 3D Printing Users: Opening the Door

While capable of 3D printing through a service that insulates them from the technical details of printer maintenance and operation, newcomers still encounter the metaphorical door which often requires external-guidance to open. This door may be opened by advertising accessible printing services, increasing awareness of printing costs, providing means to observe others' printing, and vetting introductory web resources for 3D printing. Additionally, services should explain upfront information that 3D printing does not require significant education and learning, so *Anyone can Print*. All of these opening-strategies could be incorporated into printing service websites and procedures to broaden participation.

However, as our findings show, discovering printing services nearby and becoming aware of their accessibility is not always trivial. Directories of 3D printing services and locations could help newcomers be aware of places they could access. In addition to awareness, newcomers also need to have motivation to visit a shop or browse through a service: they need to know *why* they are printing. Catalogues of printed projects, with clearly labeled prices and explanations of costs, could aid newcomers gauge whether 3D printing is something of interest for their practices or hobbies.

6.3.2 Successful 3D Printing Collaborations

Newcomers face many challenges towards establishing the common ground required for successful prints. To better ensure success when printing, newcomers could follow formal steps sup-

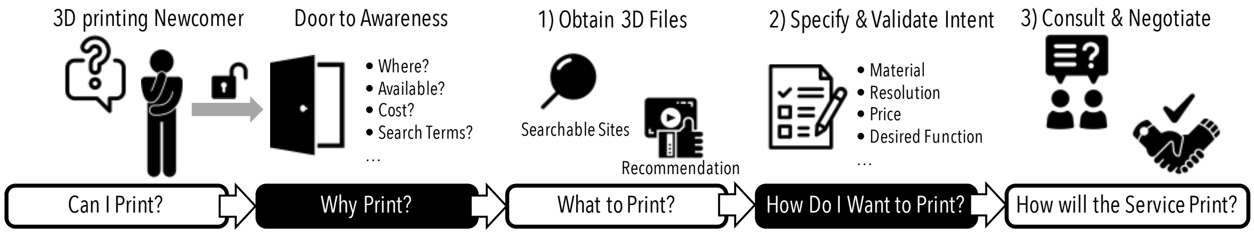

Figure 6.7: Newcomers can be guided through a series of questions to facilitate 3D printing collaborations. Preemptively delivering answers to these questions may help open the door to newcomers, and help them disambiguate 3D printer *functionality* from *operation*. Reprinted with Permission from *"Anyone Can Print: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication"*[5]

porting 3D printing collaborations: **1)** obtain 3D files, **2)** give design-specifications to a service (e.g. 3D files and design-intent), and **3)** further specify printing materials and processes in collaboration with the service. Formalizing this process, facilitated through a guided system [154] or other computational systems, could allow for newcomers to better understand the process of printing with services. This also provides distinct steps where clients have loose-coupling with the service (steps 1&2), and where clients may need to collaborate through higher-bandwidth channels in tightly-coupled work with printing practitioners (step 3).

6.3.2.1 Step 1: Obtaining 3D Files (with or without designing)

Determining what to print can be difficult without some initial guidance. The studied newcomer-participants were capable of determining printable ideas, especially after being introduced to basic 3D printing concepts, websites, and design methods. Newcomers should be given brief introduction to basic 3D printing concepts and terminology, along with information on how to locate 3D designs online. Additionally, newcomers should have knowledge of how existing designs may be modified on their own or with help. Custom Recommender Systems could help newcomers discover potential 3D printing applications (e.g. Thingiverse designs) and design-help (e.g. tutorials or designers-for-hire) that they may not have otherwise searched for immediately. Price estimations could help clients evaluate and learn *what* can be printed affordably.

6.3.2.2 *Step 2: Specifying Design-Intent to Service*

Based on *what* the client wishes to print, they need to further investigate *how* to print, constrained by *where* they can print. A directory of online printing services and local printing shops, filtered based on the clients' initial design-specifications, could help them better-establish how they could print. Further, a 3D file's intended function is not always obvious to a service. To help establish common ground, client print-specifications may be formalized by requiring some mechanisms to add required textual fields in addition to a 3D file when submitting, particularly about the prints' intended function (e.g. to withstand force) and appearance (e.g. the color and resolution). Detailed explanations such as each printing service's available materials and fabrication processes should be integrated into these forms. To avoid failing the *Double-Blink Test*, uploaded 3D files should be viewed by the client before being sent to the service. Immediate and reliable automatic estimates of printability and costs (i.e. time and money) could help clients interactively develop their printing ideas. Affordances for sketching, utilized effectively by many newcomers in the lab study, could help specify newcomers' prints. Newcomers should be given opportunity to ask questions, and view others' related questions, about service-policies and printing in general. Online forums and question-answer systems [155], informed from online 3D printing data (e.g. ThingiPano [1]), could assist clients specify their ideas before they seek help from printing facilities, where they may be more hesitant to ask others for help [156].

6.3.2.3 *Step 3: Personalized Consultation and Negotiation*

After the design-to-print is specified, now the printing service needs to respond with validation or consultation. Successful validation should always include the services' impression of what is being printed, for what purpose, and how they will print it. More reliable costs should be provided at this time. Validation failures should always provide actionable items to fix. Common validation-failures (e.g. non-manifold meshes) and consultations (e.g. modeling tutorials) could direct clients to online resources where those common questions and concerns are addressed, similar to how StackOverflow functions for programmers [157, 158]. For more in-depth consultations, where a single text-response is likely not sufficient (e.g. a design task), collaborators should communicate with media more-similar to proximal interactions to better afford tightly-coupled collaborations. As trust plays a role in newcomers' willingness to start 3D printing collaborations, authorities and community-members should be able to review and vouch for particular services and online 3D printing resources. Finally, to seed "word-of-mouth" of printing services to other newcomers, both clients and services could connect to popular social media platforms to share their experiences. With awareness of how to accessibly print, groups of new and diverse interests could discover and create 3D printing applications, innovating in directions presently unexplored in the realms of 3D printing practices and research. To adapt Anton Ego's quote at the end of Pixar's Ratatouille: *Not everyone will become a great innovator, but a great innovator can come from anywhere.*

6.4 Chapter Contributions: Anyone Can Print

This chapter establishes previously-unidentified challenges and barriers that newcomers may face when learning any 3D printing process, with lessons that may extend to other forms of digital fabrication. Knowledge of 3D printing processes and relevant online resources are not universally known. The participants in this study demonstrated that a simple introduction to 3D printing can increase interest and self-efficacy towards printing, but that they did not find many relevant 3D printing web resources without explicit recommendations. While all newcomers had better knowledge of printing processes, those who received these recommendations and visited online web resources refined priorities for *how* they would want to obtain 3D files for printing, which changes the process of how they *specify what to print*. For anyone to print, both *content* (e.g. downloadable designs) and *process* (e.g. what to tell a printer or a service) must be established. This chapter provides insight into how to successfully initiate these collaborations. The contributions of this chapter are as follows:

- Provides insights into 3D printing services and how they may lower the barrier to participation for 3D printing
- Identifies previously unidentified barriers to newcomers beginning to utilize 3D Printing

- Identifies challenges when initiating collaborations with 3D printing services
- Demonstrates that short lessons on 3D printing basics help newcomers identify as someone who can become capable of 3D printing, but that these lessons should include relevant online resources to help refine their printing processes
- Establishes that newcomers' variable awareness of printing web resources impacts their imagined design-obtainment process for 3D printing
- Discusses how HCI research may investigate initial 3D Printing Collaborations

A successful introduction of digital fabrication tools, even through services, can empower many to apply these transformative technologies to new domains and with more-diverse populations. Without establishing successful collaborations, there would be insufficient accessibility and transparency needed for Legitimate Peripheral Participation (and Communities of Practice). This chapter lays the ground work for how these Communities may be fostered, anywhere, from a distance. The following chapters further explore how newcomers perceive and specify 3D printed products, and how anyone can be introduced to printing services, anywhere, online with intelligent website interfaces.

7. REUSE OF ONLINE FABRICATION DESIGNS*

While the previous two chapters have focused on how 3D printing newcomers may perceive and learn to create printed products, this chapter aims to better understand how designs are shared online to facilitate 3D printing practices. Extending findings from literature surrounding design-sharing practices from Chapter 2.4.1, we present an analysis of public design-sharing behaviors through meta scraped from the platform Thingiverse, and then demonstrate multi-modal machine learning methodologies to further support these design-sharing practices.

7.1 Who Reuses Online Designs

As discussed in Section 2.4.1, 3D printing communities thrive by sharing files that they can download, modify, and print in their chosen fabrication facilities. Websites like Thingiverse provide a window into understanding how newcomers may learn to print. In this section, we discuss the composition of online data scraped relating to Thingiverse Designs, then we discuss how people may learn printing practices online through exploration of this data.

7.1.1 Metadata

Similar Thingiverse metadata has been previously analyzed by authors like Voigt and Flath et al. to better understand how people innovate with 3D printing [29, 31]. We are publishing a comprehensive collection of metadata for most public designs and users to help facilitate future research surrounding reuse and 3D printing. Figure 7.1 outlines the available metadata, and Section 7.1.4 demonstrates how this metadata can facilitate further analysis into Thingiverse.

7.1.2 Design Metadata

In 2018, all raw Thingiverse design HTML was scraped and parsed with custom scripts into JSON-formatted files containing metadata, described in three sections: Site Information, Designer-Annotations, and Community-Annotations. This metadata, with associated images and 3D renders,

*Parts of this chapter are reprinted with permission from "ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse" by Alexander Berman and Francis Quek in the Proceedings of the Sixth IEEE International Conference on Multimedia Big Data, September 2020.

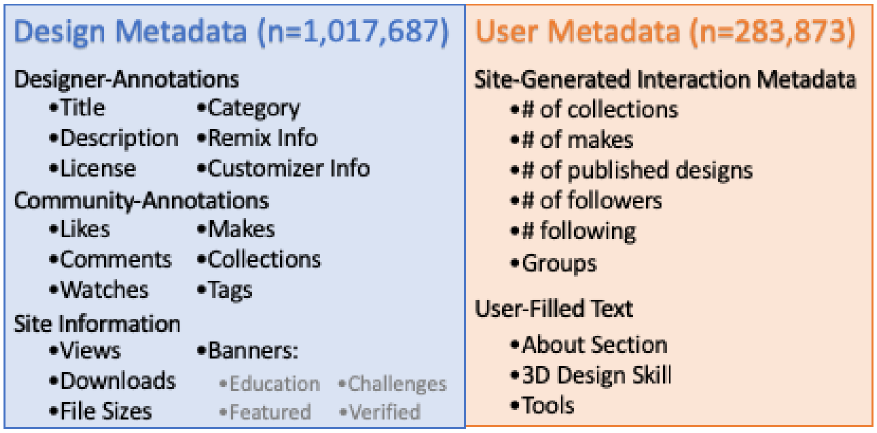

Figure 7.1: Thingiverse Design and User Metadata Available in ThingiPano. Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

are available for download in the ThingiPano dataset .

7.1.2.1 Site Information

Site information includes automatically generated information and site-moderated information about each design. Thingiverse automatically generates design-creation and design-updated timestamps along with hyperlinks to uploaded files and authoring-users. This automatic information includes the number of views and downloads for each design, and for each individual file. Site information also includes any '*banner*' given to a design. Banners indicate whether a design won a site-wide challenge, was created and approved for education applications, was verified, or was featured on the landing page at one point of time. There are also flags if a design is a work-in-progress, if the page was removed by a moderator, or if the page is in violation of Thingiverse's Terms of Service.

7.1.2.2 Designer-Annotations

Designer-annotations include text and referential information provided by the author of each design, including a description and a mandatory title. Each author is also required to enter a license, describing copyright and attribution credits. A category may be given to each design by the author out of a pre-determined list (Figure 7.4). An author may optionally write whether a design was

https://github.com/Alexander-Berman/ThingiPano/

’remixed‘, derived from other attributed designs. In addition, if a source file is not a mesh-file, but a scripting language file for openSCAD [159], it can be made a ’*Customizer*’ by the author to allow for others to more easily enter parameters and generate personalized designs (e.g. creating keychains, containers, picture frames, etc.). Interesting insights about reuse can be made by tracing the provenance and patterns of design-metadata across remixes, which make up over half of the total public designs [29, 31].

7.1.2.3 Community-Annotations

Community-annotations consist of textual comments, shared ‘*makes*’ of designs, and many binary indications (e.g. likes) that can be made by any user on any design. Only data publicly-available on Thingiverse is captured in this dataset, such as which user ‘*likes*’ each design. All comments are saved with the author information, time, and comment-order. Any user may tag designs with any words they choose, shown in Figure 7.2. Each tag is utilized in 1 to 443,358 designs, with a mean of 13 designs and median of 1 design. *Makes* are when users indicate that they have reused a particular design, and often including images of the printed replication. A portion of *makes* in the dataset have author information, time posted, and associated image URLs saved in the dataset. Lists of designs called ‘*collections*’ can be made and optionally shared by each user, and while the association of which collection each design belongs within is not saved, the count of how many times a design is added to a collection is saved. Also saved is the number of how many users have subscribed to be notified (i.e ‘*watch*’) about any design-updates. Community comments have been utilized to see how people learn about 3D printing [27], and analysis of popularity measures has revealed that designs featured on the Thingiverse home page receive higher popularity [29]. Collaborative and Hybrid Recommender Systems could be trained with ThingiPano Community Annotations to facilitate reuse.

7.1.3 User Metadata

Custom scraping scripts and parsers collected metadata of users (n=283,873) present in the aforementioned Design Metadata, including users’ number of collections, number of ‘made’ things,

Customizer		Other Remix		Original Design	
customized	(435381)	3D_slash	(2439)	holder	(9510)
customizer	(692)	openscad	(2304)	openscad	(6854)
openscad	(475)	holder	(1480)	3D	(6759)
parametric	(238)	mount	(1461)	toy	(6599)
Customizable	(163)	3D	(1354)	mount	(6546)
case	(139)	extruder	(1185)	scan	(5084)
spam	(133)	toy	(1115)	makerbot	(4786)
iphone	(123)	case	(1083)	keychain	(4703)
holder	(115)	Anet_A8	(1021)	case	(4501)
box	(98)	prusa_i3	(991)	model	(4258)

Figure 7.2: Most Frequent Tags applied to designs made with the Customizer (*left*), to other remixed designs (*center*), and to "original" designs (*right*). Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

number of published designs, number of followed users, and number of followers. Subscriptions to groups, forums on Thingiverse around particular topics, is also provided (i.e. Group Name and Number of Members). User data includes an 'About' section that serves as a Bio, an "I Am A..." section that provides occupations or titles (e.g. I Am A Maker, Designer, Artist), a self-documented 3D Design Skill Level, and the tools they use (i.e. particular digital fabrication machines and design programs). User metadata may help identify how certain designer attributes relate to reusability, like comparing which Computer-Aided Design tools are best suited for modifying particular designs.

7.1.4 Analysis of Thingiverse Users

Previous work has utilized individually-collected, private Thingiverse metadata to analyze patterns of Things [29, 31, 49] and Users [29, 27]. Corroborating and extending these works, we conducted analysis on ThingiPano metadata to investigate what reuse patterns of users over time.

7.1.5 Changes of Designing and Reuse Behavior

Corroborating Flath et al. [29] and Voigt [31], we found almost all Thingiverse users with published designs either exclusively publish original designs, or exclusively publish template-generated "Customizer" designs. From this observation, all users can be distinctly classified into

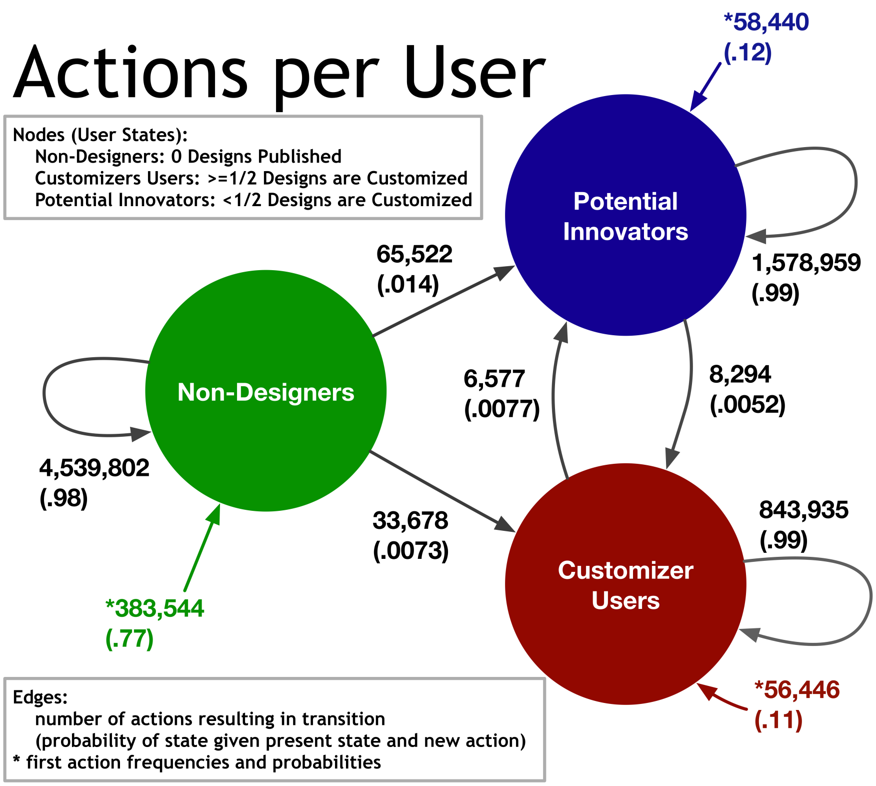

Figure 7.3: Frequency of Public Actions by Thingiverse Users over Time. Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

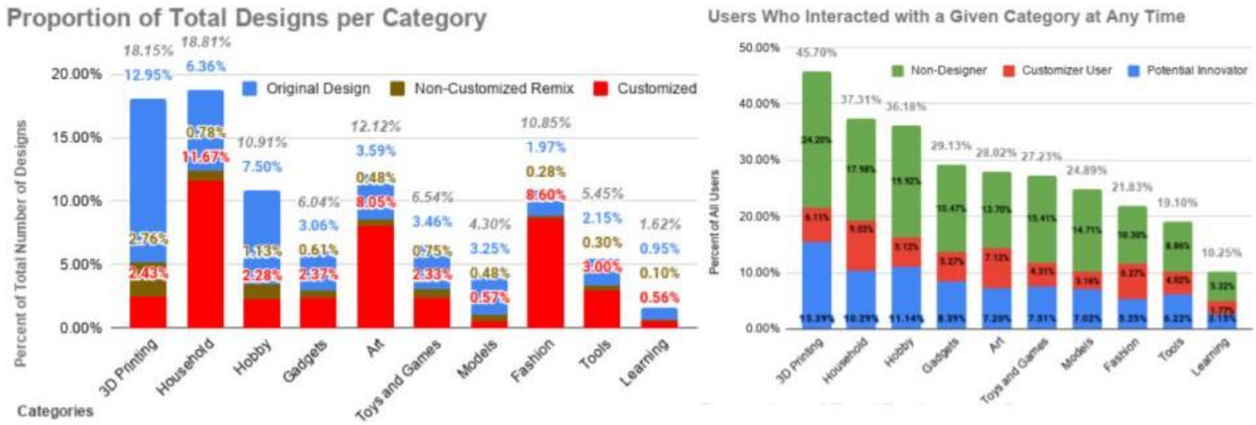

Figure 7.4: The number of categories a Thingiverse user interacts with is not proportional to the available designs per category. Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

three observable groups: *Non-Designers* who participate online but do not publish designs, *Customizer Designers* who primarily publish "Customized" designs, and *Potential Innovators* who primarily publish original work. Potential innovators create most designs to be reused by all others.

Prior work analyzes a snapshot of Thingiverse at one point in time, observing user data as an aggregate instead of a sequence. We further this analysis by mapping how users may change between these groups over time. We counted frequencies of user actions with time stamps in the ThingiPano dataset: likes, comments, makes, and published designs. Figure 7.3 illustrates the collective changing behavior of users as a state machine. Users are likely to start as Non-Designers (77%), and the rest are split about equally between the other two groups. While almost all interactions made by Non-Designers are not publishing designs (98%), a non-trivial amount of users eventually publish a design. This may indicate that as a population of users age, the proportion of that population that eventually publish original work will also increase. However, a large portion of Thingiverse users never publish a design, and since an account is not required to download designs and Customized designs can be created privately, there are likely many more reusing these designs.

7.1.6 What Users See on Thingiverse to Reuse

Investigating what motivates users to reuse designs on Thingiverse, we logged the categories of the designs corresponding to each users' actions. We found that the designs, the focal point of user interactions (i.e. likes, comments, makes, and published designs), are not proportional to the number of designs in each designer-specified category (Figure 7.4). Designs in the 3D printing category, which largely consists of parts and augmentations for 3D printer maintenance and operation, received the most interactions and are among the most designed items on Thingiverse. The 3D Printing category has more original designs and also received more interactions by Potential Innovators, even when compared to the proportional number of users who have interacted in other categories, implying that many on Thingiverse have access to directly test and modify 3D printers. Customizer Users especially interacted with designs in the Household, Art, and Fashion categories, which also have many customized designs. Future applications that encourage new users to interact with Thingiverse-like websites, or encourage broader participation in 3D printing in general, may support Non-Designing and Customizing users through the disseminating of customizable household, art, and fashion items in particular.

The number of views divided by the number of downloads for a design indicates a normalized popularity measure based on each design's audience. Out of all downloaded designs, This ratio ranged from 1 to 1192 with a mean of 2.8 and median of 2.2. As a ratio of 1 means that every view translates to a download, this median conveys that designs are often downloaded for reuse after being viewed.

7.1.7 Barriers to Understanding 3D Designs

While higher design visibility tends to relate to higher frequency of reuse [78], we cannot guarantee that anyone interested in 3D printing will be able to view designs of interest to them. Assuming interesting designs exist for any given person, knowing the semantics for searching for these designs may be challenging. As discussed in Chapter 5 and Chapter 6, knowing what terms to search for and what websites to visit can be challenging.

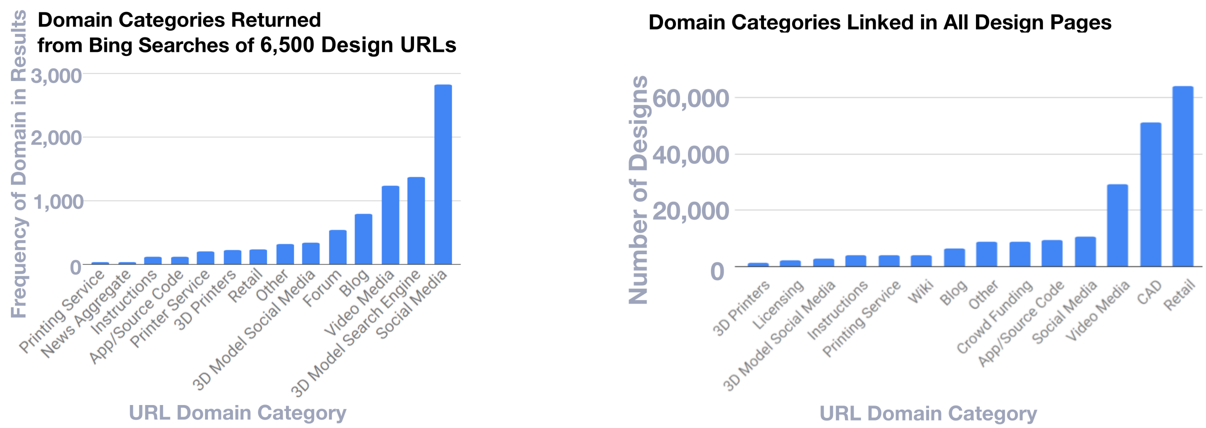

Figure 7.5: Top Websites returned from Bing searches of Thingiverse Design URL's (**left**) do not match Websites included in Design Meta-Data (**right**), so websites that link to Thingiverse are not always seen by those on Thingiverse

Even when newcomers gain access to Thingiverse, not every design may be transparent. This is explored by Chilana et al. [48], who analyzed comments on Thingiverse designs to discern four challenges to understanding and utilizing Thingiverse Designs: *1) Understanding Object Functionality* (how the end result should function, as well as how to assemble pieces if necessary), *2) Understanding Design Customizability* (how to obtain a design with minor modifications), *3) Understanding Design Printability* (how to print a given design, including settings such as support structures), *4) Understanding Design Creation* (how qualities of the designs are created by the uploader). When appropriating these online designs, these users relied on other users to provide answers. This, however, is not the only way to understand design processes, printability, and function. Each designs exists within the broader internet, where link-symmetry between online resources that reference these designs is not guaranteed.

To better understand how individuals share and find web resources situated around individual designs, website domains that linked to and from designs were categorized and counted. Links were extracted from all scraped design descriptions and comments, and links to Thingiverse were extracted from Bing searches of a random sample of 6,500 'Thing' URL's (e.g. "thingiverse.com/thing:763622"). Shown in Figure 7.5, there is a large asymmetry between the domains that link to and from designs. Social media (e.g. Facebook, Twitter, Reddit, etc.) and Video media (e.g. Youtube and Vimeo) refer to Thingiverse designs often, but do not reciprocate those referrals, meaning these types of online resources are often hidden from people browsing through designs. For example, one popular design is ostensibly just a toy boat, but serves as a benchmark for printing configurations, and the #Benchy design is referenced memetically across many online communities. These communities often link to the design, describing how it relates to their printing practices, but these references are not visible from the design page. It may be possible to increase transparency of online designs through exposing related online resources not directly linked on design pages.

7.2 Machine Learning Tools for Facilitating Design Reuse

To allow for better search, retrieval, and classification of 3D files on sites like Thingiverse, textual data alone is not sufficient. Designs have a median number of 57 words per description, which often limits their ability to be found and interpreted. Research by Flath et al. proved that designs with more descriptive text are significantly more popular [29]. In this section, we demonstrate how ThingiPano data can be leveraged to support retrieval and classification across multiple modalities, which are essential to understand designs. We first outline previous work in 3D file retrieval and classification, applications made with similar datasets, and describe the ThingiPano 3D data made publicly available. We demonstrate how training a self-supervised CNN to regress the textual embedding of the design description can help in retrieval tasks. Then, we demonstrate how similar methods could be utilized for training on the million-plus dataset of unlabeled depth-map panoramas.

7.2.1 3D File Retrieval and Classification

Previous 3D file classification and retrieval methods may aid in the development of future tools and services to support broader reuse of 3D files. Previous work, like GIFT [160] and Thingi10K [161], have created real-time and scalable 3D shape search engines from visual and statistical features extracted from 3D meshes. Below, we discuss methods and datasets for creating similar applications to facilitate reuse.

7.2.1.1 Overview of File Representations

Raw 3D files are often meshes or graphs, but lack of consistent space, standards, and resolution often make it difficult to extract meaningful features from mesh-data alone [162]. 3D files are often represented by descriptors, projections, volumetric data, and multi-view representations [162]. Descriptors are often quickly generated from 3D meshes, which then act as intermediate shallow features to be learned by a deep learning model. Volumetric analysis is effective [163], but often requires significant pre-processing or manifold meshes, which are not observed with many Thingiverse 3D files [161].

7.2.1.2 Classification with 2D Representations

Projection techniques create 2D images based on rotation-invariant representations of 3D files, such as spherical [164] and cylindrical projections [165], but lose information important for tasks like dense correspondence [166]. Multi-View techniques feed multiple 2D representations of a 3D file from multiple perspectives into a neural network to achieve results often comparable to state-of-the-art classification techniques [167]. Many learn semantics of 3D files by utilizing Convolutional Neural Networks (CNN's) on 2D representations of the files. Shi et al. created 2D panoramic depth-map representations of 3D files [165], Cao et al. utilize spherical projections [164], and Zhou et al. utilize polar representations of 3D files [168] to perform state-of-the-art classifications with CNN's. Sfikas et al. utilize multiple panoramic view representations of multi-channel images consisting of Spatial Distribution Maps, Normals' Deviation Map, and Magnitude of Gradients alongside an ensemble of CNN's [169]. SPNet demonstrated effective classification with Stereographic Projections [170]. Modern attention models have been leveraged on similar cylindrical projections to aid in 3D file classification and retrieval tasks [171, 172].

7.2.1.3 Relation to ThingiPano

We utilized code from Shi et al.'s DeepPano [165] to generate depth-map panoramas for multiple views, creating a dataset containing millions of panoramas. This methodology was utilized because it leverages publicly available code, and may provide similar advantages to multi-view representations. The ThingiPano dataset contains significantly more 3D file representations (n=1,052,017) than other 3D file datasets like ModelNet (n=127,915) [173] and ShapeNet (n=51,300) [174], but does not contain researcher-annotated and curated categories for supervised learning. We recommend that this data could be employed in unsupervised, semi-supervised, and self-supervised machine learning methods. In particular, self-supervised methods that leverage models trained with images and metadata associated with 3D files, could support many potential applications. Previous self-supervised techniques have demonstrated training image supervised CNN's to regress textual document embeddings on multimodal data like Wikipedia articles [175], social media posts [176, 177], and Darknet market listings analysis conducted by the author [178]. The ThingiPano dataset provides text, image, and 3D rendered projections for similar multimodal classifications and retrieval models.

7.2.1.4 Thingiverse and 3D File Datasets

Similar 3D file datasets have been released to encourage analysis relating to 3D file printability, classification, and retrieval. Baumann conducted an analysis of *31,121* 3D files available on Thingiverse, demonstrating popularity statistics and metrics of these files, including slicing statistics with default parameters [179, 180]. However, Baumann's dataset does not provide parsed fields from the HTML and does not provide any files besides the 3D files per design. Similarly, Zhou and Jacobson's Thingi10K provides 3D file information on over *10,000* 3D files featured by moderators on Thingiverse, providing detailed geometric features and user-generated tags on the provided files [161]. Zhou and Jacobson created a search interface with their collated features and compared Thingiverse models with ShapeNetCore [174] models which are not intended for 3D printing, showing that the Thingiverse models demonstrate a larger variety of items and more-appropriate geometries. Both our and Zhou & Jacobson's investigations found no other large Thingiverse collections that are publicly available. The ThingiPano dataset contributes the reagents for better understanding reuse through JSON-formatted metadata on over a million 3D files, along with associated images and panoramic renderings.

7.2.2 Design Files

While any media type and format may be uploaded to Thingiverse for each design, the site provides affordances particularly for 3D printing by providing a slideshow of images on each design page, and by providing a rendered thumbnail image and 3D-viewer for meshes. The ThingiPano dataset includes 1,816,288 images, across 1,017,687 designs. Similarly, most but not all designs for 3D printing include mesh-objects suited for printing. Some designs for 3D printing contain no 3D files, sometimes only containing files for specific CAD programs, or only contain sliced (e.g. '*gcode*') files to be used with specific printers. Some files in formats sufficient for general 3D printing may not be trivial to print, like when they contain non-manifold meshes (i.e. holes in the intended solid sections of the geometry) or requiring certain printers and settings not specified in the documentation. Many designs may have extremely short designer-written descriptions [29], so many 3D files may be implicitly intended by authors to be self-explanatory via visual features of the uploaded design files. Analyzing reuse of 3D files will require qualitative analysis or machine learning models capable of distinguishing visual features across the dataset.

7.2.3 3-axis Panoramic Depth-Map Projections of 3D Meshes

2D representations of 3D files have often been utilized to train many state-of-the-art classification and retrieval systems [165, 164, 169]. ThingiPano includes 1,052,017 2D panorama triplets that each represent a 3D file from the uploaded designs. To the best of the author's knowledge, this is the only known large public dataset with 2D representations of 3D printing files. This dataset contains an order of magnitude larger quantity of 3D file representations than similar datasets like ShapeNet, which has *51,300* files [181], and the *~12,000* files in ModelNet [173]. This wealth of image data is sufficient to train neural network models from the ground up, which could better support other 3D file classification domains via transfer-learning [164].

The panoramas were generated over the the duration of a year, with MATLAB code that was modified from DeepPano [165] to generate panoramas for the X, Y, and Z axis from the default orientation as downloaded from Thingiverse. All panoramic 360×751 grey-scale images are higher-

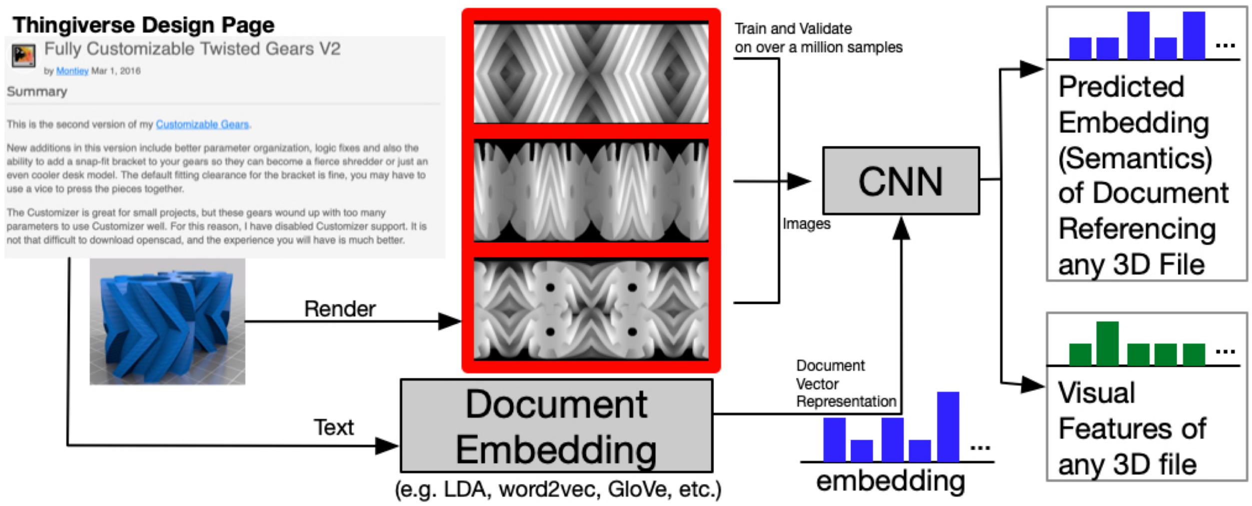

Figure 7.6: Self-Supervised methods for predicting semantic- and visual-features by labeling panoramas with pre-generated textual embeddings. Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

resolution than the 64×96 images utilized in the original DeepPano paper [165], allowing for potentially richer views of high-resolution 3D files. The multiple views help obtain a more complete view of each file, as the intersection where multiple cylinders rotated around one center point estimates a sphere. Most of the triplets rendered in under 30 seconds on a quad-core i7, 2015 Macbook Pro. Files that contained multiple objects were not split, like the two gears in Figure 7.6. The files' orientation was not normalized before rendering, as many uploaded files may be purposely oriented to optimize time, material, and strength for 3D printing [9].

ThingiPano is the only present dataset known by the authors that includes both 3D file representations and associated multi-modal information in the 3D printing domain. Section 7.1.4 analyzes ThingiPano metadata to better understand which users reuse which designs, and Section 7.2.4 demonstrates machine learning models to support reuse through cross-modal classification and retrieval.

7.2.4 Multi-Modal Analysis

To allow for better search, retrieval, and classification of 3D files on sites like Thingiverse, textual data alone is not sufficient. Designs have a median number of 57 words per description, which often limits their ability to be found and interpreted. Research by Flath et al. proved that designs with more descriptive text are significantly more popular [29]. In this section, we demonstrate how ThingiPano can be leveraged to support retrieval and classification across multiple modalities, which are essential to understand designs. We demonstrate how training a self-supervised CNN to regress the textual embedding of the design description can help in retrieval tasks. Then, we demonstrate how similar methods could be utilized for training on the million-plus dataset of unlabeled depth-map panoramas.

7.2.4.1 Self-Supervised Deep Learning Models for Images

Following methodology by Gomez et al. [176], we trained a CNN to predict the design textual document embedding that would correspond to a given image. This is completed by training Word2Vec [182] on all text from the ThingiPano metadata, then producing document-embeddings by computing TF-IDF weighted sums of the contained word-embeddings in each design. These document-embeddings are then employed to self-supervise a CNN that inputs a image, and returns the predicted document embedding that the image would belong within. We employed the XCeption architecture [183] pre-trained on ImageNet [184] for transfer-learning [185], adding new dense layers to output the matched dimensionality of the text embeddings (d=400). Similar to Patel et al., we utilize Stochastic Gradient Descent with a learning rate of 0.0001 and momentum of 0.9 to minimize sigmoid cross-entropy loss. This results in a model that affords semantic- and visual-feature extraction from images, greatly aiding in multimodal retrieval between images and text. Figure 7.7 demonstrates a euclidean distance nearest neighbor query of a microscope phone adaptor image retrieving similar 3D printed phone adaptors, comparing the CNN-predicted embedding with actual TF-IDF weighted word2vec textual embeddings of Thingiverse designs.

Representing designs' texts with weighted-sums of word-embeddings, and then projecting images into this embedding-space, allows for a shared space for comparing and classifying words, bodies of text, and images. Next, we describe how 3D files can share this same semantic space.

Figure 7.7: A Multi-Modal retrieval example utilizing a deep learning model trained with ThingiPano images and metadata. Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

7.2.4.2 3D File Deep Learning Models

Text and images alone may not capture all features of a design, such as the implicit printability and functional aspects of meshes. Similar to Section 7.2.4.1, the experiment was repeated to utilize the multi-view depth panoramas in the ThingiPano dataset. As the many grey-scale panoramas are significantly different than resolutions in available pre-trained models, we did not utilize transfer learning. Employing the same document-embeddings from the image-model in Section 7.2.4.1 as labels, we trained a CNN utilizing row-wise max-pooling for rotation-invariance [165] to input three principle-axis panoramas separately. Each image's output from the shared-weight XCeption CNN [183] was then concatenated into two dense layers that learn to predict the 3D file's associated textual embedding, optimized with Adadelta to minimize sigmoid cross-entropy loss. This trained model can be utilized to bootstrap classification of 3D files, similar to how ImageNet-trained models can be utilized for transfer-learning [185], and can serve in a variety of 3D-retrieval applications. As shown in Figure 7.8 (right), embeddings predicted from panoramas for a remote's battery cover was closest in euclidean distance to other 3D files of battery covers and containers,

Figure 7.8: ThingiPano-trained models may aid future CAD systems to retrieve related online resources based on Work-in-Progress geometry (left), employing machine learning models like this chapter demonstrates (right). Reprinted with Permission from *"ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse"*[1]

less biased by popularity and text.

ThingiPano can facilitate the visual- and semantic-extraction of features relating to 3D files within the domain of 3D printing. This can enable the next generation of printing toolkits and applications facilitating reuse: an online file-sharing platform that affords search and recommendations based on 3D file content, a CAD program that recommends related online resources (see Figure 7.8), a slicing application that changes settings automatically based on similar prints.

7.3 Exploiting Machine Learning to Facilitate Design-Reuse

The ThingiPano dataset provides sufficient data for many multi-modal machine learning applications, aiding in better understanding and facilitating reuse of 3D printing designs. Better understanding *who* prints *what* can help us better facilitate broader participation in 3D printing, which could promote more diverse and wide-spread innovations. We envision ThingiPano's employment in the following possibilities:

7.3.1 A Window into Real 3D Printing Users

Similar non-public datasets have been utilized in a number of studies investigating 3D printing designs and users. ThingiPano has the sufficient data for analysis on many topics, like how file-sharing communities and printing can help those with disabilities [186], to explore how people mix and modify each others' designs [29, 31, 23], and to better understand what knowledge people share online about 3D printing [27]. In Section 7.1.4, we demonstrated how the dataset can be utilized to better understand who posts original or derivative designs, and what types of designs these users tend to interact with on Thingiverse. As there is provenance data on how designs are remixed into other designs, learning models may be trained to better understand how certain designs may be leveraged by designers to understand future applications of 3D printing [187]. Models may predict what design will likely be remixed [29], and further predict semantic qualities of the resulting remix. The rich modalities and associations in ThingiPano may facilitate many future machine learning applications, and may facilitate broader analysis of 3D printing communities.

7.3.2 A Training Resource

ThingiPano provides sufficient images and panoramic image representations, along with tags and other metadata, to train a large variety of machine learning models. Additionally, this dataset is the first to provide massive quantities of 2D image representations derived from 3D files. The images and panoramas facilitate a unique multi-modal view of 3D printing designs. The textual metadata could be utilized to train Natural Language Processing applications specifically in the domain of 3D printing.

Some examples of trained models include supervised classification based on curated metadata elements or hand-labeling, and self-supervised methods like demonstrated in Section 7.2.4. Future work could utilize techniques inferring image, panorama, and textual similarity based on their associations to particular designs or other metadata groupings. For example, optimizing CNN's via triplet loss to predict whether whether one panoramic-view is from the same design as another panoramic-view, similar to He et al. [188]. These models may classify and retrieve based on both visual and semantic qualities, and bootstrap other models' via transfer-learning [185]. Future classifiers could perform object localization in objects, finding functional aspects of different 3D files like screw threads or hinges. These models could classify beyond *what* class each 3D file belongs within, extending to *how* files may be reused.

7.3.3 Online Search and Recommendation

Models trained on ThingiPano may be employed to improve platforms like Thingiverse, by allowing users to search with more than exact text matches. Users could utilize 3D printing domain-specific reverse image and 3D file search. A future where depth cameras are more commonplace, like on the Microsoft Kinect or on smartphones, may facilitate finding geometry similarities to real world objects via automatic comparison to ThingiPano panoramas. NLP models of the 3D printing domain could allow for better textual searches and displaying of pertinent term-definitions, allowing newcomers searching on 3D printing platforms to be better guided without requiring user-knowledge of exact spellings and terminologies related to 3D printing. Further, improved 3D file searches could help facilitate automatic Copyright and Terms of Service violation-detection systems.

The user interaction data (e.g. 'likes') could be employed in conjunction with the other user metadata to build 3D file recommender systems, through collaborative filtering, content-based, and hybrid recommendation approaches. Especially for people without much exposure to 3D printing, such recommender systems could provide the initial knowledge of *what* designs they could immediately reuse in their everyday life. Much like shopping in a hardware store to build or fix physical items, it's often difficult to imagine the full scope of a problem and solution until we've seen *what* is available and has been done before [34]. Intelligent assistants trained with ThingiPano, paired with more accessible 3D printing hardware and services [156], may broaden and diversify reuse of designs for 3D printing.

7.3.4 Design Assistance

ThingiPano can help usher in future intelligent Computer-Aided Design tools that broaden participation in reuse and remixing of 3D files, like how the Thingiverse Customizer parameterized design tool led to a significant increase of users on the platform [29]. As demonstrated in our metadata analysis (Section 7.1.4), the metadata provided can help identify areas where parameterized designs are already available and popular. Future analysis on ThingiPano could identify why certain categories have more popular Customizers, and provide more feedback on how to generally support Customizer-like applications for a variety of domains. Retail stores could allow for better personalizing of items through similar tools, extending on present automatic tooling 'vending machines' like dog tags and keys, or offering new services like custom eyeglass frames based on head measurements and desired styles.

Where Customizers cannot trivially be created, CAD programs could be augmented to provide suggestions on visually-similar and semantically-relevant designs and terms, illustrated in Figure 7.8. These CAD applications could aid designers, inspiring their designs as they create, or by replacing crude work-in-progress designs with polished pre-existing designs, much like how programmers copy and paste code snippets online [189]. Similarly, CAD programs could highlight important term-definitions and common questions associated with the design-in-progress, similar to how mentors have guided newer CAD users in situ through the MarmalAid system [48]. Remixing designs is already a common practice on Thingiverse [29, 31], and creating systems that can further facilitate the sharing, modification, and combining of open-source models could broaden participation with 3D printing. ThingiPano can help identify which design programs are popular among different designers, and can help relate design-semantics and design-intent to designers, helping facilitate future applications which automatically support designers reuse others' shared innovations.

7.4 Chapter Contributions and Limitations

The number of users and designs are likely larger than presented with ThingiPano when accounting for private uploads and interactions. It is possible that users behave in private differently than the public-only data in ThingiPano. Additionally, the random design sample we used to search for search engineer (Bing) results is much smaller than the total number of designs available, potentially influencing the presentation of symmetry. The mentioned machine learning methodologies to facilitate design-reuse have not all been compared against other existing 3D retrieval and classification models which were designed to be more general-purpose. However, similar renderings to Shapenet have been published alongside ThingiPano to support future bench-marking efforts.

In this chapter we presented a novel perspective of 3D Printing users online behaviors through the large multi-modal dataset, ThingiPano. This chapter's contributions are as follows:

- Presents the large multi-modal dataset ThingiPano
- Presents empirical evidence that non-design-sharing users may eventually share innovation
- Corroborates that users tend to only publish with Customizers or only publish without Customizers, and almost never change between these classifications
- Establishes that some design categories on Thingiverse are more popular proportionally to the number of designs per category
- Demonstrates self-supervised machine learning methodologies for extracting semantics from design images and 3D files

While platforms like Thingiverse support many to download, modify, and print each others designs, there is a divide amongst its users: Most (over 80%) never publish an original, non-customized design. There are a large number of people who download items to either modify privately, or print without modifications. In the next chapter, we discuss how findings from all the previous chapters relate to existing online printing practices, and how better affordances for these practices may be incorporated in the design of a novel website. While 3D design-sharing websites, knowledge-sharing social media, and online fabrication services exist, the designed website HowDIY begins research into how websites can help facilitate the non-trivial broader situated sense-making processes required to 3D print.

8. TOWARDS SUPPORTING ANYONE TO PRINT ANYWHERE WITHOUT PROXIMAL FABRICATION FACILITIES

At one point in time, the 2D printer was not trivial to operate, which arguably may still be true today. Lucy Suchman, and many other early HCI researchers, paved the roads for these technologies to become adopted by broader populations, saying *"dynamics of computational artifacts extend beyond the interface narrowly defined, to relations of people with each other and to the place of computing in their ongoing activities. System design, it follows, must include not only the design of innovative technologies, but their artful integration with the rest of the social and material world"* [190]. While previous work has investigated how elements of the situated elements of 3D printing practices may be incorporated into printing machinery [90] and printing facilities [191], this chapter investigates how to facilitate printing anywhere through purely online interactions.

Gaining *access* to printing communities is not trivial. Newcomers often don't want to enter physical printing centers due to feeling like outsiders [23], but also cannot find introductory printing resources without guidance as discussed in Chapter 6. Learning through participation online, rather than in proximal co-participation in places like Makerspaces or Print Centers, may serve as a gateway (i.e. an open door in Lave and Wenger's analogy [10]) for anyone to enter and participate with 3D printing (Figure 8.1). This participation, even if it starts in the peripherals of printing practices, may in turn inculcate and develop future practitioners who can share the practice with their proximal communities (e.g. Chapter 4).

We first describe related literature in 3D printing services. Then, we outline findings from a content-analysis of online printing service interfaces and related social media comments. Informed by these findings, and insights from previous chapters, we present the design of HowDIY, a website to introduce anyone to 3D printing practices. Finally, we discuss the evaluation of HowDIY based on the changing perceptions and feedback of newcomer-users (n=78), outlining future directions

This chapter with completed with feedback from Joshua Howell, Ketan Thakare, Jeeeun Kim, and Francis Quek

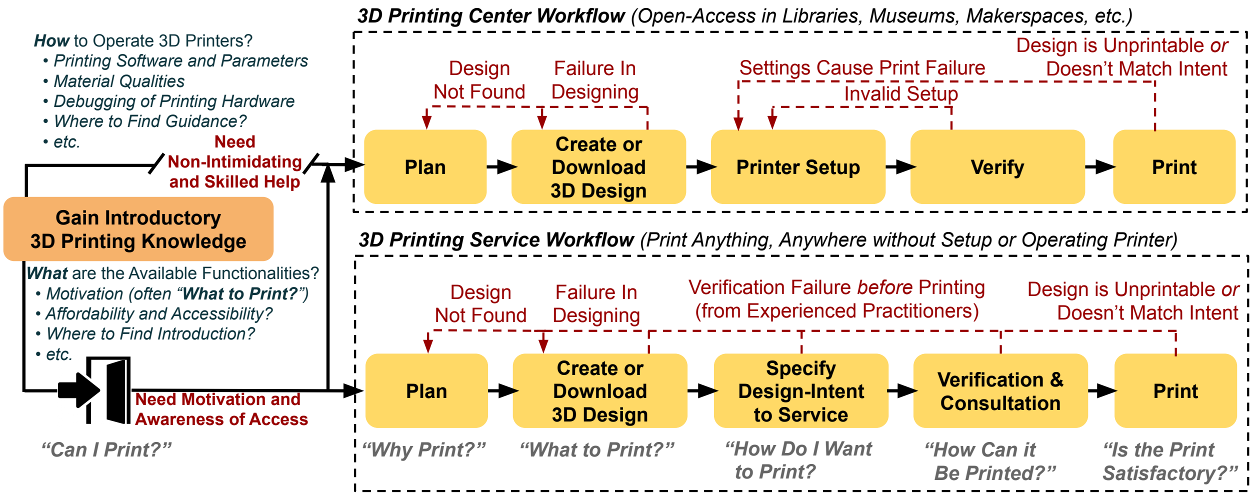

Figure 8.1: Workflow for printing services (*bottom*) differs from printing facilities where newcomers are responsible for details of machine operation (*top*), as services provide a more formal interaction with printing practitioners that can make "*opening the door*" possible from a distance.

for the development of online 3D printing interfaces.

8.1 Background on Online Printing Services

While this Chapter explores client-side interfaces for 3D printing services, there are many other Information-Technology and -System challenges towards effective distribution of fabrication on the manufacturing-side. For example, Mandhan et al. utilized the Gale-Shapely algorithm to match designer's machine-needs to manufacturers that could best provide those needs, showing it outperformed present first-come-first-served approaches utilized by services [192]. Future scheduling applications could better optimize for manufacturing and delivery speed [193], helping creating a future where in the time it takes to commute could be the time it takes for a nearby manufacturer to fabricate a design-specification you ordered from your mobile device.

Baumann and Roller explore the requirements for building online printing services, noting that many description formats or languages do not yet exist for defining printer capabilities [194] (i.e. Resource Description Language [195]). They note that design, post-processing, and Quality-Assurance require specialized software and intensive human interaction. However, Baumann and Roller's printing service back-end architecture was designed for operators accessing printers from a distance, not elaborating on the needed interfaces and collaborations for clients to specify files. Candi and Beltagui surveyed 321 managers engaged in developing products, discussing that effective coordination between IT and manufacturing can intensify the benefits of 3D printing, especially in turbulent operating environments where the flexibility of 3D printing enables flexible responses to uncertainty [196].

Wu et al listed several requirements for Cloud-Based Digital Manufacturing (**CBDM**) systems [33], which were specified for Cloud-Based 3D Printing technologies in industrial settings by Chen and Lin [197]: **1)** A 3D printing system contributes to online social networks by communicating and sharing design and manufacturing information and knowledge; **2)** A 3D printing system distributes design- and manufacturing-related data among cloud systems for users to access ubiquitously; **3)** A 3D printing system builds an open-source programming framework to facilitate the processing and analysis of big data in the cloud; **4)** A 3D printing system establishes a multitenancy architecture in which a single instance serves multiple customers; **5)** A 3D printing system monitors the states of manufacturing resources by collecting real-time and dynamic data to control manufacturing resources remotely; **6)** A 3D printing system supports various forms of cloud applications such as infrastructure as a service, platform as a service, hardware as a service, and software as a service; **7)** A 3D printing system partners with search engines to facilitate users' searches; and **8)** A 3D printing system supports online quoting for uploaded design and manufacturing specifications. Chen and Lin emphasize that factors affecting the clients' acceptability and demand of a 3D Printed object should be identified so managers may evaluate trade-offs to utilizing 3D printing within industrial applications [197].

Rayna et al create a taxonomy and typology of 3D printing platforms in 2015, classifying 20 observed 3D printing websites into four groups: **1) Design Marketplaces** where people buy and sell printable designs, optionally with design-customization options (e.g. changing text on a keychain); **2)Printing Services** where people order a uploaded design to be fabricated, with or without co-design services; **3)Printing Marketplaces** where people offer printing time on their machines without co-design services; and **4) Crowdsourcing Platforms** where various undefined elements of printing and design co-creation may occur [32]. They note that while the observed platforms provide clear creation opportunities, they do not always provide significant ways to leverage user innovation. In the next section, we discuss how the interfaces of many online printing services may help newcomers specify their ideas.

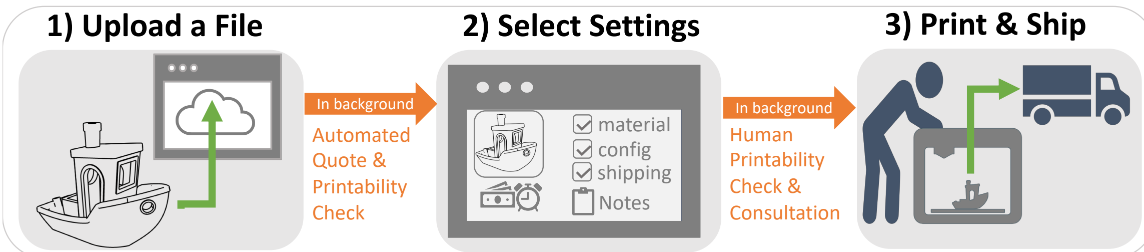

Figure 8.2: 3D Printing service interfaces presently require users to upload a 3D file, select from a large amount of printing configuration options, and then order with an optional note or file. These interfaces hide human-verification and potentially consultation, while also often burdening clients with many options that require prior printing knowledge

8.2 Exploratory Studies

As a first step in our exploration of supporting anyone to print online, we conducted two focused probes of online printing services and the surrounding perceptions of these services through the analysis of social media comments.

8.2.1 Survey of Online 3D Printing Services

To better understand the current landscape of online 3D printing services, and how to improve them, we conducted a qualitative content-analysis of 36 online 3D Printing services informed by the classification and requirements defined in the last section. Online 3D printing services were identified by searching on Google based on related keywords, and recording all names that occurred directly in searches and in related webpages (e.g. blog posts listing top online printing services). Coders reviewed each website and coded for the functions the website served. This including uploading two 3D files to websites that offered that functionality and walking through all steps of ordering before payment is required. One of the uploaded files contained thin walls and a non-manifold mesh to see if the service would automatically inform the client of these common printing-file errors. Informed by platform types by Rayna et al. [32] and by requirements listed by Chen and Lin [197], we grouped the capabilities of each websites ordering interface. In total, we reviewed 33 websites, of which six did not have a printing interface but just an email contact form. The high-level results of the remaining 27 websites are shown in Table 8.1.

Table 8.1: A range of online 3D printing service interface capabilities. Black dots denote capabilities held by each service, and red dots denote that file repair tools exist in addition to file verification tools. Note that no service has all features.

	Capabilities / Service Name	Craftcloud	Shapeways	Sculpteo	3D Hubs	i.materialize	makexyz	Xometry	Protolabs	Jawstec	Stratasys Direct	Treatstock	Fast Radius	Voodoo Manufacturing	Fathom	FacFox	SD3D	3Diligent	Jomatik (formerly Trinkle)	Kraftwurx	Beta Layout	WeNext	HK3DPrint	AutomotivMFG	RapidMade	Makeprintable	GoProto	You3DIT
Instant Design Adjustments	Online Quote Interface	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●
	No Account Needed	●				●	●			●		●					●		●	●	●					●		●
	File Verification Tools		● (red)	● (red)	●											● (red)							●			● (red)		
	Scaling Adjustment Tools	●	●	●		●	●										●	●	●							●		
	Orientation Adjustment Tools		●	●	●				●										●									
Fabrication Options	Customize Slicing Settings	●			●		●					●	●	●			●					●			●			
	Images of Material Options	●	●	●	●	●	●		●					●					●	●					●			●
	Descriptions of Material Options	●	●	●	●	●	●	●	●	●		●		●	●	●			●	●		●			●	●		●
	Direct Choice of Printer Type			●	●	●	●	●	●	●	●		●		●	●	●	●	●			●		●	●		●	●
	Multiple Manufacturer Options	●					●	●				●						●										
Social Feedback	Chat with Service (before order)	●	●	●	●			●		●	●			●		●	●					●						●
	Notes for Printing (during order)	●			●			●	●	●	●	●	●	●	●			●					●	●	●		●	
	Additional File Uploads (not 3D)							●	●	●	●		●		●			●						●			●	
	On-Site Design Catalogue		●			●						●							●	●								●
	Sharable Order Link	●	●	●		●	●				●																	

No online 3D printing service we discovered offers all the highlighted capabilities. Each service aims for a different audience, some designed for more industrial applications and some designed to be more "newcomer-friendly". All follow the online 3D printing process illustrated in Figure 8.2: 1) Upload a 3D File, 2) Choose Design Adjustments and Fabrication Options, and 3)

Order Print. However, as discussed in Chapter 6, a 3D file may not describe all aspects of a users specification or design-intent. There are elements of design-intent, influenced by both geometry and fabrication options (e.g. material) that are implicit to these interfaces but require significant background in 3D printing to understand within the contexts of printability. Some printing services offer ways to discuss ideas before printing, but these chat interfaces often are relegated to a corner of the screen. Some services allow for writing notes or uploading files while ordering, but this also is not a required step before ordering a print. All services surveyed do not provide clear affordances for expressing design-intent in addition to 3D files, so services may often print files that do not match the intent of a less-experienced user. Knowledge of 3D printing is required for a client to not waste time and effort, especially if they do not explicitly ask for design-validation with a service.

However, many services do require some operator-verification before printing a clients order, although not all services explicitly state this when placing an order. Some also explicitly state that they repair 3D files that contain common errors, as shown by the red dots in Table 8.1, although many may do this behind the scenes. Online 3D Printing services presently try to be transparent, offering slicing settings only printing practitioners would know, but regardless have operators-in-the-loop who catch obvious errors. However, the printing interfaces only assume printing configuration and file geometry compose a print-specification, which we have observed in previous chapters to be false. This operator-in-the-loop now can only catch issues that arise due to conflicts in print configuration and geometry, not the users' print intent. In many cases, interfaces do not contain ways to understand what is being specified, like printer-material do not contain illustrations or descriptions to help newcomers without experience with these materials.

Design Implications: To support newcomer-clients, online 3D printing systems need to provide more affordances for expressing design-intent than just a text-box that says something similar to "file description", and these systems need to provide ways to educate users on the different options available for each mandatory decision (e.g. material). Finally, all but seven of the surveyed services did not provide example designs that could be printed, which requires newcomers know what they can print and what file formats are expected. Specifications will require different sets of knowledge as users progress through unique printing applications, so all resources aimed to increase the knowledge of the user should be thoroughly situated in this online printing process.

8.2.2 Social Media Content Analysis

Next we carried out a qualitative analysis to understand the content of users online conversations about printing services. We scraped all mentions of the above printing services from the following three online platforms: Thingiverse, Reddit, and the 3D Printing Stack Exchange. We utilized the same scraping methods as in Chapter 7 for Thingiverse, utilized PushShift for collecting Thingiverse comments, and downloaded the Internet Archive's complete metadata from the 3D Printing Stack Exchange.

To systematically classify content of conversations surrounding 3D printing services, we first created a separate sample of 471 comments evenly distributed amongst the 3D printing services (167 from Thingiverse, 54 from Stack Exchange, and 250 from Reddit). Three researchers conducted an open coding analysis [149] to identify frequent reasons people mention 3D printing services online. We found that commenters often were sharing stories or providing recommendations about particular 3D printing services, providing advice about how to print in general, and were participating in many community-building behaviors. From these observations, we iteratively developed a coding scheme until it converged on this subset of comments.

We created another sample of 301 comments (127 from Thingiverse, 162 from Reddit, and 12 from Stack Exchange), again randomly chosen but evenly distributed amongst all 3D Printing Services, to assess the reliability of our coding scheme. We utilized the Fleiss' Kappa score and found strong agreement in the coding of online social media posts (κ=0.7984). Below we outline the key findings of this social media analysis, emphasizing the barriers and challenges people mention relating to utilizing printing services.

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https://pushshift.io/

https://archive.org/download/stackexchange

8.2.2.1 Who Uses 3D Printing Services?

> *"If your interest is not towards 3d printing in general but is really limited to getting project done, than you could consider having a printing service doing that for you instead... It will be cheaper and probably of a higher quality than what you could achieve yourself. Certainly it will require less time investment from your side." (Stack Exchange User)*

3D Printing services were often regarded as good places to get started, especially if you just wanted the product of printing without becoming a printing enthusiast. People mentioned using services because *"I don't want to feel overwhelmed early on"* (Stack Exchange User). While services were utilized for a wide range of 3D printing applications within these comments, most were oriented towards personal projects, not job-oriented or commercial applications.

8.2.2.2 Why Visit a 3D Printing Service Website?

> *"You can find experienced people who own a printer and want to print for you. They can tell you what is printable and what not... If you did that a couple of times you can decide to go to a fablab or makerspace where you lent/rent a printer"* (Stack Exchange User)

In our analysis, we noticed that people had a mix of good and bad things to say regarding 3D printing services. Each service's websites had many aspects mentioned in addition to the printing service. Many had design-shops that could be visited, to either order fabrications directly from a proven design or to purchase for downloading only. Others had information sheets, on subjects like how to design for a service or about material qualities (e.g. *"[The] printing service has some post-processing articles" - Stack Exchange User*). Some users mentioned uploading files to services to see if they were printable, even in cases where they did not plan to utilize the service (e.g. *"Shapeways wouldn't accept the battle-damaged mask" - Thingiverse User*). Some services host a forum, where users could discuss about printing practices. Few users mentioned using design or scanning services offered by these websites. For the printing services, users mentioned the following qualities: *Newcomer Friendliness*, *Price*, *Quality*, and *Community-Building*.

Newcomer-Friendliness: 3D Printing services were often recommended for newcomers, so that they could start printing without the initial overhead. Many mentioned it cost less than buying printers initially (e.g. "*If you do not have the tools to fabricate this component yourself, but have a 3D model available, I would suggest getting someone else to 3D print it for you*" - Stack Exchange User). Additionally, for more *casual* printing users, they were often encouraged services as a way to get a print done without having to learn many technical details about printing. Many use services without owning a printer themselves (e.g. *"submit files for printing–I don't own a 3D printer either :)"* - Reddit /r/3DPrinting User).

Community-Building: Some referred to these printing services for communities that have formed around them (e.g. *"Some quick notes on my build to share with the community [about materials]..."* - Thingiverse User). However, many mentioned issues where services were damaging other online 3D printing communities, particularly by violating designers' intellectual property rights (e.g. *"I'v just found my design being sold for £373.79 !!! I did not give permission for them to sell this design"* - Thingiverse User). Many users on Thingiverse explicitly ask for their designs not to be uploaded on these service's design-stores (e.g. *"Please don't reupload this on Shapeways and the like for commercial use"* - Thingiverse User). Intellectual Property of who owned designs and resulting products was also a concern of some newcomers in Chapter 6.

Price: While less than 3% mentioned price as a reason for commenting about the service, almost all were positive reviews. Commenters often compared relatively local services versus large global services, saying that local shops were less expensive (e.g. *" order from (relatively) local shops and they're usually pretty cheap."* - Reddit /r/Vive User). Many commenters showed strong preference for local shops over the more popular services (e.g. *"The same design which would have cost over $50 at shapeways cost me only $21.28." - Thingiverse User*). However, commenters did admit that the popular service's pricing tools were a good way to get a rough estimate of price (e.g. *"their instant quotation service can give you a rough order of magnitude* *when it comes to price"* - Reddit /r/SmallBusiness User).

Quality: Very few commenters explicitly mentioned quality of the end-product from a service, but many mentioned printing in more exotic materials like metals. Proximal printing services were often preferred if available to print complex designs (e.g. "For more complex designs, I would recommend working with a local manufacturer" - Reddit /r/SmallBusiness User). Some printing services would sometimes completely fail to successfully print a model (e.g. *"I'm surprised they sent you that - frankly, it would be unacceptable to me from a paid service"* Reddit /r/PrintedMinis Users).

8.2.2.3 How to Print with a Online Service?

> *"So I ordered two sets of these from two separate manufacturers... and neither fit... I am extremely [$#@!]ing upset, I don't think it's the designers fault but rather the printers I guess? I don't [$#@!]ing know." (Thingiverse User)*

One large challenge in utilizing 3D printing services, especially with pre-made designs, is being able to trust and verify that both the design and the end-fabrication match your intent. Without printing experience, or the ability to perform and interpret measurements on 3D files, it can be very difficult to distinguish between or evaluate either without guidance.

Trusting and Verifying Designs: Some commenters on Thingiverse explicitly asked for measurement details (e.g. *"What are the exact measurements so that I know [i.materialize] will print the correct size. I have never 3D printed anything and have am really new to this process" - Thingiverse User*). Research by Kim et al. have investigated and demonstrated how verifying and adapting measurements on 3D printable models may be conducted in future applications [54].

Trusting Services: While services often were applauded for helping people print, there were some common words of caution: "*They have incentive to make sure you succeed when using their products. Just beware the salesmanship*" (Stack Exchange Users). Some services do not have a great reputation with our analysed users. Often people were skeptical with particular services, saying that the "*challenge for a consumer is how to pick one that's actually going to deliver*"

(Reddit User). Many users, particularly on Reddit, mentioned difficulty gaining users for their own 3D printing services for this reason. One individual who prints as a service mentioned *"It is EXTREMELY hard to get clients away from either service [Shapeways and Sculpteo] because 'that is the way they have always done it"*. Some mentioned needed to use expensive, more reliable printers to gain this trust, saying *"start marketing to your target market BEFORE you have a machine and just sub out all the work"*. Overall, both these small services and clients value the community aspects of social media. This was exemplified through a testimony from a service on Reddit: "*95% of our business is from this community. They helped me start it (check my submitted post history to see) and helped me get the right machine and I, in turn, provide fast, reliable, and interactive experiences for them*". However, the barrier towards creating a trustworthy and reliable service-interface is still challenging, requiring extensive programming knowledge: "I would love for an easy way for clients to upload 3D Files and get an immediate quote based on volume of the piece. Having them be able to see it in 3D and select the material would be wonderful... The issue has been plaguing me for some time but I cannot think of a good way to make it work" (Reddit User).

Verification and Consultation: Services often assist with helping clients print satisfactory products, however most stories and comments about this consultation and negotiation process (i.e. like in Section 6.2.1.1). Many asked services for general advice, relating to the aforementioned qualities of 3D printing services. One Reddit user said they frequently asked services on how to reduce the cost of their order, others mentioned messaging the service to ensure certain slicing settings were utilized (e.g. "*Please print it standing up right*" - Reddit User). Some commenters mentioned not to specify too much about slicing parameters to the service, but just explain the qualities of the desired end-product.Sometimes services, when receiving these messages in orders, would say they cannot print these items (e.g. *"Shapeways and studiofathom were both very polite but passed on the project, studiofathom said "we reviewed the conversation and those requirements will not be possible on our equipment" and shapeways response (via phone) was similar"* - Stack Exchange User).

8.2.3 Overview of Online 3D Printing Services

3D Printing services are a gateway for many to begin 3D printing without significant up-front investment of finding, purchasing, or learning about particular printers. While these online services do appear to consult and negotiate printing ideas similar to the proximal printing services discussed in Chapter 6, their interfaces do not encourage sharing aspects of design-intent that may not be obvious to newcomers (e.g. materiality [93]).The burden is presently on clients to convey their intent, and to do research on several aspects of the printing process before beginning. Next, we discuss how we designed a website to introduce anyone to printing, including affordances for beginning collaboration with proximal and online 3D printing services.

8.3 Design Probe: Introducing Newcomers to 3D Printing through HowDIY

The goal of this study was to design a website that would *"open the door"* to 3D printing practices by helping newcomers understand examples of what they could print, helping them find relevant online resources, and helping them start collaborations with printing facilities. Informed by the analysis in previous chapters and the online service analyses in this chapter, we conducted a card generation and card sorting study to elicit what content 3D printing mentors would imagine in this introductory website, HowDIY.

8.3.1 Formative Design

We approached five experienced printing practitioners (3 Male & 2 Female, ages 19-29), most having experience running printing services where they help newcomers at least once a week. The staff first wrote on cards all the concepts that should be conveyed to any newcomer (i.e. *Card Generation* [198]). Then, they were asked to organize these cards as they would appear on a website with thinking-aloud solicitation (i.e. *Card Sorting* [199]). Afterwards, we asked the participants to provide websites and social media pages that related to their cards.

8.3.1.1 Card Generation - 3D Printing Concepts

Concepts written by all staff-participants are seen as crucial elements in HowDIY, outlining what should be presented to support *anyone* to begin 3D printing. Obviously, all included printing service details and contact information. They all included some type of walk-through of how someone could print through their service, including critical requirements with surrounding knowledge, such as requirements for a printable 3D file. All wanted to convey that 3D printing takes time to complete, as some newcomers frequently wanted prints faster than feasible.

These mentors all mentioned newcomers did not know about 3D printing because it was not “mainstream”, and newcomers that visited them already had prior interest to 3D print. They suggested that users should see examples of what to print, with notes on price and fabrication-duration, to help recruit more newcomers. Many mentioned that displayed examples should be personalized to the newcomers’ interests, with searching capabilities to browse through different example projects. Some mentioned displaying images of example prints from the service, with the ability to compare products of different materials and printer-types. All mentioned showing links to webpages they frequently utilize when planning 3D printing projects, such as Thingiverse, and to social media channels of 3D printing practitioners. They all mentioned that there should be mechanisms for promoting the newcomers’ prints through the service on social media. Some mentioned having a glossary of many common 3D printing terms (e.g. support material, orientation, etc.).

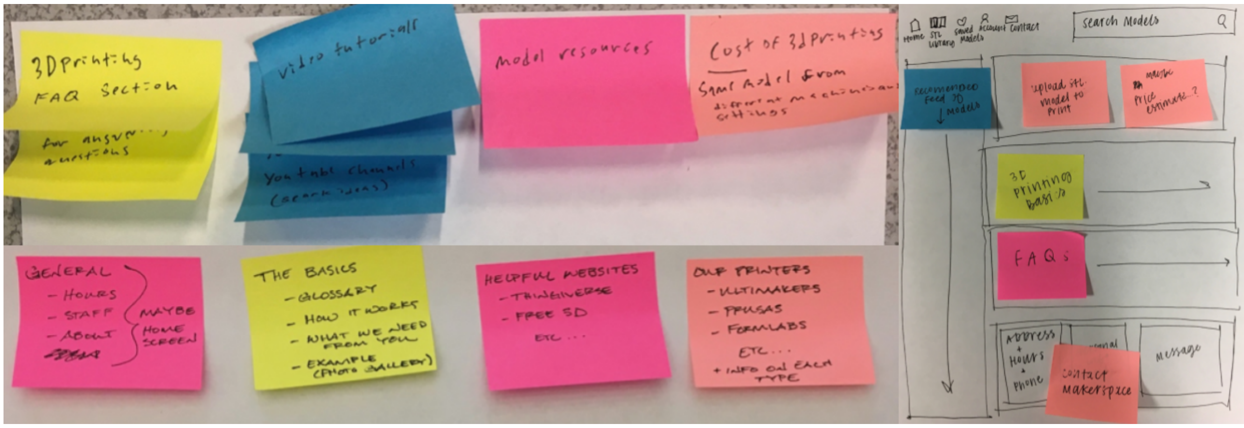

Figure 8.3: 3D Printing Mentors generated several concept-cards to introduce newcomers to 3D printing services, then sorting cards into groups (e.g. left) and imagined websites (e.g. right)

8.3.1.2 Card Sorting - Two Different HowDIY Layouts

The five printing service staff had different two main themes of how their printing concepts should be presented on the HowDIY webpage. Most had most of the concepts available in one large-scrollable page (e.g. Figure 8.3-*right)*. This page would first display quick shortcuts to upload files and receive quick price estimates, with 3D printing basics, FAQs, and contact information following below. There would also be *recommended* designs featured on the side. There would be ways to curate, or "*save*", and search through different designs. This layout would present a lot of information all at once, ensuring that newcomers have avenues to see all the needed information, but burdening them with processing the order of how all the steps are connected in the printing process.

The second layout is more of a introduction-*Wizard* (like Fong et al. [200]), asking users to enter information in a prescribed order to determine how to introduce them to 3D printing. For example, if someone says they are not experienced in CAD and do not wish to learn CAD, they would be shown downloadable or easily-customizable 3D designs before CAD tutorials. If someone said they are experienced in 3D designing, more emphasis would be placed on how to design for 3D printing in particular. These mentors referred to their imagined website as providing "*learning pathways*", where newcomers could receive tailored 3D modeling and printing tutorials tailored to user-preferences and printing-desires, mentioning web applications like *DuoLingo* and *Stich Fix*. This layout theme would place less of a burden on users by only showing information thought to be relevant at a given time, but risks making too many assumptions and hiding information that newcomers could utilize or could pique newcomers' curiosity.

8.3.1.3 Combining the Two Layout Themes into a Prototype

Informed by these two themes, the discussions with printing practitioners, and the prior Chapters' findings, we designed the website HowDIY to introduce anyone to 3D printing. HowDIY was created as a hybrid combination of the two themes, hiding guidance in plain sight as users navigate between options of *what* can be printed and through web tutorials on *how* to print. This hybrid approach may allow newcomers to not face many subsequent choices without context of why they relate to printing processes, and not be overwhelmed with options of what to print without guidance.

8.3.2 Final Design of HowDIY

The goal of HowDIY is to introduce newcomers to interesting 3D printing opportunities and help develop individuals awareness and knowledge of online 3D printing resources relating to these opportunities, so that they may *begin* co-participation in printing processes. In other words, the goal of HowDIY is to open the access-blocking door so that newcomers may cross it to co-participate with MKO's. We evaluate the opening of this door in the next subsection by reviewing user-feedback and newcomers' co-participation with printing processes. We developed HowDIY informed by the previously-listed contributions of this dissertation, the formative studies of the last section, and iterative qualitative and usability feedback from newcomers and experienced printing practitioners. In this section, we discuss what any user may experience when visiting the website.

8.3.2.1 Indexing Methods: Providing Guidance to Relevant Online Resources

Indexing Designs: Several design-indexing strategies were employed during iterative development based on various forms of recommender systems: Content-Recommendations that compared vectors representative of each design's semantic content, Collaborative Filter Recommendations that compare designs purely based on user-interaction data on Thingiverse, and Hybrid Recommendations that compare designs by both content and user-interactions. We chose content-based recommendations and search queries, because otherwise many of the displayed designs became too diverse and appeared overwhelming to users. Content-based querying was performed by creating a Approximate Nearest Neighbor (ANN) model (with Hierarchical Navigable Small World graphs [201]) for all of Thingiverse and each category on Thingiverse. Content vectors for designs and design-files were created by performing TF-IDF on the corpus of design-text to do a weighted sum of each of the documents term word-vectors in Word2Vec (W2V) [202], which has been shown to produce good document-level vector representations [203, 204]. Images and 3D File representations in the same space were created by neural network models described in Chapter 7.

Query Inputs: Queries are directly converted into the vector space for ANN queries, while only a random subset of terms from the user-written interests are queried for recommendation views. Recommendation per design (e.g. *"similar to this"*) are also computed by querying the TF-IDF weighted W2V vectors against all the documents. Based on design guidelines for recommender systems [205], we added diversity in the recommendations per design by querying each category separately and inserting top results from multiple categories into the final recommendations. Results from user-queries are collected in a larger number than shown, which are then by default sorted by popularity (i.e. number of views divided by number downloads per design) and items containing exact terms from the user's query are moved to the front. This makes the top results all appear both relevant and more likely to be printable, as they are indirectly validated by the Thingiverse community.

Closed-Domain Question-Answer System: In addition to querying designs, HowDIY also contains a large dataset of social media comments similar to Section 8.2.2 from Reddit, the 3D Printing Stack Exchange, and Thingiverse. Unlike the social media analysis that gathered comments that contained a keyword (i.e. a printing service name), comments in this dataset were collected from *all* comment threads that included a link to Thingiverse, indicating at least tangential relation to 3D printing. All comments were fed into a Closed-Domain Question-Answer system (**CDQA**) that retrieves a large sample of webpages with comments that may likely contain an answer to a given question (based on TF-IDF scores like DrQA [206]) and then employs DistilBERT [207] to read and score the answers within these webpages. The interface for this system appears in every non-homepage view of HowDIY, with slight variations. As discussed in depth in Chapter 6, it is difficult to ascertain good questions without a good understanding of the domain. To combat this, we give many example questions in a drop-down so that users can understand the types of questions that may be asked. Upon asking a question, the user is shown a link to the *"How to Print"* Page and several text snippets determined as relevant by DistilBERT with the predicted answers highlighted, shown in Figure 8.6 (bottom-right).

8.3.2.2 Home Page: Asking Introductory Questions

The first thing users see are questions informed from Chapter 6: Why Print, Print What, How to Print, and Where Can I Receive Printing Help? Each of these has a short blurb addressing and linking to how the website will help answer these questions. The website does not assume all these questions are unanswered, as newcomers may have some knowledge about any or all of these questions. Instead, it gives one choice that will direct newcomers to the answers they request. Before directing them to these answers, the website asks the user to create in a profile consisting of their email and a set of their interests. This profile will inform and facilitate 3D printing opportunities offered to the newcomers.

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https://github.com/cdqa-suite/cdQA

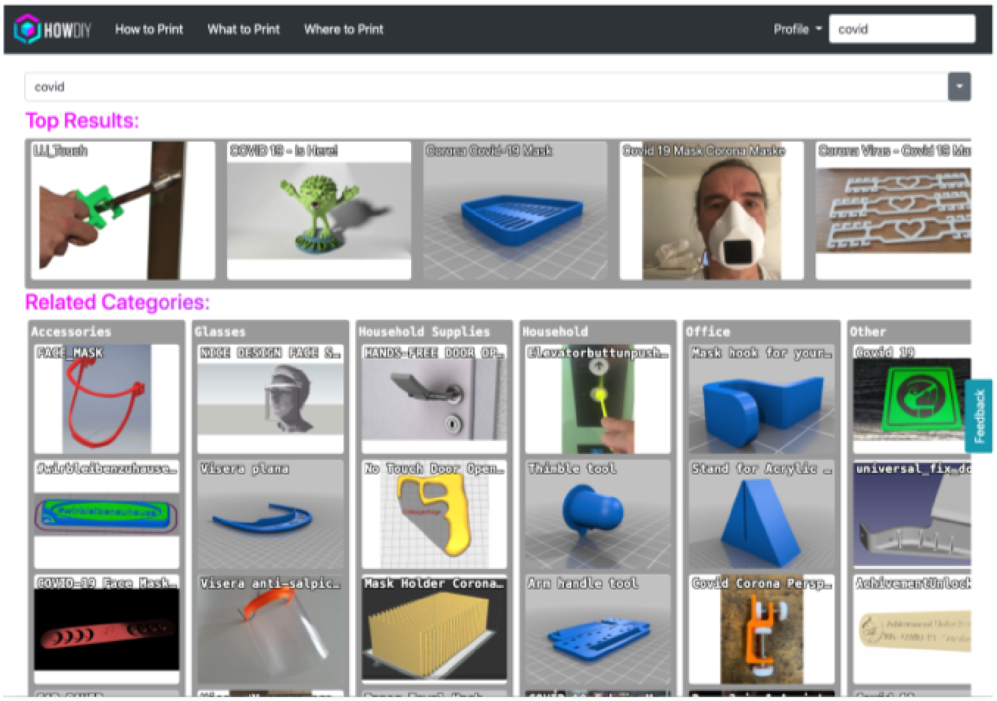

Figure 8.4: Users can browse through millions of designs to learn what can be printed. HowDIY shows the top search results, also breaking up the results per category so that users can distinguish between different semantic relations to their interests or query.

8.3.2.3 Why Print and Print What?: Search and Recommendation of Free Designs

When seeking answers for the questions "Why Print?" and "Print What?", or using the top-right search-bar, newcomers are shown a page full of designs based on their interests or query. Designs were taken from ThingiPano (Chapter 7), with a scheduler that downloads and indexes designs.

Browsing Interface: The goal of the browsing interface is to show many example designs of *what* can be printed, hoping that users will click them to discover *how* to print. Each design is represented by the same thumbnail that is utilized in Thingiverse, where on hover it will display *"How to Print?"*. The top row is the typical "best" results, showing the most popular recommendations or query-results. Below are 81 columns representing Thingiverse category-specific transpositions of the search results, so that users may better understand the wide variety of domains that relate to their interests or query. These categories are sorted by the number of appearances in the overall results, so relevant categories are displayed first without extra horizontal scrolling. Like discussed in Chapter 5, one query can have one intended meaning but can be easily be confused by search interfaces for other meanings. Showing the array of category-columns can help users disambiguate these multiple meanings that are not as obvious by viewing a one-dimensional list of results. If the user scrolls beyond the bottom of the screen, there are direct links to elements of HowDIY's one-page library of online online resources to "Visit other Model-Search sites", "Hire a Designer", or "Learn to Design". Similar links to locations of this library are situated throughout HowDIY, including individual design views.

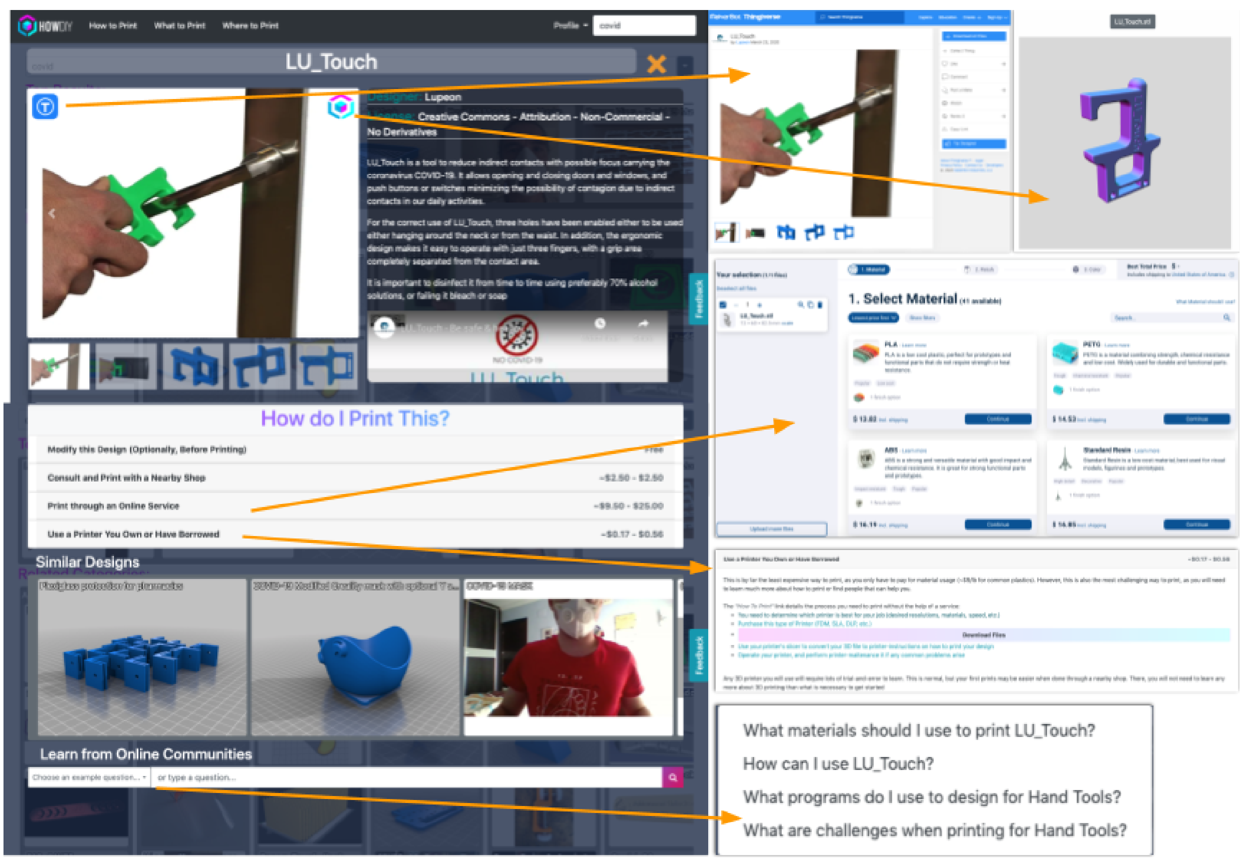

Figure 8.5: The Design View displays functional details of the design, and provides pathways to modify or print this design (How to Print). Recommendations encourage further browsing

Design-View *Thingiverse-Metadata*: Clicking *"How to Print?"* on any design-card will elicit a overlay screen showing detailed information about the design from Thingiverse, information on how to print this file generated by HowDIY, and a CDQA interface. An automatically switching gallery of author-uploaded images is shown, with a title and Thingiverse thumbnail that links to the Thingiverse design url. There is also a logo to view all 3D files, which displays all 3D files in a list. A 3D file viewer downloads the file client-side and renders the file with multiple multi-colored directional light-sources and an rotating 3D object, so that users do not confuse the color of the render as the color of the final print (e.g. Chapter 5). While users can rotate the mesh by dragging the mouse on the render, newcomers often have difficulty with understanding and operating these interfaces [23], so the meshes rotate by default to give users full view of the file. In addition to the images and 3D viewer, all other Thingiverse textual metadata (e.g. design description) is compressed to a single scrollable text box. License Information designated by the author and links added by HowDIY are displayed at the top of this box as Intellectual Property Issues were concerning to some newcomers (e.g. Chapter 6).

Design-View *How to Print*: Below the Design-View contents generated from Thingiverse Metadata are HowDIY generated detail on How to Print the design. There are four options, each with a dynamically calculated price: **1)** *"Modify this Design"* gives users a button to download the design files and links to the HowDIY library on how to modify designs in introductory CAD programs (e.g. TinkerCAD); **2)** *"Consult and Print with a Nearby Shop"* describes nearby shops and links to the "talk" page (section 8.7; **3)** *"Print through an Online Service"* gives a link to the "talk" page but also gives links to 3D printing services with 3D files already uploaded; **4)** *"Use a Printer You Own or Have Borrowed"* provides a link to download the files, and several links on how to purchase and operate 3D printers in HowDIY's library. Each of these options starts collapsed in an accordion-view, with the collapsed view showing the above options and estimated prices for each options. Design modification is always free, while the other prices are calculated by the volume of the mesh. For the online-service cost, the same API that creates a pre-uploaded order link also is utilized to eventually give a more-exact price range for the designs' models.

While these prices are usually fairly accurate, it should be noted that some designs only require a subset or require multiple copies of one mesh, which is not presently taken into consideration in HowDIY.

Design-View *Recommendations*: The average vector representation of the design text and files is combined to query each category's ANN individually. Only taking at most two per category, the closest neighbors are sorted into one list that is rendered in a "Similar Designs" list similar to the overall search results.

Design-View *CDQA*: Below all other information is the CDQA system, which has example questions tailored to the particular design. These questions were informed by the taxonomy of questions asked on Thingiverse by Alcock et al. [27]: "What materials should I use to print X?", "How can I use X?", "What programs can I use to design X?", and "What are challenges when printing X?". Having these example questions can give newcomers a starting point to understand how and why the design was made.

Overall, the browsing view exists to help inform newcomers of what they can print, situating knowledge of how they may print these items, much like navigating and browsing through tools in a hardware store [34]. The goal is to help newcomers to identify opportunities for collaboration defined by what they are printing, establishing a more-defined common ground of *what to print* (i.e. content common ground) and *how to print it* (i.e. process common ground) based on existing designs.

Figure 8.6: The *"How to Print"* page encourages navigating through a library of online resources that help newcomers identify 3D printing websites and develop technology readiness. The top-right demonstrates how the steps are highlighted based on the categorical tabls, and the bottom-right demonstrates the CDQA interface present in all aspects of HowDIY.

8.3.2.4 *How to Print: A Library of Online 3D Printing Resources*

Based on the collection and organization of 3D Printing websites gathered in the formative study, we created a dynamic one-page library of various online web resources related to 3D printing. This contains several media formats from social media to PDF books for download. The page has five sections, from top to bottom: Instructions to navigate HowDIY, Printing Process Steps, Categorical Tabs, Related Websites, and a CDQA interface. The HowDIY navigation instructions are static instructions detailing the parts of this page, and explaining that you only need to obtain a 3D file before ordering a print. The steps (obtain a file, slice a file, and operate printer) illustrate the printing process and double as clickable links that go to the appropriate categorical tabs. Categorical Tabs are a hierarchy of subjects relating to 3D printing, each with descriptions of what you will learn by visiting the related websites. Each categorical tab triggers the steps above to be highlighted, signaling which stages of the printing process directly relate to these web resources. The Related Websites (n=115) are the collected websites collected in the formative study, filtered by the selected Categorical Tab. Each website contains a description of the site to be viewed and evaluated by users before visiting.

Tabs include subjects like where to obtain designs without designing, where to learn how to design, how to buy and operate printers, and where to learn about 3D printing persistently on social media. Videos are included in each tabular view, because videos were often requested in feedback by participants in Chapter 6's study, and are embedded directly into the view for convenience. The bottom has another CDQA interface, with example questions relating to the tabular categories. This includes questions that experienced practitioners may know but is not always obvious to newcomers, like "How can I make prints food-safe?" which returns comments on how to coat prints of various materials. At the end of these results, it links to the "talk" page where users are instructed on how to order or ask printing services questions. The goal of the "How to Print" page is to make users more technology-ready for future printing collaborations.

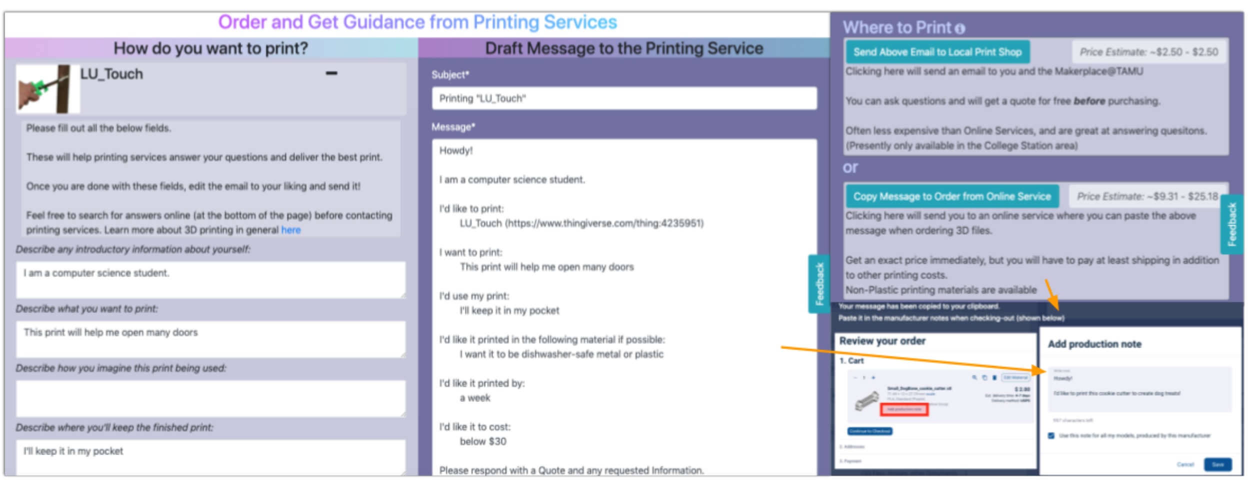

Figure 8.7: The *"Talk"* Interface provides questions that helps users draft and send messages to different printing services who may lend their printing expertise.

8.3.2.5 *Where Can I Receive Printing Help?: Guidance on Communicating with Services*

The goal of this page is to help newcomers begin collaboration with services, focusing on which services to pick and how to better-establish common-ground. This page differs depending on where it was visited from, linking to different locations online (i.e. loose-coupling) or nearby (e.g. tight-coupling) where one can print if visited from the menu or home page, or linking to a "talk" page if linked from other sources. This "talk" page helps newcomers structure questions about what they want to print so that they may not leave out pertinent details as observed in Chapter 6. The questions users answered are immediately translated into a draft message that can be sent to a service. Questions include information about the user, descriptions of what they want to use printing to accomplish, where the print will be used, descriptions of material qualities, and constraints in cost or money. All questions are optional, but exist to help newcomers think more about their printing goals and relate them to the service. A CDQA interface is below all other page elements, populated with popular questions people ask from scraped social media comments (Figure 8.6, bottom-right). Thingiverse comments were scraped from the same methods utilized in the social media content analysis earlier in this chapter.

After a message is drafted, users can edit the message as they see fit, and either email it to a local print shop or send it as a message to an online printing service. Neither commits the user to ordering a print and spending money, however cost estimates similar to the design-view are generated for these options. The email is sent from the HowDIY system to both the user email and the shop, but for online services the message is copied to the users' clipboard and then users are given instructions on how to message online printing services. Note that in our survey of online services, many had affordances to add notes during an order or ask questions before ordering. In addition, five of these services personally called the telephone number of the researchers to see if they needed help with the order. Both proximal services as studied in Chapter 6 and online services as studied in this Chapter provide human-verification and -consultation of printing ideas. The talk page aims to help newcomers be more collaboration-ready and establish common-ground with printing services, starting with a loose coupling of work.

8.4 Evaluation of HowDIY

We conducted a "*in-the-wild*" study where we recruited newcomer-users over email to utilize the system indefinitely, assessing the efficacy of the system, and providing further insight towards developing intelligent interfaces that can empower anyone to identify how they can start 3D printing. We evaluated HowDIY's affordances for "*opening the door*" to 3D printing, or persuade newcomers to willingly co-participate in printing practices.

8.4.1 Methodology

To assess the efficacy of HowDIY's ability to introduce individuals to 3D printing, we conducted a study where printing-newcomers recruited from Texas A&M campus-wide email (i.e. faculty, staff, students, and former-students) used HowDIY for a period of two weeks. All participants had zero prior experience 3D printing in-person or through a service. Participants were given a questionnaire before using the system, and again two weeks after. Some participants participated in an semi-structured interview after the final questionnaire, focusing on their perceptions surrounding 3D printing practices and their perception of HowDIY. Logs of HTML DOM events were logged and saved for each user. All aspects of the study were conducted online.

The first questionnaire contained questions relating to their prior exposure with CAD and 3D Printing, demographic information, and several likert-scale measures discussed below. The followup questionnaire repeated these measures and asked short response questions relating their perception of 3D printing and relating to Olson and Olson's framework for initiating successful distance collaborations [14]. We conducted quantitative analysis of usability and of users' changing perception towards 3D printing, and qualitative analysis of newcomers' readiness to begin successful 3D printing collaborations. 22 Participants completed both sets of questionnaires, consisting of interests ranging from Finance to Chemical Engineering and ages from 18 to 49.

Measures: Participants completed several Likert-scale measures relating to participants' perceptions towards 3D printing and browsing behavior online: self-assessment on the **1)** attitude and behavior toward careful information seeking on the web [151], **2)** individual interest adapted for 3D printing [152], and **3)** self-efficacy for finding resources to successfully identify and solve problems in 3D printing, and to successfully print for their work and hobbies [153]. Participants completed two measures evaluating HowDIY: the System Usability Scale (**SUS**) [208] and the Creativity Support Index (**CSI**) [209] on the task of learning 3D printing. While the SUS was intended as a quick questionnaire to evaluate ease-of-use, it has been shown to be also effective at separately evaluating sub-scales of learnability and usability [210]. Together, these measures help evaluate newcomers changing perceptions toward learning to utilize 3D printing in relation to their perceived usability of HowDIY. A grounded theory approach was utilized to analyze the qualitative interactions and questionnaire data [149], relating axial codes to themes in Olsons' Framework.

8.4.2 Results: Opening the Door for Newcomers

The following results were based on the 22 participants that completed both sets of questionnaires. Overall, newcomers found the website usable, perceived it as helping them learn 3D printing, and gave feedback that helps us evaluate their willingness and ability to begin collaborations with printing practitioners as aligned with Olson and Olson's framework.

8.4.2.1 HowDIY Usage Logs: Demonstrating Sustained Use

Users spent an average estimated 24.7 minutes on the site, split across an average of 4.8 sessions. Users made an average of 28 searches per visit, viewing on average 5 design-views. Visiting at an average of 4 tabs in the "*How to Print*" page, going to an average of 4 external links. Users visited the 'talk' page 4 times on average, but only two participants sent emails to printing services. One of those participants sent a email asking for a Thingiverse earbud holder to be fabricated, and the other asked for guidance designing and replacing a broken latch for their cooler with various images (Figure 8.8).

Figure 8.8: A Specification Sent from a HowDIY user asking for advice on how to design and print a replacement latch for their cooler (*right*) containing uploaded images of the cooler (left)

8.4.2.2 System Usability Scale: Evaluating Ease of Use, Usability, and Learnability of HowDIY

The SUS consists of ten likert-scale questions from 1 (“Strongly Disagree”) to 5 (“Strongly Agree”), where half are questions about positive aspects of the system (5 is good) and half are questions about negative aspects of the system (5 is bad). While the end scale is represented by a single number from 0-100, these numbers are not percentages, with 68 being average and 80 being excellent [208]. Results of the SUS are outlined in Figure 8.9, showing that while most users found the system usable (median=65), there were some users that disliked the system. Below we discuss how newcomers’ other responses relate to these scores.

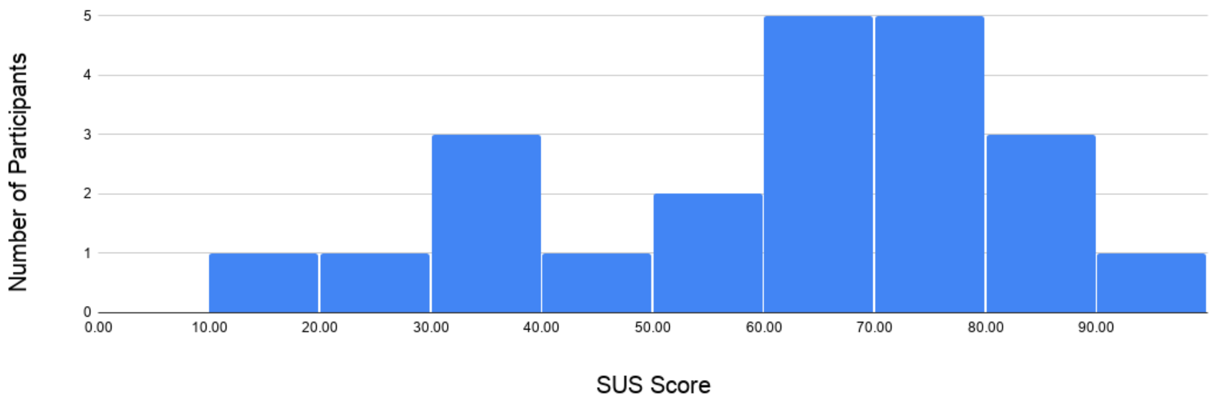

Figure 8.9: SUS Scores from Participants Evaluating HowDIY

Positive Scores: Most users (n=16) gave a passing score on the SUS, with 7 giving scores near or above the excellent mark (80) for the SUS [208]. These seven high-scoring users ranged from a variety of backgrounds, from food science to geology and engineering, aged 18-40 (median=23). Half had some idea about 3D printing processes, but mentioned that they would need to design in order to print, and the other half said something similar to "Not Sure", corroborating findings from Chapter 6. After using HowDIY for two weeks, three had started 3D printing projects, two in-progress and one completed. All but one of these users said they would refer HowDIY to others. These users liked the number of example designs, and some mentioned they learned "*the theory behind 3D printing*". These users most common complaint was a lack of familiarity with the website design (e.g. "I'm not familiar with the visual tropes used in its design"). Overall, many had positive perceptions of the site, saying *"despite being a complex subject HowDIY made learning 3D printing easy"* and *"[HowDIY] demystified the process for me a bit, which increased confidence"*.

Failing Scores: Users who gave HowDIY a score less than 50 (n=6) all gave learnability (e.g. "*I needed to learn a lot of things before I could get going with this system*") sub-scores greater than the median of all users, but all gave usability scores below the mean. This implies that all users were confident in being able to use the system themselves, but some users were often not happy with other aspects of the system. We explore these aspects by looking at these users' questionnaire responses. These users were older than other participants, with a median age of 37, with most having obtained a 4-year degree in engineering or STEM field (e.g. mechanical engineering and computer science). Half demonstrated prior knowledge on how to print (i.e. "*3D model using computer software - Send the design to the printer - Print out the computer model into a physical model*") and where to print (*"Open access lab in Zachary building"*). Only one of these users said they did not learn how to start printing after using HowDIY. All but one mentioned that they would not like to print pre-made designs without modifications. These users generally gave feedback that they wanted "*more of a novice step by step tutorial*" in a "*more comprehensive and organized way*", indicated they would prefer the Wizard-like interface imagined in the Formative Study (Section 8.3.1.2). One of these users said to reorganize "*information and links by the level of familiarity to 3D print*". Similarly, two of these users indicated that they would refer HowDIY to others that have some prior exposure to 3D printing. One user said they would rather "*Google it and follow the path/trail until I found what I was looking for*" instead of employing HowDIY, but according to findings in Chapter 6 Google alone is often not sufficient for many to get started with 3D printing in a short amount of time. To support similar users in the future, more-guided approaches similar to Massive Open Online Courses (e.g. Khan Academy) could be developed to help guide these users through desired 3D printing basics.

8.4.2.3 Creativity Support Index: Improving Creative Support for Online 3D Printing Learning

The CSI requires users to evaluate which factors (Collaboration, Enjoyment, Exploration, Expressiveness, Immersion, and Results Worth Effort) are needed for a given task by picking between all possible pairs of factors, then requiring the users to score each factor with two ten-point Likert scale questions. The factor counts are relative to each other, ranging from zero to six, where as one increases another must decrease. The scores range zero (bad) to twenty (good), so anything above a ten generally indicates some support of that factor in the system. The overall score is calculated by the weighted sum of the score and the counts divided by three, resulting in the final CSI score. The average CSI score was 60.74 (SD=22.3), above the failure threshold of 50 [209]. Almost all failing scores in the SUS matched to a failing score in the CSI, with the two being strongly correlated (r=0.82, p<.0001). All CSI factor scores had significant (p<0.001) positive correlation with the overall CSI and SUS scores, with *enjoyment* being the most highly-correlated (r=0.826). In other words, all factors were deemed by newcomers as important aspects of learning 3D printing, which in turn effected perceived usability. Below we describe each of the factors in respect to newcomers counts and scores, presented in order of highest count to lowest count:

Table 8.2: Creativity Support Index Counts, Scores, and Weighted Scores for each factor when learning how to 3D print with HowDIY

Scale	Avg. Factor Counts (SD)	Avg. Factor Score (SD)	Avg. Weighted Factor Score (SD)
Exploration	3.64 (1.18)	13.30 (4.08)	49.50 (23.69)
Results Worth Effort	3.00 (1.54)	12.18 (4.81)	35.91 (22.10)
Enjoyment	2.95 (1.40)	12.23 (5.48)	36.68 (24.24)
Expressiveness	2.64 (1.29)	11.86 (5.41)	31.00 (22.49)
Immersion	2.09 (1.41)	9.50 (4.89)	21.27 (20.44)
Collaboration	0.68 (0.95)	11.23 (3.95)	7.86 (14.56)

Exploration: The average count and average score is the highest of all the factors, which emphasizes that users value exploring different avenues for learning 3D printing, and that HowDIY helps newcomers users in this exploration. This aligns with findings from Chapter 6, demonstrating that newcomers want exploration support in addition to often needing guidance in this area.

Results Worth Effort: The count is 3.00 (i.e. chosen over half the other factors) indicating that newcomers value the knowledge they gain when learning to 3D print. The score was also relatively high, indicating that HowDIY helped facilitate this learning for most newcomers.

Enjoyment: The count is 2.95, indicating that newcomers want an enjoyable experience when learning 3D printing online. They do not want learning to be a chore, and HowDIY generally performed satisfactory at helping learning be enjoyable. Gamification could potentially increase enjoyment.

Expressiveness: While a lower count than the above, newcomers still valued being able to express themselves while learning 3D printing. The scores demonstrated satisfactory levels in this factor, but more could be done in HowDIY to help newcomers with this factor. For example, tools that help newcomers design or modify 3D files within HowDIY could help improve scores in this factor.

Immersion: The count is relatively low, indicating that newcomers only slightly value forgetting that they are using HowDIY while learning 3D printing. Scores were also low, indicating that HowDIY did not allow itself to be forgotten easily. This is consistent with some newcomers' comments that they were not familiar with the website organization structure. While not a high priority compared to the above factors, this may be improved by changing elements like search and recommendation to be more like familiar websites (e.g. Google).

Collaboration: The count is extremely low, with most newcomers not ranking collaboration above the other factors, indicating that they view learning 3D printing as a more remote activity. This aligns with many findings of how newcomers may be hesitant to talk to others in makerspaces or print centers when they are starting to learn [23, 156]. While 3D printing often involves learning with MKO's, newcomers do not value this before beginning collaborations. The score is satisfactory, but could be improved upon. While HowDIY does provide affordances to contact proximal and online printing services through email messaging, more support could be given for different couplings of work throughout the website. Design-, Scanning-, and Various Consultation Services could be incorporated directly into HowDIY with ways to request live text-based chats, video chats, and other specific forms of communication to facilitate collaboration. Systems like MarmalAid [48] could encourage more collaboration in 3D design.

8.4.2.4 Olson and Olson's Distance Matters Framework

We present qualitative findings indicating newcomers' self-perceived readiness and ability to begin collaboration with printing practitioners. In this subsection, we present how the logged user-activity on the site, followup questionnaires, and semi-structured align with Olson and Olson's four concepts for initiating successful collaborations.

Collaboration Readiness: Participants were asked questions regarding their willingness and ability to 3D print with the help of skilled technicians. Fourteen of the 22 said they would definitely want to collaborate with these technicians, with only two saying outright no. Many wanted initial guidance or mentorship when getting started, citing concerns like "*[I am] worried I would somehow break something*" without help when printing. Only one participant mentioned the reason they would not want to collaborate: "*[There is nothing] useful and not aesthetically pleasing*" that he wanted to print in general. Many gave conditions about whether they would seek collaboration or try to learn on their own. Whether or not to collaborate often depended on the complexity of the desired print for one newcomer. Three others mentioned that they wanted to eventually want to learn printing on their own without help, with one saying they would only collaborate if their Mechanical Engineering work made them, and another saying they would only collaborate "*if stuck*". One participant mentioned that they would be hesitant to collaborate in-person because of privacy concerns (e.g. "*I'd rather print whatever I want without having to tell someone what I'm doing*"), but that she would be open to using online services because *"The lack of human interaction would give me more freedom to print what I want without judgement!"*. So while may participants expressed readiness to collaborate following the study, not all may be willing to collaborate unless deemed necessary.

Technological Readiness: Out of all the participants that answered the followup-questionnaire, only one said they would be presently be comfortable ordering from purely online services. Common reasons were because these services are expensive, and that the newcomers would want to increase their confidence before doing that. Almost all participants said they would feel confident in their ability to contact printing practitioners (e.g. services) through remote technologies. Only one participant mentioned that they did not know how to start 3D printing at all, saying "*I wasn't able to learn about it as I didn't know where to look first at the website*." This aligns with the usability concerns from Section 8.4.2.2 where some users wanted more course-like organization (e.g. MOOCs).

Coupling of Work: Participants were asked how they would prefer to talk with printing practitioners after using HowDIY (e.g. “How would you communicate with skilled technicians for 3D Printing? For what tasks?”). Many preferred initial contact be made by email (n=11) or in-person (6), but four suggested that a follow-up after initial contact be made in-person or with video chat. Some offered to differ their choice of communication methods to those that their collaborators would prefer. Many mentioned COVID-19 limiting their options to purely online interactions.

Common Ground: Common ground was more difficult to directly observe in this study, as we do not know all the details of how participants may have communicated with various printing practitioners. However, we can infer that some level of common ground was established in stories told by newcomers about starting 3D printing. Two participants contacted the the university printing shop linked through HowDIY: one failed due to asking for a Thingiverse user-designed earbud holders for a price that was well-below the estimated amount on HowDIY, and another had successfully asked questions on how to measure and design a replacement latch for their cooler. One participant mentioned that she worked with a friend who printed her a butterfly fidget toy since she joined HowDIY, and another just started printing with high-temperature filament (PEEK) to fabricate a cat jaw for surgical implants. From the short period of time we have observed these participants, it appears that newcomers were more likely to start printing with close acquaintances, but were willing and able to ask questions from printing services.

8.4.2.5 Long-Term effects of HowDIY

None of the self-efficacy, interest, or information-seeking measures demonstrated significant ($p<0.05$) difference in the before and after questionnaires. Longer-term studies may be needed to observe the changes in self-efficacy and how newcomers may *become* printing practitioners [211]. However, some individual questions did demonstrate an significant increase: “Get someone not near me to help me when I get stuck on a 3D printing problem” ($W=14.0$, $p=0.04$), “How likely are you to believe the information contained in the web pages returned by a Web search engine?” ($W=0.0$, $p=0.03$), “How likely are you to believe the information about shopping you find on the Web?” ($W=22.0$, $p=0.05$). These may indicate that newcomers are more likely to seek help online and may trust less-familiar websites like Thingiverse if seen in search results unlike observed in the unguided newcomer-participants in Chapter 6. While most evidence we found of HowDIY "*opening the door*" to 3D printing exists in qualitative responses surrounding positive and negative reviews of quantitative reviews of HowDIY's ability to facilitate 3D printing learning, future studies could further investigate more-quantitative impact of similar systems (i.e. "*opening*") on self-efficacy and emergent interest with larger samples of printing participants over a longer period of time (Section 3).

8.5 Design Implications: Opening the Door to 3D Printing

Our results revealed that the varying guidance most newcomers require to start 3D printing can be facilitated through online applications, but that aspects like price and trust in services still played a significant role in whether newcomers *initiated* collaborations (i.e. concrete evidence of "*opening the door*"). Below we describe how online 3D printing service interfaces and processes may be informed by our design probe and our results.

8.5.1 Creating Linear Pathways for Learning

While the social media analysis and HowDIY evaluation demonstrated that many can learn from websites that offer many branching and less-formal learning pathways, the HowDIY evaluation revealed that many prefer more class-like experiences. As such, future introductory systems should have some type of optional tutorial that explains the overall website structure, and potentially offer multi-media courses that would guarantee that newcomers have the knowledge and confidence to begin utilizing printing facilities through the printing service system.

8.5.2 Exploration and Curation

Exploration was the most prioritized CSI factor, and is paramount to newcomers' understanding what can be printed. While HowDIY users generally liked being able to see a wide-variety of printable designs, many mentioned wanting more options for filtering and curation of search results. Showing the 'best' categories worked well in HowDIY, as demonstrated by the exploration factor scores in the CSI, but simple ways to select by category or filter searches could facilitate more exploration. One interviewed user mentioned writing down on paper designs he liked for when he wanted to print in a few months. Giving users affordances to collect and annotate designs could encourage more long-term use of systems like HowDIY. Recommender and Search Systems could be further informed by user collections and annotations, and potentially provide more-familiar interfaces more reminiscent of popular social media (e.g. Pinterest).

8.5.3 Empowering Greater Expression

HowDIY only presented very common avenues for 3D printing design, not providing explicit affordances for modification or customization of 3D geometries. Providing means to modify geometries in the application, similar to Thingiverse's Customizer described in Chapter 7, could encourage more prints as each person's designs would be unique. Additionally, affordances to immediately upload and modify open source designs in online CAD programs could help newcomers create novel designs and not feel as daunted by the prospect of learning CAD. This is already demonstrated by retailers (e.g. HeroForge), who combine specification and design into a fixed menu of parameters by limited the scope of what they will print. However, such meta-design applications should beware of opposite pitfalls in end-user development: 1) the "Turing Tar Pit": where everything is possible, but nothing of interest is easy, and 2) the inverse of the Turing Tar Pit: where specialized operations are easy, but little of interest is possible"[36]. Another danger is Blikstein's *Keychain Syndrome*, where newcomers may only choose to use a specialized application without learning other avenues of expression [141]. As a 3D file is not required to specify a 3D printing idea, means to express ideas through sketches, images, gestures, and other media could encourage 3D printing online. Instead of solely designing in popular CAD programs, one could craft printable 3D geometries by scanning faces to create custom masks or glasses, by tracing around an object in mixed-reality to create a custom stand or holder [212], by drawing a sketch to create a desktop ornament (Figure 6.3), or many other means of expression that do not require traditional CAD applications. Systems like HowDIY, and online retailers, could provide creative

https://HeroForge.com
https://www.3dprintingmedia.network/3d-scanning-customized-3d-printed-mask-fitter/
https://3dprint.com/228272/kite-and-layer-providing-customizable-3d-printed-eyewear/

but constrained means of crafting designs to support broader individual expression through 3D printing.

8.5.4 Encouraging Collaboration to aid in Specification

The printing service interface analysis revealed that many services only require the uploading of 3D files, with optional parameters for describing what is being printed. While a HowDIY users did use images and text, sometimes without 3D files, many were still hesitant to begin communication with services in general. The collaboration factor results in the HowDIY user CSI indicated that collaboration was consistently the lowest priority when learning 3D printing, meaning that newcomers did not value collaboration as part of the learning process. While this collaboration count is likely influenced by socio-cultural variables that are difficult to influence, there are two pathways to further encourage newcomers' co-participation with 3D printing practitioners: **1)** provide less daunting avenues to begin communication or **2)** automate elements of print-shop communication. Broader social acceptance of printing services could help make initial contact less daunting, which could be facilitated by more socially-mediated recommendations (e.g. reviews) of printing services by third parties. Additionally, facilitating printing service interactions and deliveries in popular areas could facilitate more familiarity and curiosity towards the process. Many may be shy to begin interacting with these services, so systems that could suggest actionable warning and error items similar to grammar and spelling validation systems could allow users to refine their ideas and potentially build confidence before contacting a service.

8.5.5 Initiating Successful Collaborations

Our social media analysis demonstrated that many learned about what can be printed through information sheets and consultation facilitated by online services. However, in the HowDIY design probe, there were many barriers and challenges that inhibited many from considering contacting 3D printing services. Some could not imagine printing out anything that they would find useful, so further means to help newcomers explore and express their ideas are needed. Beginning communication in-person or by email were near-universally suggested by the studied newcomers. For printing online services, motivations for collaborations included to print without judgement. For local printing services, participants wanted to learn more about printing processes and receive guidance if stuck. Many preferred printing with the guidance of personal acquaintances, if possible. The lower barrier for printing with acquaintances may be better afforded anywhere if one enthusiast is fostered per community by external training or online websites like HowDIY, empowering printing communities anywhere.

8.6 Chapter Limitations and Contributions

Our investigation of online 3D printing service interfaces revealed many underlying assumptions of how they expect users to present specifications (e.g. a 3D file and a material selections), but we did not attempt to order specifications from these services to empirically evaluate their collaboration and end-product quality. We only analyzed three social media platforms, between which were stark differences in why comments were generated, limiting our findings on how services may be utilized in populations not well-represented in these online platforms. The design-probe study only included newcomers that were recruited in an email that included the words "3D printing", meaning that many potential participants may have decided on their participation based on an existing interest or low self-efficacy towards learning 3D printing. Further research, with recruitment done more randomly, and with longer study durations may reveal more about HowDIY's effects.

This chapter's contributions are as follows:

- Presents a taxonomy of online 3D printing services visible features while specifying prints
- Presents a taxonomy of social media commenters perceptions of online printing services
- Presents the requirements and design of HowDIY, a website to introduce anyone to 3D printing practices
- Demonstrates that HowDIY can help some newcomers learn to specify how and what to print (i.e. *"opening the door"*)
- Describes remaining challenges towards designing introductory 3D printing systems

In our analysis of 3D printing service interfaces, we noticed a wealth of disparate printing resources offered through printing interfaces that often assumed the existence of refined user printing specifications. However, in the social media analysis, we observed that many leverage online resources to utilize these services, and that perceptions of printing price and quality are generally well-received but are sometimes muddled with issues surrounding designing for printing. Through the development and evaluation of a design-probe HowDIY, we explored how 3D printing service platforms may better inculcate newcomers into 3D printing communities through co-participation in print specification. HowDIY opened the door to multiple 3D printing newcomers without guaranteed human introduction, through supporting the learning and exploration of 3D printing design-spaces, affording access to printing anywhere. While the design-probe did not reveal any new major issues with printing online, it helped strengthen the requirements for supporting newcomers to print anything online, presented in a meta-design framework in the next chapter.

9. SUMMARY OF CONTRIBUTIONS AND FUTURE WORK

The research presented in this dissertation established barriers, challenges, and means to open the door to 3D printing co-participation to anyone, anywhere. However, there are several challenges that still remain to supporting anyone to print anywhere without requiring broad technical knowledge about 3D printing processes. Namely, specifying what to print and what can be printed (e.g. *printability*) is a non-trivial meta-design task. While we identified barriers and challenges to 3D printing in our studies, there are likely many that we were not able to identify and many that may be more specific to certain demographics or applications.

This echos themes from research in *Meta-Design*, which demonstrates how end-users consume and learn to develop digital artifacts through *Cultures of Participation* that shift creation by large contributions from few users to small contributions by many users [213, 35, 36]. We investigate how meta-design systems relate not only to the development of digital artifacts, but their subsequent fabrication. Through Fischer and Giaccardi's meta-design framework [36], we argue that existing meta-design systems for 3D file generation and fabrication should be situated in overall printing process, as end-users may not easily find associated tools without guidance from humans or intelligent systems (e.g Chapter 6).

The creation of accessible technologies does not guarantee their adoption into everyday lives and practices. Adoption, instead, is incremental, manifesting through changes in social organizations and human behavior as technologies become more embedded and situated in everyday life and practices [36, 35, 11]. This does not mean transferring the responsibility of design to the end-user, but to enable domain experts to support their practices through design [214]. Meta-design supports a dialogue between end-users, meta-designers, and technological artifacts so that all move beyond their original states [36]. In this chapter, we consider 'design' to include both the dialogue for creating 3D designs and the dialogue for fabricating these designs, with their inter-dependencies. Meta-Design systems, like HowDIY demonstrated in Chapter 8, can broaden

This chapter was completed with feedback from Francis Quek and Jeeeun Kim

participation in 3D printing and inform the co-evolution between design-tools and end-user behaviors by "*opening the door*" to 3D printing facilities and co-participation.

Printing Platforms / *Levels of Meta-Design*	**Proximal Printing Collaborations**	**Online Printing Services**	**HowDIY Meta-Design Platform**	**Concurrent End-User Problems**
1) Designing Design • What can be Printed • Launching Point	• Reuse and Remix Designs • Metamodels • Initial Specification	• Instant Price, Time, & Printability Estimation • Metamodels with Validated Fab. Config.	• Guides & Recommends Designs to Fabricate • Embeds Design & Fab. Instructions with Designs	*anticipation*
2) Designing Together • Collaboration • Evaluate Printability	• Printing Facilities • Tools to Facilitate Negotiation & Collaboration	• Formalized Choices • Open-Ended Text • Printability Verified by practitioners	• Grants awareness of online consultation • Scaffolds Initial Specifications	*participation*
3) Designing the "In-Between" • Sustain Practices • Tools & Users Co-Evolve	• Printer-Specific Shared Resources • Design- & Practice-Sharing Media	• Share Configurations and orders • Communal Resources & Processes -> Trust	• Situates 3DP Resources in Printing Processes • Locates Relevant Social Media	*socio-technical*
Barriers to 3D Printing Collaborations (greater to lesser)	*Access to Mentor Printing Practitioners* >	*Awareness of Printing Configurations and Online Consultation* >	*Confidence & Resources to Begin Collaboration*	

Figure 9.1: Each level of meta-design (**rows**) corresponds to technologies that may support broader participation in 3D printing by addressing different end-user problems. Each **column** from left to right represents further abstraction of 3D printing processes, supporting creation of digital-designs and physical-fabrications with fewer barriers imposed by location, social-capital, or education.

9.1 Future Work: The Three Levels of 3D Printing Meta-Design

End-users may face many challenges to begin 3D printing processes (Chapter 6), while engaging in 3D printing processes [23], and end-products may not always match their expectations [37, 90]. Evolution of meta-design systems shift focus from *"large efforts of a small number of people"* towards *"small contributions of a large number of people"* [36] in cultures of participation. Effective meta-design can facilitate users progression from passive consumers of designed technologies towards well-informed users and effective meta-designers, informing meta-design tools in the process [213]. Fischer and Giaccardi outline how meta-design encompasses three levels of design: **1)** Designing Design, **2)** Designing Together, and **3)** Designing the "*in-between*" [36]. The first level serves to help end-users establish the necessary conditions for successful design, helping approach the challenging task of fully anticipating end-users' *needs and tasks* at design-time. The second level supports how designers and users may *collaborate* on design activities, both at use time and design time, to address unresolved discrepancies between design-intent and the resulting design with respect to the aforementioned needs and tasks. The third level aims to support or create social networks to foster participation with design technologies, facilitating embodied sensing, emotioning, and "affective" activities.

The previously presented research may reveal how online and proximal printing processes may be situated within this framework, shown in Figure 9.1, to incrementally broaden potential participation in 3D Printing practices. We demonstrated the potential of situated meta-design systems with HowDIY, a website that introduces diverse end-users to various 3D printing practices by supporting their specification process. Below, we describe how many existing and future technologies may be situated within a meta-design framework to aid newcomers specify objects to fabricate, empowering anyone to fabricate anything from anywhere.

9.1.1 Designing Design: Imagining and Planning What to Print

Designing Design for 3D printing entails how people design or reuse designs to fabricate, which does not require utilizing traditional CAD applications. Many barriers exist to 3D printing even before interacting with any printing programs, machines, or facilities. Chapter 6 outline workflows and challenges towards specifying 3D printing ideas in formal collaborations with 3D printing services that insulate clients from many technical details of machine operation and maintenance. In chapter 8 we investigate similar workflows for 3D printing via services, shown in Figure 8.2, to support anyone to participate with 3D printing without requiring that all end-users participate with CAD programs and printing machinery. This allows us to present 3D printing meta-design challenges that emerge irrespective or particular programs or hardware.

Reuse and Remixing: Many in 3D printing print existing designs or modify them to make printing more expressive, more expedient, or more accessible [28]. In this process, end-users download designs from 3D printing file-sharing platforms like Thingiverse to modify them before printing [78]. Similarly, 3D scans of objects can be utilized in this remix process [212]. Various

3D file search and retrieval systems may be employed to facilitate reuse of these designs [215, 216, 217, 218, 1], informed and situated in end-users' environments [156, 219].

Metamodels: Previous research demonstrated how meta-design may apply to the digital-design of printable objects, where derivatives of metamodels can be designed by specifying simple parameters (e.g. text and size) to generate a 3D file that matches a pre-coded template (i.e. the metamodel) [220, 53]. When Thingiverse added the Customizer tool, which supported the sharing of metamodels and consequent design-generation, the number of users on the platform rapidly increased [78]. Metamodels can broaden participation in 3D design, but alone may not be enough to facilitate broader participation with 3D printing [31, 141].

Specifications: Design and Printing services, from designers-for-hire to crowd-sourced designs, require that end-users specify what they wish to print [32]. However, end-users expectations of what to print are dependant on their previous exposure to real 3D printing processes (e.g. Chapter 6, [93]). It is important to consider that the end-product is more than just geometry, but has material qualities dependent on the printing configuration [37]. Additionally, capturing accurate measurements for a particular specification may often be challenging without assistance or training [54]. Regardless of material, newcomers to 3D printing have been shown to value their participation in the printing process [93]. However, participation in printing processes is not trivial as design-intent is often not conveyed in 3D file formats [92], and there are often miscommunications conveying design-intent to others [5]. Designing Design supports end-users specification of design-intent, which is necessary for communication within *any* 3D printing process.

9.1.2 Designing Together: Collaboratively Developing Print Specifications

Designing Together involves collaboration between end-users and others to refactor and refine their ideas until they become printable. Evaluating printability of an idea involves broader embodied and collective sense-making tasks [9]. Certain designs may only be printable on certain machines, with certain materials, and with certain practitioners. *Designing Together* entails helping people find the needed expertise and facilities to print, and then facilitating the needed collaborations and negotiations to refactor how and what to print.

Facilities: What is printable depends on the available tools and expertise available. Based on initial specifications, initial facilities should be recommended to end-users, as newcomers often have difficulty accessing printing facilities on their own [5, 23]. As many newcomers may be shy to interact with experienced printing practitioners [156, 219, 23], any meta-design system should help encourage and initiate collaboration.

Communication: Chapter 6 investigates barriers and challenges to 3D printing service collaborations. Some communication is necessary as printing practitioners may often mistake aspects of end-users design intent when collaboratively printing a given design [21]. Communication may be in-person or remote (e.g. email or web-chat), even situated in 3D printing practices like CAD procedures [48, 27].

Verification: Similar to how a compiler gives a designer feedback in the form of warnings or errors, meta-design systems should guide end-users around common mistakes and help them navigate trade-offs within their design and their chosen printing configuration [197]. This could be provided via human-human consultation, but may also be facilitate by intelligent assistants and crowd-sourced social media [32, 221]. Similar to how programmers may utilize Stack Overflow to ask questions and find answers, future 3D printing meta-design media may help users verify their designs and printing configurations [189].

9.1.3 Designing the In-Between: Validation and Sharing of Printing Practices

Designing the In-Between entails how end-users may share their experiences with the world. We focus on how printing tools, social media, and online printing services can serve as the *in-between*.

Tools: Ludwig et al. investigated how people operating 3D printers may share aspects of their practice by sharing logs on Twitter collected by various sensors integrated into a 3D printer [90]. Presently, there are not standard for defining printing capabilities (e.g. a Resource Description Language [195]) or sharing logs [194]. Standardizing similar log-collection and -sharing software in printers may help foster a Internet of Practices where operators can better share every detail of how they appropriated their machinery [90], but this is not the only step of the printing process.

Validation: End-users need to be able to evaluate and contribute opinions relating to collective trust towards particular printing facilities, tools, and processes. Transparency, the ability to gain knowledge of why people performed actions and why certain tools were utilized in a practice [10], is necessary at each step of the process to help people become printing practitioners. End-Users sharing successful prints, and engaging documentation of how the print was successfully made, may help facilitate printing practices. Also, intelligent interfaces that help people find designs and processes relevant to end-users' interests may help anyone find the appropriate shared documentation. For example, one could capture images of a 3D print or similar real-world objects to find relevant 3D designs, how they were made, and how they could quickly fabricate copies through a service. As present Thingiverse-users gain insight into design creation and functionality [27], future meta-design systems could help crowd-source annotations, answer questions relating to particular design-ideas, and inform verification systems as found in some online printing service interfaces (e.g. Table 8.1).

9.2 Broadening Participation in 3D Printing through Meta-Design

Meta-Design systems, integrated into printing hardware and software, can broaden participation in 3D printing by helping end-users specify printable ideas. While initial meta-design systems may help facilitate more human collaborations, future systems could utilize data from these human-interactions to bootstrap the design and implementation of intelligent specification-assistants. These specification assistants could help guide newcomers to modifiable designs, help them communicate design-intent, and help them address various trade-offs between printing processes. These intelligent assistants will need to leverage the "in-between", which presently exists on websites like Thingiverse and related social media (e.g. Chapters 7 and 8) , either extracting answers or guiding end-users to these social learning resources. Regardless, all levels of printing meta-design require linking to this in-between where users can learn from each other and are encouraged to share their printing experiences with various communities.

Over time, Intelligent Specification Assistants could better learn how steps and nuances of printing processes relate to various online resources. Then, these Intelligent Assistants could better aid services in speedy consultation, and determine what user file-specifications relate to particular action items, aiding newcomers' learning of concepts before seeking costly human-consultation. Analysis of specifications and resulting consultations could also inform what features printing services and 3D printing technology developers add to their respective repertoires, iteratively improving newcomers' interactions with 3D printing technologies. 3D Printing Intelligent Assistants, informed by service-facilitated interaction data in concert with online resources and users' environments, could broaden participation with any 3D printing process through an egalitarian democratization of innovation through semi-automated consultation of print-specifications. Intelligent assistants could support learning technical details of 3D printing hardware and software within end-users' ZPD, facilitating more community-oriented fabrication projects and consequent studies (Chapters 3 and 4). Similar to how people today shop through online retailers, additive manufacturing technologies and processes may affordably blend into the background with Intelligent Assistants, so that future manufacturers can directly sell their services to the general population by supporting anyone to fabricate anything from anywhere.

9.3 Conclusion

The research presented in this dissertation focuses on how to support newcomers to online digital fabrication practices (e.g. 3D printing) by helping start initial proximal (e.g. local shops) or distal (e.g. online) collaborations with fabrication practitioners. We demonstrated that service-like printing processes can help students develop interest in printing while expressing science concepts similar to how they normally use craft-materials, an approach that has been adopted by Stanford during the COVID-19 pandemic. Through both observational and lab studies, we gained an empirical understanding of barriers and challenges anyone may face before starting their first 3D printed project, extending existing HCI literature [23, 27]. We also analyzed how newcomers to 3D printing perceive material qualities of 3D prints versus mass-manufactured products, helping establish further understanding on how newcomers would describe 3D prints and why they would 3D print. We analyzed how many may learn to print through online printing communities, online printing

https://www.sandia.gov/news/publications/labnews/articles/2020/07-17/Stanford$_3D.html$

services, and demonstrated with HowDIY how to open the door to co-participation in 3D printing practices. Through systems like HowDIY, populations traditionally isolated from printing practitioners may gain entry into digital fabrication processes by utilizing online resources and services, encapsulating knowledge of what can be printed while minimizing knowledge of how to identify and operate various machines. Those who gain entry may help facilitate communities surrounding their interests and location, further empowering broader participation in digital fabrication processes (e.g. Chapter 4). This broader participation, in turn, can help inform future printing technologies to help newcomers convert their expressive specifications into physical artifacts.

9.4 Summary of Contributions

This section summarizes the main research findings with regard to supporting anyone to specify 3D printing designs. In addition to contributions listed in each chapter after Chapter 3, we summarize the main contributions below.

- We demonstrate that learning to express ideas through technology can be sustained by peer interactions, even within formal education settings where only online technologist mentorship is available (Chapter 4).

- We demonstrate how interest in 3D printing may be developed through participation in processes emulating clients' roles in fabrication services (Chapter 5).

- We establish unexplored empirical barriers and challenges that anyone may encounter when first learning to 3D print, before interacting with people or machines situated within printing facilities. (Chapter 6).

- We distribute a unique dataset for exploring and facilitating 3D printing design reuse, and demonstrated uses of this dataset with statistical and machine learning methodologies (Chapter 7).

- We demonstrate how online 3D printing services may be situated within broader online sense-making processes through the HowDIY design probe, highlighting how it can help newcomers gain introductory knowledge of how and what to print (Chapter 8).

- We provide a meta-design framework to ground research investigating how end-users may 3D print. This framework can be utilized with any printing process, including co-participation with online services that may empower anyone to print from anywhere (Chapter 9).

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APPENDIX A

LIST OF PUBLICATIONS

- Berman, Alexander, Ketan Thakare, Josh Howell, Francis Quek, Jeeeun Kim. "HowDIY: Introducing Anyone to 3D Printing Services through Online Computational Tools". IUI 2021, ACM (to be submitted)
- Berman, Alexander and Quek, Francis. "ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse". IEEE BigMM 2020 (**Best Paper Candidate**)
- Berman, Alexander, Osazuwa Okundaye, Francis Quek, Jay Woodward, Jeeeun Kim. "Anyone Can Print": Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication". NordiCHI 2020, ACM.
- Osazuwa, Okundaye,Sharon Chu, Francis Quek, Alexander Berman, Glen Hordemann, Larry Powell, Leming Yang. "Investigating Telepresence Robotics for Supporting Hands-on Distance Instruction". NordiCHI 2020, ACM.
- Natarajarathinam, Malini, et al. "Making in The Colonias: Motivating STEM Participation through a Making as Micro-Manufacturing Model". 127th Annual Conference for the American Society for Engineering Education (ASEE). 2020 (poster)
- Berman, Alexander and Paul, Celeste. "Making Sense of Darknet Markets: Automatic Inference of Semantic Classifications from Unconventional Multimedia Datasets". HCII, Springer. 2019. (**Best Paper Award**)
- Nam, Beth, Alexander Berman, Brittany Garcia, Sharon Chu. "Towards the Meaningful 3D-Printed Object: Understanding the Materiality of 3D Prints". HCII, ACM. 2019 (poster)

- Berman, Alexander, Sharon Chu, Francis Quek, Osazuwa Okundaye, Leming Yang, Beth Deuermeyer, Enrique Berrios, Skylar Deady, and Jessica Doss. “Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools”. Fablearn 2019, ACM. NY, NY. 2019

- Natarajarathinam, Malini, et al. “Developing Communities of Practice through Peer Mentorship in Making through Micro Manufacturing Model”. 126th Annual Conference for the American Society for Engineering Education (ASEE). 2019

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- Okundaye, Osazuwa, Sharon Chu, Francis Quek, Alexander Berman, Malini Natarajarathinam, Matthew Kuttolamadom. “Making to Micro-Manufacture: Catalyzing STEM Participation in Rural High Schools”. Fablean Europe, ACM. 2018.

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- Chu, Sharon Lynn, Elizabeth Deuermeyer, Rachel Martin, Francis Quek, Alexander Berman, Mario Suarez, Niloofar Zarei, Beth Name, and Colin Banigan. "Becoming Makers: Examining Making Literacy in the Elementary School Science Classroom." Proceedings of the 2017 Conference on Interaction Design and Children. ACM, 2017.

- Berman, Alexander, Brittany Garcia, Beth Nam, Sharon Chu, Francis Quek. "Toward a Making Community of Practice: The Social Aspects of Elementary Classroom-Based Making." Proceedings of the 6th Annual Conference on Creativity and Fabrication in Education. ACM, 2016.

APPENDIX B

OBSERVATION RUBRIC FOR CHAPTER 6 ETHNOGRAPHY

Observation Rubric

Concept	Description	Key Details
Initiation	How the user presents their problem to the practitioner	•Familiarity with operator/space •Familiarity with 3D Printing •Familiarity with practice desired object will be used within
Translation	How the operator interprets the initial presented problem	•Is this agreed upon immediately? •What discrepancies occur? •Do operators have any common biases or paths they steer customers? •Familiarity with particular customer
Negotiating and Compromising	How the two parties resolve any discrepancies in desired task for operator	•Did the customer have to change their idea? Why? •How did the operator initially misinterpret the user's intentions, and how was this resolved by the operator?
Recommendations/Examples	Did either party point to existing prints/processes while negotiating the desired outcome?	•What type of example was given? Physical, Digital, or Purely Spoken? •Where did the presenting person find the example originally? •Why was the example given with respect to the desired outcome?
Breakdowns	Did either party give up during some aspects of negotiation?	•Where did the breakdown occur? •Why did it occur? •What situated aspects of the space or the people involved led to this breakdown?
Final Result	How satisfied/interested were customers after ordering?	•Complaints/Compliments •Curiosity Questions •Indications of Future Orders

APPENDIX C

INTRODUCTORY QUESTIONNAIRE FROM CHAPTER 6 LAB STUDY

Please answer the following Questions:

Age? ______________________

Gender? ___________________

Education (select the highest that you have completed):
□ No Highschool Degree
□ Highschool Degree / GED
□ 4-year college (Baccalaureate)
□ Master's Degree
□ Doctoral Degree

Major(s) (if applicable) -____

Ethnicity/Race?
□ Indian/Alaskan
□ Asian
□ Black
□ Hispanic/Latino
□ Hawaiian/Pacific Islander
□ White
□ Unknown
□ Other ____________________________

If you are employed, what is your job description?

How experienced are you with Computer-Aided Design (CAD)?
□ No Experience □ Little Experience □ Moderate Experience □ Working Experience □ Expert

Which CAD programs (if applicable)? ____

How often have you seen 3D printers?
□ Never □ Once or Twice ever □ Once a year □ Once a Month □ Once a Week □ Once a day

What have you seen being 3D Printed? ____

How many friends or family members do you know work with 3D Printers? _________________

How many of these people have shown you products of their 3D Printing? _________________

Short Response Questions:

How often do you search for things on the internet? What do you typically search for?

What device(s) do you typically search on?

Which websites do you typically visit when searching for new information?

Do you ever find information that is relevant to your search, but was not what you were searching for? If so, please list examples of what you were searching for and which site you learned the new information.

Do you do many projects that involve designing physical items? If so, what?

Do you use internet websites to aid in the design of these items? If so, how and which sites?

What are the largest challenges when designing these items?

APPENDIX D

FOLLOWUP QUESTIONNAIRE FROM CHAPTER 6 LAB STUDY

Short Response Questions:

Have you participated in 3D printing activities since the study? If so, please describe where and what the activities were.

Have you seen 3D printing activities since the study? What did you see and where did you see it?

Have you seen items created via 3D printing since the study? What did you see and where did you see it?

Have you seen 3D printing-related media since the study? What did you see and where did you see it?

Have you asked anyone for 3D printing-related help or information since the study? Who did you ask, what help did you receive, was the help useful, and why?

Have you searched online for 3D printing-related help or information since the study? How did you search, where did you look, what did you find, was it useful, and why?

List some examples of what 3D printing can accomplish:

What is your experience with 3D printing?

How could you imagine utilizing 3D printing?

What steps are involved in 3D printing?

How would you obtain a 3D file to print?

Where would you look for ways to create, download, or modify 3D files for printing?
Which websites do you imagine visiting?

(if computer-mentor case) Would you use the application from the study? If so, why and how?

Are there any other comments you would like to make regarding your experiences with 3D Printing and/or finding information online?

Check one item per row: (https://journals.sagepub.com/doi/pdf/10.1177/0013164409355699)

	Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree or Disagree	Somewhat Agree	Agree	Strongly Agree
How to find information online is practical for me to know							
Finding information online can help me in my daily life outside of work or school							
It is important for me to be a person who can find information online							
Thinking about how to find information online is an important part of who I am							
I enjoy the practice of finding information online							
I like the idea of finding information online							
I enjoy finding information online							
Finding information online is exciting to me							

	Strongly Disagree	Disagree	Somewhat Disagree	Neither Agree or Disagree	Somewhat Agree	Agree	Strongly Agree
3D Printing is practical for me to know							
3D Printing can help me in my daily life outside of work or school							
It is important for me to be a person who can 3D print							
Thinking about 3D printing is an important part of who I am							
I enjoy the practice of 3D printing							
I like 3D printing							
I enjoy doing 3D printing							
3D printing is exciting to me							

(http://www.uky.edu/~eushe2/BanduraPubs/BanduraGuide2006.pdf)

Rate your degree of confidence for each item by recording a number from 0 to 100 using the scale given below:

0	10	20	30	40	50	60	70	80	90	100
Cannot do at all					Moderately can do					Highly certain can do

Self-Efficacy in Enlisting Social Resources for 3D Printing

____ Get someone near me to help me when I get stuck on a 3D printing problem
____ Get someone *not* near me to help me when I get stuck on a 3D printing problem
____ Get help when stuck on a 3D printing problem
____ Find websites to receive help online when stuck on a 3D printing problem
____ Get help online when stuck on a 3D printing problem
____ Remember 3D printing information given by people nearby
____ Remember 3D printing information given by people online
____ Remember 3D printing information found online

Self-Efficacy for 3D Printing Creative Processes

____ Identify a problem that 3D printing can solve
____ Identify a problem that you can solve with 3D printing
____ Present a problem solvable with 3D printing to receive useful help
____ Find useful information to help make ideas for a 3D printing project
____ Find useful information to help narrow and refine ideas for a 3D printing project
____ Think of an interesting idea for a 3D printing project
____ Think of a feasible idea for a 3D printing project
____ Improving on my best ideas for a 3D printing project
____ Selecting and integrating the best ideas into the result of the 3D printing project

Self-Efficacy for 3D Printing Achievement

____ Finish a 3D printing project on my own
____ Finish a 3D printing project with help of someone nearby with experience in 3D printing
____ Finish a 3D printing project with guidance on where to look online
____ Plan the steps needed to complete a 3D printing project
____ Organize information and ideas for my 3D printing project
____ Successfully print your ideas on a 3D printer that someone else maintains and runs
____ Successfully print your ideas on a 3D printer that you maintain and run
____ Afford the resources necessary to order 3D prints from a service
____ Afford the resources necessary to maintain and run a 3D printer
____ Successfully utilize 3D printing in your school or work
____ Successfully utilize 3D printing in your recreational activities
____ Effectively explain 3D printing solutions to others in person
____ Effectively explain 3D printing solutions to others online

Check one item per row: (http://rerank-lab.org/papers/yamamotoCIKM2018explore.pdf)

	None of it	Almost None of It	Some of It	Almost All of It	All of It
How much of the information available on the Web do you think is believable?					
How believable do you feel is the information on the Web?					

	Not likely to believe it	Not likely to believe it	Somewhat likely to believe it	Likely to believe it	Very likely to believe it
How likely are you to believe the information contained in the web pages returned by a Web search engine?					
How likely are you to believe the high-ranked (approx. 1st-5th) search results returned by a Web search engine?					
How likely are you to believe the lower-ranked (approx. 5th-10th) search results returned by a Web search engine?					
How likely are you to believe news you find on the Web?					
How likely are you to believe the information about entertainment such as sports, celebrity, or hobbies you find on the Web?					
How likely are you to believe the information about health or disease you find on the Web?					
How likely are you to believe the information about health or disease you find on the Web?					
How likely are you to believe the information about factoids you find on the Web?					
How likely are you to believe the information about education you find on the Web?					
How likely are you to believe the information about shopping you find on the Web?					
How likely are you to believe the information about recreation such as travel you find on the Web?					
How likely are you to believe the information shared by other online friends?					

	Never	Almost Never	Somewhat Frequently	Very Frequently	Almost Always
I try to check whether the information on the page is up-to-date.					
I try to check whether the information on the page is complete and comprehensive.					
I try evaluating whether the views represented on the page are facts or opinions.					
I try to consider the author's goals/objectives in posting information on the page.					
I try to identify the author of the page.					
I try to look for a stamp of approval or recommendation from third parties on the Web page.					
I try to check whether the author's contact information is provided.					
I try to verify the author's qualifications or credentials on the page.					
I try to click multiple Web pages when using a search engine.					
I try to browse both lower- and higher-ranked search results					
I try to click search results in which I can easily identify the author of the page, such as an official site of a company.					
I try to check the domains of search results before clicking them.					
I try to issue multiple queries in general.					
I try to use a search tool to filter recently updated Web pages .					
I try to spend as much time as possible on Web searches.					

	Strongly Disagree	Somewhat Disagree	Neither Agree or Disagree	Somewhat Agree	Strongly Agree
Thinking is not my idea of fun.					
I try to anticipate and avoid situations in which I might be required to think in depth about something.					
I would rather do something that requires little thought than something that is sure to challenge my thinking abilities.					
I would prefer complex to simple problems.					
I find little satisfaction in deliberating hard and for long hours.					
I trust my initial feelings about people.					
I believe in trusting my hunches.					
My initial impressions of people are almost always right.					
When it comes to trusting people, I can usually rely on my "gut feelings."					
I can usually feel when a person is right or wrong even if I cannot explain how I know it.					
Most people are trustworthy.					
Most people will respond in kind when they are trusted by others.					
Most people are trustful of others.					
Most people are basically honest.					
I am trustful.					
Most people are basically good and kind.					

APPENDIX E

QUESTIONNAIRE FROM CHAPTER 9 HOWDIY STUDY WITHOUT SUS AND CSI

Please answer the following Questions:

Age? ______________________

Gender? ___________________

Education (select the highest that you have **completed**):
□ No Highschool Degree
□ Highschool Degree / GED
□ 4-year college (Baccalaureate)
□ Master's Degree
□ Doctoral Degree

Major(s) (if applicable) -____

Ethnicity/Race?
□ Indian/Alaskan
□ Asian
□ Black
□ Hispanic/Latino
□ Hawaiian/Pacific Islander
□ White
□ Unknown
□ Other ____________________________

If you are employed, what is your job description?

____

How experienced are you with Computer-Aided Design (CAD)?
□ No Experience □ Little Experience □ Moderate Experience □ Working Experience □ Expert

Which CAD programs (if applicable)? ____

How often have you seen 3D printers?
□ Never □ Once or Twice ever □ Once a year □ Once a Month □ Once a Week □ Once a day

What have you seen being 3D Printed? ____

How many friends or family members do you know work with 3D Printers? ________________

How many of these people have shown you products of their 3D Printing? ________________

Short Response Questions:

Which websites do you typically visit when searching for new information? On which devices?

Do you ever find information that is relevant to your search, but was not explicitly what you were searching for? If so, please list examples of what you were searching for and which site you learned the new information.

Do you do many projects that involve designing physical items? If so, what?

Do you use internet websites to aid in the design of these items? If so, how and which sites?

What are the largest challenges when designing these items?

What are the steps needed to 3D print?

List some examples of what 3D printing can accomplish:

How could you imagine utilizing 3D printing?

How would you obtain a 3D file to print?

Would you download and print designs from online **without** modification? Why or Why not?

Would you print designs you downloaded from online after some **modification**? Why or Why not?

Would you print designs that you **designed from the ground-up?** Why or Why not?

Are there any other comments you would like to make regarding your experiences with 3D Printing and/or finding information online?

Check one item per row:

	Strongly Disagree	Disagree	Somewhat Disagree	Somewhat Agree	Agree	Strongly Agree
How to find information online is practical for me to know						
Finding information online can help me in my daily life outside of work or school						
It is important for me to be a person who can find information online						
Thinking about how to find information online is an important part of who I am						
I enjoy the practice of finding information online						
I like the idea of finding information online						
I enjoy finding information online						
Finding information online is exciting to me						

	Strongly Disagree	Disagree	Somewhat Disagree	Somewhat Agree	Agree	Strongly Agree
3D Printing is practical for me to know						
3D Printing can help me in my daily life outside of work or school						
It is important for me to be a person who can 3D print						
Thinking about 3D printing is an important part of who I am						
I enjoy the practice of 3D printing						
I like 3D printing						
I enjoy doing 3D printing						
3D printing is exciting to me						

Check one item per row:

	Cannot do at all	Mostly certain cannot do	Mostly certain can do	Highly certain can do
Get someone near me to help me when I get stuck on a 3D printing problem				
Get someone *not* near me to help me when I get stuck on a 3D printing problem				
Get help when stuck on a 3D printing problem				
Find websites to receive help online when stuck on a 3D printing problem				
Get help online when stuck on a 3D printing problem				
Remember 3D printing information given by people nearby				
Remember 3D printing information given by people online				
Remember 3D printing information found online				

	Cannot do at all	Mostly certain cannot do	Mostly certain can do	Highly certain can do
Identify a problem that 3D printing can solve				
Identify a problem that you can solve with 3D printing				
Present a problem solvable with 3D printing to receive useful help				
Find useful information to help make ideas for a 3D printing project				
Think of an interesting idea for a 3D printing project				
Think of a feasible idea for a 3D printing project				
Improving on my best ideas for a 3D printing project				
Selecting and integrating the best ideas into the result of the 3D printing project				

	Cannot do at all	Mostly certain cannot do	Mostly certain can do	Highly certain can do
Finish a 3D printing project on my own				
Finish a 3D printing project with help of someone nearby with experience in 3D printing				
Finish a 3D printing project with guidance on where to look online				
Plan the steps needed to complete a 3D printing project				
Organize information and ideas for my 3D printing project				
Successfully print your ideas on a 3D printer that someone else maintains and runs				
Successfully print your ideas on a 3D printer that you maintain and run				
Afford the resources necessary to order 3D prints from a service				
Afford the resources necessary to maintain and run a 3D printer				
Successfully utilize 3D printing in your school or work				
Successfully utilize 3D printing in your school or work				
Successfully utilize 3D printing in your recreational activities				
Effectively explain 3D printing solutions to others in person				
Effectively explain 3D printing solutions to others online				

Check one item per row:

	None of it	Almost None of It	Some of It	Almost All of It	All of It
How much of the information available on the Web do you think is believable?					
How believable do you feel is the information on the Web?					

	Not at all likely to believe it	Likely to not believe it	Likely to believe it	Very likely to believe it
How likely are you to believe the information contained in the web pages returned by a Web search engine?				
How likely are you to believe the high-ranked (approx. 1st-5th) search results returned by a Web search engine?				
How likely are you to believe the lower-ranked (approx. 5th-10th) search results returned by a Web search engine?				
How likely are you to believe news you find on the Web?				
How likely are you to believe the information about entertainment such as sports, celebrity, or hobbies you find on the Web?				
How likely are you to believe the information about health or disease you find on the Web?				
How likely are you to believe the information about health or disease you find on the Web?				
How likely are you to believe the information about factoids you find on the Web?				
How likely are you to believe the information about education you find on the Web?				
How likely are you to believe the information about shopping you find on the Web?				
How likely are you to believe the information about recreation such as travel you find on the Web?				
How likely are you to believe the information shared by other online friends?				

	Never	Infrequently	Frequently	Always
I try to check whether the information on the page is up-to-date.				
I try to check whether the information on the page is complete and comprehensive.				
I try evaluating whether the views represented on the page are facts or opinions.				
I try to consider the author's goals/objectives in posting information on the page.				
I try to identify the author of the page.				
I try to look for a stamp of approval or recommendation from third parties on the Web page.				
I try to check whether the author's contact information is provided.				
I try to verify the author's qualifications or credentials on the page.				
I try to click multiple Web pages when using a search engine.				
I try to browse both lower- and higher-ranked search results				
I try to click search results in which I can easily identify the author of the page, such as an official site of a company.				
I try to check the domains of search results before clicking them.				
I try to issue multiple queries in general.				
I try to use a search tool to filter recently updated Web pages .				
I try to spend as much time as possible on Web searches.				

	Strongly Disagree	Somewhat Disagree	Somewhat Agree	Strongly Agree
Thinking is not my idea of fun.				
I try to anticipate and avoid situations in which I might be required to think in depth about something.				
I would rather do something that requires little thought than something that is sure to challenge my thinking abilities.				
I would prefer complex to simple problems.				
I find little satisfaction in deliberating hard and for long hours.				
I trust my initial feelings about people.				
I believe in trusting my hunches.				
My initial impressions of people are almost always right.				
When it comes to trusting people, I can usually rely on my "gut feelings."				
I can usually feel when a person is right or wrong even if I cannot explain how I know it.				
Most people are trustworthy.				
Most people will respond in kind when they are trusted by others.				
Most people are trustful of others.				
Most people are basically honest.				
I am trustful.				
Most people are basically good and kind.				

APPENDIX F

AUTHOR PUBLICATIONS AT THE TIME OF DEFENSE

F.1 Publications included in Dissertation with Permission

- Berman, Alexander and Quek, Francis. “ThingiPano: A Large-Scale Dataset of 3D Printing Metadata, Images, and Panoramic Renderings for Exploring Design Reuse”. IEEE BigMM 2020 **(Best Student Paper)**

- Berman, Alexander, Osazuwa Okundaye, Francis Quek, Jay Woodward, Jeeeun Kim. “Anyone Can Print”: Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication”. NordiCHI 2020, ACM.

- Berman, Alexander, Sharon Chu, Francis Quek, Osazuwa Okundaye, Leming Yang, Beth Deuermeyer, Enrique Berrios, Skylar Deady, and Jessica Doss. “Proximal and Distal Mentors: Sustaining Making-Expertise in Rural Schools”. Fablearn 2019, ACM. NY, NY. 2019

- Berman, Alexander, Elizabeth Deuermeyer, Beth Name, Sharon Chu, Francis Quek. “Exploring the 3D Printing Process for Young Children in Curriculum-Aligned Making in the Classroom”. IDC, ACM. 2018. **(poster)**

- Berman, Alexander, Brittany Garcia, Beth Nam, Sharon Chu, Francis Quek. "Toward a Making Community of Practice: The Social Aspects of Elementary Classroom-Based Making." Proceedings of the 6th Annual Conference on Creativity and Fabrication in Education. ACM, 2016.

F.2 Publications Not Included in Dissertation

- Osazuwa, Okundaye,Sharon Chu, Francis Quek, Alexander Berman, Glen Hordemann, Larry Powell, Leming Yang. “Investigating Telepresence Robotics for Supporting Hands-on Distance Instruction”. NordiCHI 2020, ACM.

- Natarajarathinam, Malini, et al. “Making in The Colonias: Motivating STEM Participation through a Making as Micro-Manufacturing Model”. 127th Annual Conference for the American Society for Engineering Education (ASEE). 2020 **(poster)**

- Berman, Alexander and Paul, Celeste. “Making Sense of Darknet Markets: Automatic Inference of Semantic Classifications from Unconventional Multimedia Datasets”. HCII, Springer. 2019. **(Best Paper Award)**

- Nam, Beth, Alexander Berman, Brittany Garcia, Sharon Chu. “Towards the Meaningful 3D-Printed Object: Understanding the Materiality of 3D Prints”. HCII, ACM. 2019 **(poster)**

- Natarajarathinam, Malini, et al. “Developing Communities of Practice through Peer Mentorship in Making through Micro Manufacturing Model”. 126th Annual Conference for the American Society for Engineering Education (ASEE). 2019

- Okundaye, Osazuwa, Sharon Chu, Francis Quek, Alexander Berman, Malini Natarajarathinam, Matthew Kuttolamadom. “Making to Micro-Manufacture: Catalyzing STEM Participation in Rural High Schools”. Fablean Europe, ACM. 2018.

- Berman, Alexander, Leela Krishna Chaitanya Gottumukkala, Zepeng Huo, Seth Posley, Francis Quek, and Tracy Hammond. "iCanTrace: Avatar Personalization through Selfie Sketches." WIPTTE. 2017 (poster)

- Chu, Sharon Lynn, Francis Quek, Sourabh Bhangaonkar, and Alexander Berman. "Physical Making Online: A Study of Children’s Maker Websites." Proceedings of the 7th Annual Conference on Creativity and Fabrication in Education. ACM, 2017.

- Chu, Sharon Lynn, Elizabeth Deuermeyer, Rachel Martin, Francis Quek, Alexander Berman, Mario Suarez, Niloofar Zarei, Beth Name, and Colin Banigan. "Becoming Makers: Examining Making Literacy in the Elementary School Science Classroom." Proceedings of the 2017 Conference on Interaction Design and Children. ACM, 2017.