

Understanding and Supporting Newcomers to 3D Modelling and Digital Fabrication

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Material, ideas, figures, and tables from this dissertation have appeared previously in the following peer-reviewed publications. The following list show long papers and short papers. After each paper, the chapters from which the material is used are noted.

Celena Alcock, Nathaniel Hudson, and Parmit K. Chilana. 2016. Barriers to Using, Customizing, and Printing 3D Designs on Thingiverse. In *Proceedings of the ACM Conference on Supporting Groupwork (GROUP '16)*. (Chapters 1, 2, 4, 6)

Nathaniel Hudson, Celena Alcock, and Parmit K. Chilana. 2016. Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers. *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. (Chapters 1, 2, 3, 6)

Abstract

Interest in understanding and facilitating 3D digital fabrication is growing in the HCI research community. However, most of our insights about end-user interaction with fabrication are currently based on interactions of professional users, makers, and technology enthusiasts. This thesis documents my studies of newcomers to 3D modelling and printing, users who have no prior experience with fabrication and mainly explore walk-up-and-use 3D printing services at public print centers, such as libraries, universities, and schools. I first carried out exploratory research consisting of 32 interviews with newcomers to 3D printing, print center operators, and fabrication experts to better understand the motivations, workflows, and barriers newcomer face in appropriating 3D printing technologies. A major theme in these interviews was the use of online platforms to retrieve and print premade models as an alternative to the complex 3D modelling workflow. I conducted further investigation into Thingiverse, the largest online 3D design sharing community, investigating users' activities and their conversations by using quantitative and qualitative analyses. Finally, based on my observations with newcomers and the conversations on Thingiverse, I developed MarmalAid, an online 3D modelling system integrated with contextual help that can facilitate conversations and help seeking throughout the 3D modelling process.

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Dedication

To my parents, Candace and David Hudson

And to Stephanie Wu

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Chapter 1: Introduction¹

The declining cost of digital fabrication hardware over the last several years has catalyzed the design of ‘prosumer’ 3D printers and created new opportunities for consumers to make, create, and innovate [35]. This has led to the emergence of makers, a community of enthusiasts who focus on fabrication, invention and experience sharing, and who collaborate and learn in environments known as makerspaces [18]. Inspired by the makerspace concept, thousands of public institutions, such as schools [37], libraries [63], and universities [16,65], are now setting up print centers or creative hubs for end users to make use of digital fabrication technologies. However, unlike makerspaces that are often run by enthusiasts and have formal memberships that attract engineers, entrepreneurs, inventors, hackers, craftsmen, and artists [33,45,52,62], public print centers welcome users of all ages and skill levels [3] and offer 3D printing services for free or at nominal rates.

Although focus on makers and enthusiasts [3,33,54], and professional users [26,27,49,68] is growing in human-computer interaction (HCI), we are only beginning to understand the emerging population of novice users of 3D printing. This population is particularly interesting to study because these novice users can serve as a proxy for what it will be like for the general public to use 3D printing once this technology becomes even more economical and ubiquitous. I believe that if HCI is going to be at the forefront of inventing new fabrication design tools and interfaces [32], we need to

¹ Portions of this introduction have previously been published at the 2016 ACM Conference on Human Factors in Computing Systems [20].

look beyond enthusiasts and understand the challenges and opportunities that exist in facilitating the interactions of novice users with fabrication technology.

In Chapter 3, I investigate how newcomers explore the world of walk-up-and-use 3D printing services, focusing on their motivations, workflows, and barriers. I carried out semi-structured interviews with users who had little or no prior fabrication or 3D modelling experience, but had recently visited a print center to try out 3D printing. To understand the full spectrum of digital fabrication by newcomers, I also solicited perspectives of print center operators and experts in fabrication. Based on findings from 32 interviews, I provide a comprehensive analysis of what it is like for these newcomers to interact with complex 3D printing workflows at public print centers, the role of operators, and how newcomers' interactions differ from fabrication experts.

My main findings in Chapter 3 indicate that there is a strong interdependency between the different stages of a newcomer's fabrication workflow (Figure 2) that impacts the whole user experience. Furthermore, I found that newcomers often struggle in every part of this workflow, from creating their 3D model to forming a mental model for 3D geometry to creating their final printed outputs. I found that newcomers were successful only with the help of print center operators at every stage—from bootstrapping their 3D printing workflow, to seeking help and troubleshooting, to verifying their outputs. However, the operators could not always address the nuanced needs of newcomers as the operators were not formally trained in fabrication. Although some of my participants sought to avoid the difficulty of learning 3D modelling by turning to downloaded 3D models available through services such as Thingiverse.com, they were often deterred by the limited options to customize the models.

Inspired by the popularity of downloaded 3D models among newcomers to 3D printing, in Chapter 4 I investigate Thingiverse, the largest online 3D design-sharing community with millions of users. Thingiverse provides a low barrier-to-entry way for novices and users inexperienced with 3D modelling to explore 3D printing, as users can quickly download premade 3D designs and ask design-specific questions. In this chapter, I investigate users' activities on Thingiverse and their conversations by using quantitative and qualitative analyses. My findings shed light on various barriers in

using, customizing, and printing premade 3D designs. The results suggest that although Thingiverse plays a key role in helping users get started with basic 3D printing and seek help with in a social context, there are many opportunities to streamline the design-download-customize-print workflows. In particular, opportunities exist for designers to provide richer metadata, clarifications, and expert tips to help users succeed in printing objects and customizing existing 3D designs.

A key finding in Chapter 3 was that help-seeking as a casual maker is highly social, with newcomers depending on operators throughout the 3D printing workflow, and in Chapter 4 I observed a rich culture of social help seeking and sharing on Thingiverse, which was stymied by difficulties describing design intent. As a result of these findings, in Chapter 5 I present MarmalAid, a novel online 3D modelling and sharing platform with integrated help-seeking and communication tools. This tool is my early vision of what a system that contextually allows users to socially seek help within the context of a 3D modeling task may look like.

This thesis makes the following main contributions:

- Establishes an empirical understanding of newcomers to 3D printings' motivations, workflows and barriers in using 3D printing technologies and illustrates the role of print center operators in providing support throughout the process.
- Provides insights into public print centers and how they lower the barrier to access for 3D printing technologies, but currently lack the kind of community expertise and knowledge sharing that is the hallmark of makerspaces.
- Provides a quantitative and qualitative overview of current user behaviors on Thingiverse.
- Sheds light on the barriers users face in using, customizing and printing premade 3D models from online sources
- Demonstrates an initial vision for integrating social Q&A help-seeking tools directly into a 3D modelling tool through the design of MarmalAid
- Highlights the opportunities that exist in building the next generation of interconnected fabrication tools with features for supporting expertise sharing.

The insights from this thesis will be beneficial for: 1) designers inventing the next generation of fabrication technology; 2) researchers seeking to improve user interaction with complex feature-rich software; and, 3) educators designing training programs and services for newcomers to 3D printing.

Chapter 2:

Related Work

Since 3D design and fabrication tools have traditionally targeted professionals or technically inclined users, much of the extant HCI literature focuses on experts. However, research on facilitating consumer end user interaction with digital fabrication and making has recently been growing [32]. To situate my findings, I draw upon research related to makers and makerspaces, observational studies of 3D printing in other contexts, pedagogical experiences, studies of Thingiverse, and existing HCI innovations into in-application contextual help.

Makers and Makerspaces

Recent years have seen the emergence of *makerspaces*, community organizations where enthusiasts, known as *makers*, brainstorm, build, and share their work [33,62]. Typically run by enthusiasts and makers [11,45,62], these spaces attract technically literate users who often have formal engineering, science or design training. Makerspaces provide a number of benefits to their members. In exchange for a membership fee (usually a commitment of \$50 to \$100 monthly [3]) makers gain access to a space outfitted for creative work and a wide range of tools from humble handsaws up to 3D printers and other digital fabrication tools. More importantly, however, makers become part of an informal network of expertise sharing [3,33,62] and undertake projects that they would otherwise be unable to do on their own [33,52,62]. All of this creates a strong sense of community among the members of the makerspace. However, my research shows that print centers do not offer this type of expertise sharing—they are run by operators who usually do not have any formal training in 3D printing and are mainly there as facilitators.

Other works have considered the culture of these makers [18,24,35]. These studies describe a culture of customization, collaboration and knowledge sharing by technically inclined users who may or may not have formal training in 3D workflows but are intrinsically motivated by the process of learning new skills. This drive to tinker separates these enthusiasts from the newcomers using library print centers that I examined in my study.

3D Printing and Modelling Behaviors in Other Contexts

Much of the work examining user interactions and experiences around 3D printing and modelling has focused on technical or professional users. For example, Lee et al. [26] evaluated the usability of ten different professional 3D software packages and highlighted issues related to confusing terminology, form design, help systems, and more. Sadar and Chyon [49] and Ludwig et al. [28] document experiences of professionals using 3D printing in research and artistic contexts respectively, showing how they experimented to learn how printer settings influenced output. Mellis and Buechley [31] document a case study of fabrication of customized electronic products through workshops with trained users which employed 3D printing. In these workshops they found the limited time they had available made it difficult for these users to produce finished 3D prints. While these papers document a range of usability issues, they have primarily considered enthusiasts and professional users—that is, they were trained or technically literate in fabrication. In contrast, as I demonstrate in the paper, newcomers may have different needs and motivations, cannot draw upon formal technical training, and face additional usability issues.

Shewbridge et al. [53] consider users who most closely match the population of newcomers using library print centers that I studied. They investigated the types of objects that users would wish to create in a typical household equipped with a 3D printer. However, the authors used an idealized form of a 3D printer capable of creating anything, and requiring no technical knowledge or time investment on the part of the user. While they found interest in a wide variety of objects including modifications and customizations of existing designs, their study was not concerned with the entirety of the complex 3D modelling and printing workflows that was the focus of my study.

Finally, recent studies are looking at the online 3D model sharing culture emerging in websites such as *Thingiverse*. For example, large-scale analyses of Thingiverse 3D models have shed light on how users modify each other's designs, with a focus on network structures [25,38,41], the sharing of assistive devices [5], and license choices [34]. Although model sharing was a topic of discussion in my interviews, sharing culture was not the focus of this study. However, I do add insights about limitations of using shared 3D models in newcomers' workflows.

Teaching and Pedagogical Experiences in 3D Printing

3D printing and modelling is also receiving increased attention in the education space, with studies documenting experiences implementing and teaching 3D printing in academic environments. Some have explored the educational potential of making in a formal learning environment [4,13,65], finding that it provided students with hands-on experience and increased student motivation, performance and information retention. Additionally, Buehler et al. [7] studied the use of 3D printing and modelling in special education classrooms, and found that even with novice-oriented tools such as TinkerCAD, students struggled to create their own designs. My results in Chapter 3 corroborate these findings in a non-formal context, and shed light on further challenges faced in other parts of the 3D printing workflow.

Several case studies have investigated experiences installing 3D printers in public and university libraries [15,16,47,50]. These cases provide some insight into how these print centers were set up, but do not provide detailed insights into the workflows and barriers of newcomers independently trying to fabricate digital objects using the tools provided by these print centers.

In summary, although literature on various aspects of makers, 3D modelling and digital fabrication is growing in HCI, to my knowledge, my study is among the first to investigate the population of newcomers using library print centers and their use of walk-up-and-use 3D print centers.

Studies of Thingiverse

Although Thingiverse facilitates the process of sharing 3D designs, both novice and expert users often have a number of questions related to the printability, functionality, or assembly of the resulting 3D objects [29]. One problem is that designers who post 3D designs do not always share details about whether their design will print on a specific 3D printer, what materials would work, or what the machine settings should be [42]. In addition, designers may be new to 3D modelling and may not be actual users of the objects that they design (e.g., in the assistive technology domain [6]). Furthermore, designers rarely document changes to their design files, and if they do, it is usually through a comment which can be overlooked and difficult to decontextualize [59]. Since Thingiverse is largely community-driven, there is currently no formal provision for screening 3D designs to check for potential issues before the designs are shared on the site.

In-Application Contextual Help and Commenting

In order to address some of the struggles I observed with help-seeking by newcomers to 3D printing and communicating design intent I investigated how in-application contextual help and comment-based communication may be employed by 3D modeling users. A number of prior works have investigated contextual help-seeking tools. For example, IP-QAT [30] allows a user to ask questions in the form of forum posts to other users by accessing a context menu on elements in the application's menu bars that they had questions about. LemonAid [9] adopted a similar approach for web pages, instead opting to create a help overlay where users could select any anchor tag on the page to ask questions about, as well as view and search previous user questions and answers. Finally, CheatSheet [61], facilitates help-seeking by allowing users to take notes and record information by annotating shareable screenshots in the context of their current tasks.

The idea of using comments on 3D objects for communication has also previously been explored. For example, CyberReview [58] demonstrates a system that allows engineers and management to engage in collaborative product design reviews, using

shared comments on a 3D object to communicate. However, in contrast to my MarmalAid system introduced in Chapter 5, these comments do not exist in 3D space and are not specific to any one part of the object. Additionally, CyberReview is explicitly targeted at experts working within more formal design environments. The *Adobe Acrobat*² system also offers functionality for creating notes on 3D PDF files for design feedback. However, this differs from my approach in several ways:

- Acrobat's comments are not directly integrated into the 3D modelling software, meaning that in a help-seeking context the help-giver will not be able to access editing tools or metadata in providing help.
- These comments do not actually exist in 3D space and are only visible from one vantage point.
- These comments do not support replies or media embeds, limiting their use as a social help-seeking system.

Furthermore, only a select number of advanced modelling packages can export to the 3D PDF format, making this largely unsuitable for novices.

² <https://acrobat.adobe.com/us/en/acrobat/pdf-reader.html>

Chapter 3: Understanding Walk-Up-And-Use 3D Printing³

In this chapter I present a study of *casual makers*, a term I use to describe the emerging population of users who have no prior experience with fabrication and mainly explore walk-up-and-use 3D printing services at public print centers, such as libraries, universities, and schools. I carried out 32 interviews with casual makers, print center operators, and fabrication experts to understand the motivations, workflows, and barriers in appropriating 3D printing technologies.

Research Approach

To establish an empirical understanding of the needs, workflows, and barriers faced by casual makers, I carried out 32 semi-structured interviews⁴. My interviews were inspired by seminal works on understanding and illustrating the complexity of user interaction with machines [43,57]. Although my primary target audience was casual makers, I also considered the perspectives of print center operators (as they interacted with these casual makers every day) and fabrication experts (to compare my findings about casual maker workflows).

³ A version of this chapter was published at the 2016 ACM Conference on Human Factors in Computing Systems [20].

⁴ Quotes with casual makers in this text are attributed to P1-P18, quotes with operators to O1-O9, and quotes with experts to E1-E5

Recruitment and Participants

Most of my data and analysis is based on interviews with 18 adult casual makers (11 male, 7 female) from our local metropolitan area (See Appendix A for interview questions). These casual maker participants varied in age: 33% were between 18-24, 29% were 25-34, 21% were 35-49, and 17% were 50-64. All of the participants had been using computers for at least 10 years, but only one had extensive experience with programming. Half of the participants had no experience with 2D graphic design software (*e.g.*, *Photoshop*), 3 had formal training in graphic design, while the others fell somewhere in-between. I recruited participants who did not have any prior 3D modelling experience or formal training and had recently visited a print center to explore 3D printing. They had explored 3D printing out of interests in areas such as robotics, kinesiology, games, and arts, with varying degrees of success.

I also recruited print center operators for my study as they interacted with casual makers every day and could share observations of these users' workflows and potential struggles as they tried out 3D modelling and printing. The operators in my study were all paid staff or volunteers who managed the operations of public print centers and came from backgrounds such as library science, education and IT. None of them had formal domain expertise in 3D modelling and were not self-identified makers. I interviewed 9 operators at 5 different local print centers, including my own university, public libraries, and schools. I interviewed 5 of the print center operators on site, as that helped us capture an understanding of the resources available and the processes in place at these locations.

To compare my findings about casual makers, I also wanted to have perspectives of fabrication experts. I interviewed 5 expert users of 3D printing and modelling, who self-identified as makers or had formal education in 3D modelling (*e.g.*, industrial design, architectural design).

I recruited participants using personal contacts, email advertisements, and snowball sampling over a period of 6 months in 2015. Each of the interviews lasted 30-45 minutes.

Data Collection

During the interviews with casual makers, I asked questions about what motivated the participants to begin learning 3D tools, what their first experiences had been like, their typical workflow, and the kinds of challenges that the participants faced along the way. In my interview with operators, I inquired about the operator's role, experience and training, and their perception of casual makers' experiences, as well as resources (such as materials for learning 3D modelling) and processes instituted by the print center (such as print approval). I encouraged both groups to describe how casual makers sought help and resolved issues, and to provide specific examples whenever possible. Finally, I talked to fabrication and 3D modelling experts about their "ideal" 3D printing workflows so I could compare my findings about casual makers.

Data Analysis

All transcripts were organized, coded, and analyzed using the *Atlas.ti* qualitative data analysis software. To understand different facets of my data, I used an inductive analysis approach [55]. In the coding process, I focused on highlighting different aspects of the casual makers' workflows, the kinds of challenges that they faced, and how they attempted to resolve these challenges.

Print Centers and their Operators

To understand casual makers' workflows, I first wanted to better understand the print centers where casual makers were accessing 3D printing technologies. Through my field visits, I found that these print centers were recent endeavors (less than 2 years old), equipped with *fused deposition modelling*⁵ (FDM) type 3D printers. Among the print centers that I visited, three of them were using two *MakerBot Replicator 2* printers, which are single nozzle FDM printers. These two locations charged a nominal fee based on the time taken for an object to print, and offered mandatory training classes covering how to set up and use the printer before a user could use the printer. Another center was using a single newer version of the same printer, a *MakerBot*

⁵ *Fused deposition modelling* describes a common and relatively inexpensive 3D printing process whereby melted plastic is deposited layer by layer to form a 3D object.

Replicator 5th Gen., which is also a single nozzle FDM printer, and provided it for free along with optional training classes. All of these locations used the *Makerbot Desktop* slicer. The remaining location employed a single high-end *Stratasys Fortus 360mc* printer, which is a dual-nozzle enclosed FDM printer along with the associated *Insight* slicing software, and charged at-cost by material use.

According to the operators, these print centers presented benefits not found in the original makerspaces (Table 1). For example, although local makerspaces offered a few hours weekly for free community access, they were not generally accessible without paying the membership fee, which turned away newcomers to 3D printing. However, print centers had a low barrier to entry as they usually had no formal membership or membership fees, allowing less committed users to easily access the tools. Casual makers also commented that the presence of enthusiasts and experts in makerspaces often intimidated the casual makers who had no prior fabrication experience and considered themselves to be “outsiders”.

The operators in my sample filled many roles: providing 1-on-1 or group training, approving user designs for printing, assisting users to find help resources, troubleshooting printers, managing user frustrations, managing other tools at the print centers, and more. All of them had learned on the job or through tutorials, but had no formal training in 3D modelling and printing. As such, these operators did not see themselves as experts (compared to makers), nor did they know the particulars of the various technicalities and advanced features of the 3D modelling and printing software. However, operators were able to defer to other experts in their networks with more expertise to address users’ issues. These more experienced people were local enthusiasts, software or hardware vendors, or other more experienced operators, as described by one of the operators, a librarian by training:

When we launched this service, none of us knew anything about 3D printing - we just knew it was cool. In terms of training, then, we brought in someone from a local Makerspace... day one he opened the [3D Printer] with us and did some training with us and then he went

away. Staff got to practice for a week and then [he] came back just to make sure everything was okay. (O6)

I found that operators deferred to experts for specific software problems, malfunctioning or broken equipment, particularly problematic prints, or other instances where a user or operator was unable to resolve the issue.

Casual Makers' Motivations for Using 3D Printing

I now describe the focus of my study—characteristics of casual makers and their motivations, workflows, and challenges in using 3D printing technologies.

The casual makers in my sample demonstrated several distinctive qualities. For example, unlike makers and enthusiasts, who often find learning new technologies and tools to be intrinsically motivating [12,48], I observed that casual makers were more driven by the printing output. The casual makers were motivated to produce their desired objects, whether those objects were practical or novel in nature. For most casual makers, 3D printing was merely a means-to-an-end. I observed that they often became involved with 3D printing to accomplish a specific fabrication goal. For example, one participant with a physiotherapy background wanted to prototype a new therapeutic device he had designed:

At first, I didn't know about 3D printing. It's just, like, "Okay, how can I make a plastic model?". You know those molds and pouring stuff in. I first thought about that, and then..."Aw, man, this is ridiculous." I don't even know what my design looks like. It's tough... It was an article that I read that I heard about 3D printing. That's when I was like, "Whoa! That's the answer! I've got to do 3D printing!" (P6)

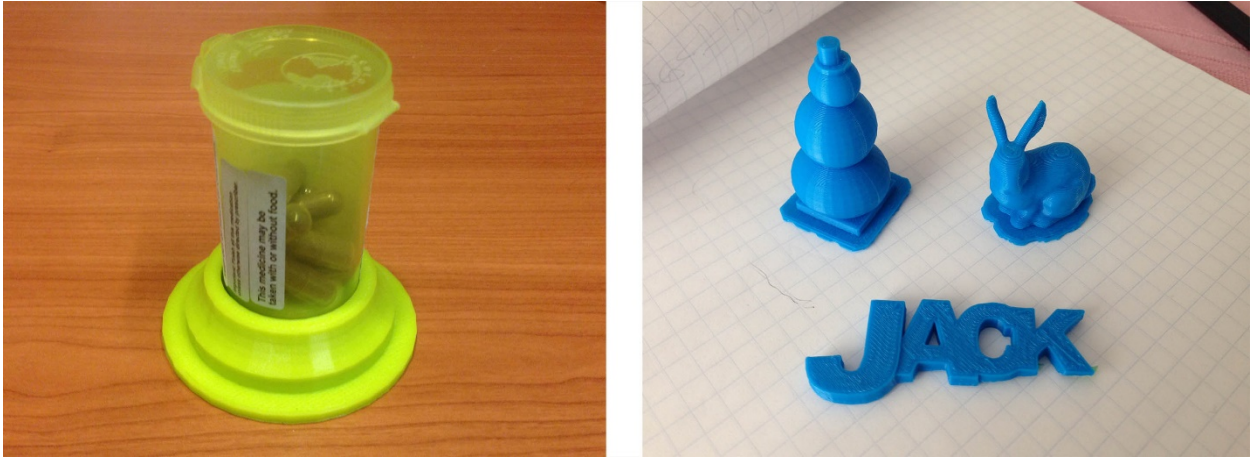


Figure 1: 3D printed objects seen in my interviews

Other casual makers reported printing a variety of practical and emotionally appealing objects. For example, they described projects, such as 3D text, simple jewelry and cell phone cases, along with objects, such as missing board game pieces and pill bottle holders (Figure 1):

I needed [better] medicine containers. My father has daily medicines, so we have these little cups and they always get knocked over. I 3D printed almost like a holder for it. So they're a little bit more stable. I took the thing, I measured it and I modeled it up and printed it in different colors... (P4)

As their use of 3D printing was not part of a long-term desire to print 3D objects, these casual makers were not yet ready to buy their own home printers and preferred to use free or low cost public access printer (such as the libraries I visited). Use of shared printers allowed casual makers to avoid both the financial cost of buying the printer, as well as the learning and time burden that comes with selecting, setting up and then maintaining the printer:

I think that if you're an engineer and you're interested in the technology itself or investigating what you can do with new materials or new speeds or new apparatuses then by all means get the printer. But I don't care, 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. (P2)

Table 1 summarizes the types of projects that the casual makers in my study described, illustrating that they were usually driven by a specific practical need.

Table 1: Types of Projects Casual Makers Created

Type	Users (/18)	Example Project
Artistic	8	Design and fabrication of new kinetic art installation
Novelties	6	Small figurines and toys not part of any larger theme
Personalized Gifts	5	Custom novelty rings and decor for a bridal shower
Utilities	5	Pill bottle organization system
Hobbies	4	Parts for small model racing cars
Academic	4	Test for just noticeable difference in size for psychology experiment
Entrepreneurial	3	Design of a new prosthetic

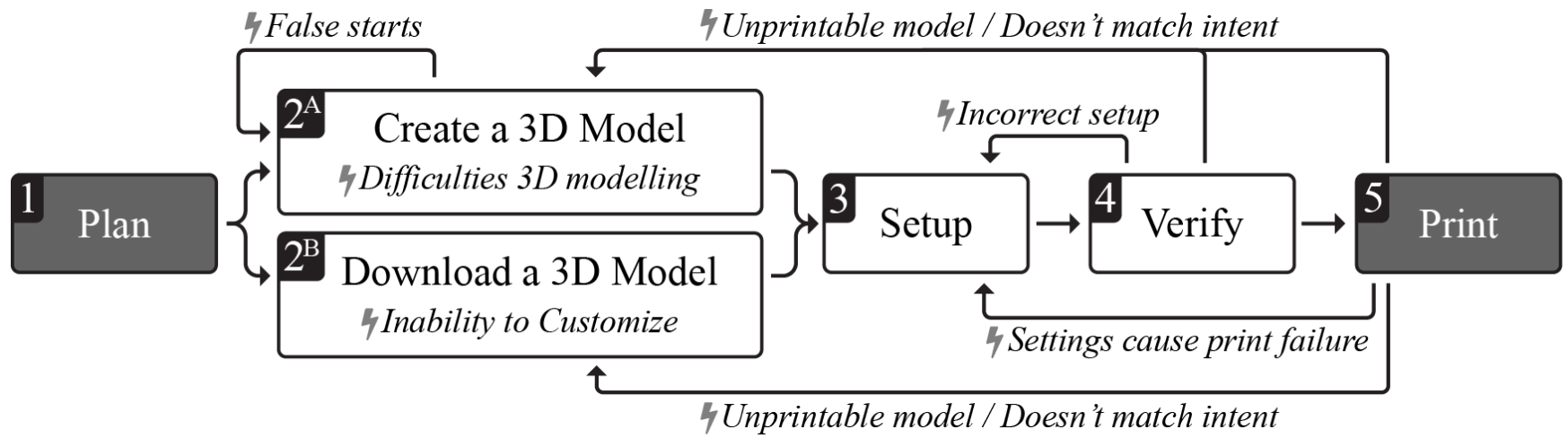


Figure 2: A casual maker passes through several steps when attempting to 3D model and print, and may have to return to earlier steps in response to some errors. Different parts of the workflow are associated with different user challenges.

Casual Makers' 3D Printing Workflows

Based on casual makers' own descriptions and operators' observations, I synthesized a 5-step model for a typical casual maker's workflow with 3D printing (Figure 2).

Step 1: Plan the 3D Object

Before beginning the modelling or printing process, a user must first have an idea of what they want to create. I did not observe significant difficulties in idea generation, with casual makers attempting a wide range of projects, as discussed above. However, I did observe that whereas fabrication experts invested heavily in planning by using paper-based sketching and other techniques, casual makers jumped into creating their digital model with only minimal planning.

Step 2A: Create a 3D Model

Next, whereas fabrication experts would choose a modelling tool from their repertoire that was most suitable for the modelling task, casual makers tended to consistently use a single tool for all kinds of models. Casual makers either used software already installed on print center computers or opted to install modelling software on their own computers. Casual makers used and attempted a wide variety of software, with 33 different 3D tools being mentioned across my 18 casual maker interviews. Popular tools included *SketchUp* (attempted by 44% of participants), *123D Design* (22%), *openSCAD* (17%), *Solidworks* (17%) and *Blender* (11%).

Step 2B: Download a 3D Model

As an alternative to creating their own 3D model, users could download a premade 3D model from a website such as Thingiverse. Thingiverse is a platform for sharing user-contributed 3D models designed for 3D printing. On this site, members upload 3D model files (typically STL files⁶), which can then be downloaded by users of the site. I found this to be popular among users who were frustrated by the difficulty of using 3D

⁶ The STL file format is a format commonly used for 3D printing, and describes a 3D surface built up of triangles. STL files are typically not used natively by 3D software, but are generated to be shared online or processed by the 3D printer [14].

modelling software, and was mentioned by the participants in 11 of the 18 casual maker interviews, and in all operator interviews.

Step 3: Set up the Printer

The next step after creating or downloading a digital model was to prepare it for printing. With help from operators, participants would set up their 3D prints by processing their 3D model into instructions for the printer and physically preparing the printer. Processing the 3D model occurred in specialized software known as a *slicer* (as it slices the model into layers for the printer), which allowed users to select print settings, such as layer height and print speed.

Step 4: Verify the Model

In the print centers that I visited, operators sometimes checked the user's digital model via an onscreen inspection before printing. This check was designed to evaluate whether the design was likely to print properly and whether the printer's settings were correct. As a result, the user may have had to adjust their design or print settings.

Step 5: Print the Model

After the validation step and any resulting changes, participants were finally able to print their model. Any issues not caught by the verification step resulted in the failure of the printing step. If the user's print failed or did not match their design intent, they would have to adjust either their model or print settings to correct the issue, often with the operator's assistance. When the casual maker was satisfied with their final model, they were not likely to pursue another 3D printing endeavor for a while. Unlike the fabrication experts who engaged in many projects requiring the use of 3D printing and modelling (often in immediate succession), casual makers had more of a one-time or short-term engagement with 3D printing.

Challenges in 3D Printing Workflows

As I uncovered the typical workflow in casual makers' 3D modelling and printing activities, I also became aware of a number of challenges that these casual makers faced in every stage of the workflow. I saw four key themes related to these challenges: dealing

with false starts, using complex modelling software, understanding the 3D domain, and matching output with design intent.

Dealing with False Starts

Although casual makers' attempts to get involved with 3D printing were initially enthusiastic, my interviews indicated that there were many barriers to entry, especially in a casual maker's planning (Figure 2.1) and first steps (Figure 2.2A).

In contrast to fabrication experts, casual makers reported an aversion to planning out their models in any detail prior to using the 3D modelling software, even in situations where it led to multiple false starts or trial and error iterations:

I just started drawing in the software. I actually have started over many times, like, "This doesn't look good. Start fresh." ... If it doesn't work out as I want, I just start from the beginning. (P9)

Casual makers often made naïve assumptions about what software would be suitable and found it difficult to select appropriate software tools as there were many 3D software options optimized for specific purposes. This confusion contributed to the highly varied software tool choices described earlier. For example, one user selected Cinema 4D since he was aware that a television show that he enjoyed used it:

Since I'm not really familiar with 3D software the only thing drove me to Cinema 4D because I knew that his TV show that I watch uses Cinema 4D in order to make animated scenes. This is the only reason I went and got it. Like, there's a lot of options so I don't know which one should I choose. (P12)

Early in the casual makers' learning process motivation appeared to be very fragile. All the operators I interviewed observed that early failures, even when they were not the casual maker's fault (such as a printer hardware failure), could result in casual makers completely giving up. As seen in other studies of learning complex software [17], I observed that casual makers also had a hard time maintaining motivation once they had a false start. For example, one of the casual makers explained how he gave up when

faced with instructions that required more unfamiliar math formulae or programming to create a desired custom object:

It [the tutorial] would get into the parts where it was like, "well, if you put this diameter and this ratio whatever." And I was like, "Nope! I'm done – Can't do that!" ...I'm a new person, and I can't understand half the things you're saying, even if you're not having math in it. (P10)

In summary, the casual maker participants were rarely enthusiastic about 3D printing as a long-term hobby and many of them would not want to invest in further learning after experiencing false starts.

Difficulties Creating a Digital 3D Model

After a casual maker had decided what they planned to do (Figure 2.1) they had to produce a 3D model. Participants who opted to create their own 3D model (Figure 2.2A) had to overcome a few challenges. A number of these were common usability issues [26] experienced due to the complexity of the modelling software interfaces. However, I observed additional difficulties among participants due to the fundamental nature of the 3D space. The addition of a third dimension appeared to break many of the previously formed mental models from familiar 2D software:

It's hard to understand why it's [rotating] it this way, why the control is mapped with this particular way. I'm used to 2D. I don't understand... I think there might be some standard, which I don't know. (P5)

I also observed that casual makers transferred their mental models from 2D software to 3D, resulting in difficulty aligning objects in 3D space. This misalignment occurred due to a failure to account for depth, which was not present in 2D software. One operator gave the example of a new user trying to build a snowman in *TinkerCAD* (shown in Figure 3):

So she brings in 3 spheres into TinkerCAD and then she brings me over and says, "Can I print this?" I'm looking at it, and I see little blobs

sitting on top, and I swing it around and what she had done was placed one behind the other...when you look straight on, it looks like they were connected, but they weren't. They weren't one on top of each other, they were one behind each other. That to me was a rare revelation...you realize just how hard it is just for people to think in 3 dimensions. (O2)

Users also reported losing track of objects in 3D space. For example, a 2D concept of space makes it difficult for users to locate objects that could become positioned behind the camera view. Casual makers also reported having difficulty in breaking down the task of building an object in 3D space into individual operations. Even when the software's individual tools were understood, properly composing an object using the tools in concert often eluded new users:

They don't know where to start... How do you go about dissecting a simple object, or building up an object, is not in their skillset. They don't really have the problem-solving skills. (O3)

This difficulty may be due to the way casual makers conceptualized the construction of a 3D model. In some interviews, casual makers indicated that they approached 3D modelling as a series of 2D operations or drawings. Even users who were relatively successful reported conceptualizing 3D modelling tasks as a series of 2D operations:

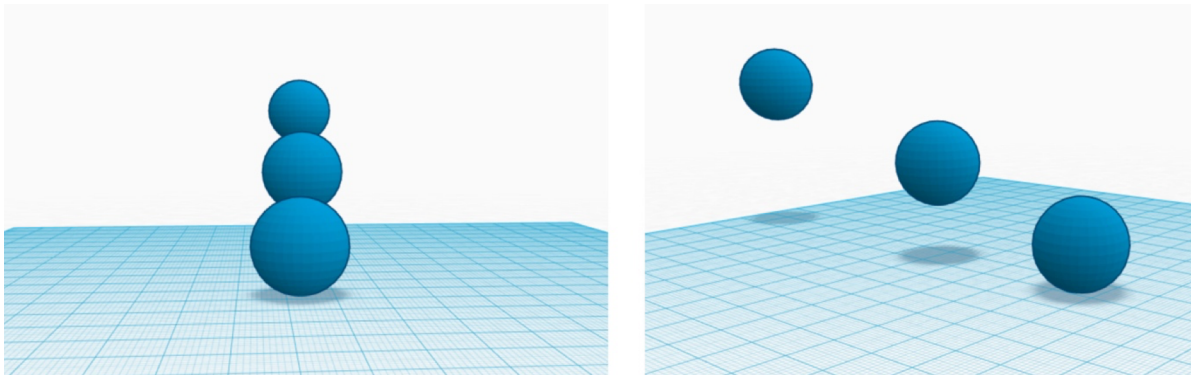


Figure 3: Challenges in aligning objects in 3D while modelling.

When I create a 3D object...it was basically doing 2D drawings and then extruding them and reorienting them and basically taking what was familiar and expanding on it. (P7)

These issues often required the assistance of a print center operator or fabrication experts. Other than navigation difficulties, these issues were often only caught as part of a final pre-print check by the operator. Since many casual makers did not even know that something had gone wrong (or exactly what had gone wrong), the operator had to explicitly demonstrate the problem or solution:

I actually had [an operator] sit down and kind of help me out, because I'm like "Oh, you've got to help me because I'm floating in space and I can't get down to the ground." [...] [The challenge] was just navigating and knowing that I'm down here and not up here and way down there. (P16)

One drawback was that casual makers' access to operators was limited both by the operator's time and the user having to visit the print center to seek help. Furthermore, unlike makers who were part of a network of expertise, casual makers typically lacked access to experts in the 3D modelling or printing domain. One operator described the situation:

There's no one here who's an expert on 3D modelling at the library. I'd say [the IT specialist], who you spoke to earlier, knows the most about it...even he is not an expert. (O5)

This lack of formal expertise among operators made troubleshooting issues related to software functionality and the 3D domain even more difficult for casual makers.

Issues with Premade Digital 3D Models

As mentioned earlier, rather than modelling an object from scratch (Figure 2.2A), users sometimes downloaded premade 3D models from the web (Figure 2.2B). Operators mentioned that they usually introduced Thingiverse to casual makers in response to their frustrations with modelling software:

Some people don't really understand that designing something in 3D is different than designing something in 2D. There [are] more dimensions. After they learn that, they feel defeated and go to Thingiverse instead and choose something. Then...once they've chosen something from Thingiverse, sometimes some things print better than others. (O5)

This “download and print” workflow was presented as a simpler alternative to modelling, where instead of a user designing and modelling new objects, they instead downloaded a publicly available model. Although many operators praised Thingiverse as a tool for quickly demonstrating 3D printing to new users, Thingiverse was not universally favored among the operators. For example, one concern was that the site’s homepage and overall design tended to showcase “featured designs” which were highly complex prints by experts (not amenable for learning). Some operators described how this showcasing of complex 3D models printed by expert users further gave casual makers false expectations:

Thingiverse users are showing off, and you don't show off with something simple. Mostly what's on Thingiverse isn't that useful within this [learning] context. (O3)

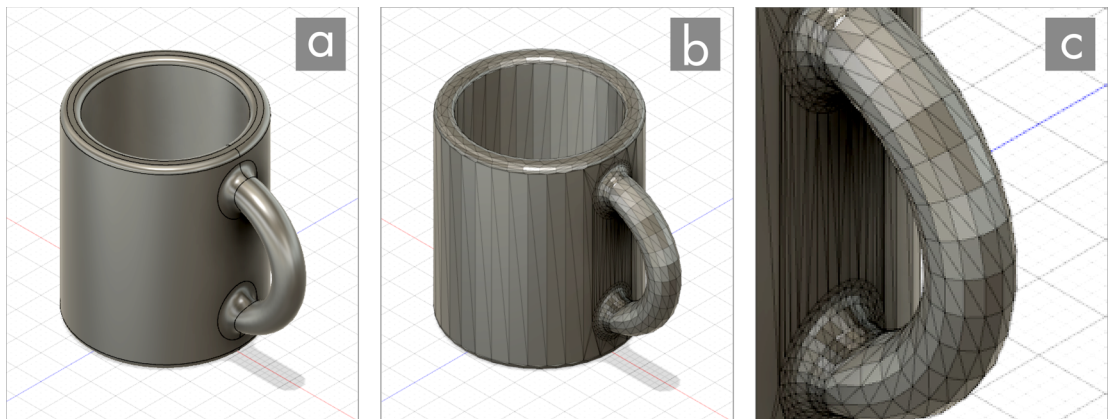


Figure 4: The native format model (a) contains complex curved surfaces that can be selected and edited as a whole. However, when the model is exported as an STL mesh (b) the resulting geometry is broken down into many small triangles (c), preventing easy editing by inexperienced users.

Some previous studies [2,41] have shown the potential for users to customize and learn from existing community-created models, an activity known as *customizing* or *remixing*. However, I did not observe successful customizing behavior in my study. Of the 11 casual makers in my sample who had used Thingiverse, 8 simply printed the models as is, while 3 had attempted to customize the downloaded model with no success. Some casual makers I interviewed were unsure if customization was even possible, while others had attempted to customize but were confused by the geometry produced (see Figure 4) when they imported the downloaded STL file into their program.

I opened the file and the way it's structured... I don't know what's happening, like how somebody even modeled that. So I'm really going to have a hard time changing it. (P6)

One operator described the problem:

Thingiverse is, for one thing, it's often STL files, which are pre-compiled into triangles for the [printer software], so you can't really get the design intent back out of it unless you have the same software that they use, and they happen to upload their source file [...] which they often don't. (O6)

The fabrication experts explained that Thingiverse does have some capabilities for creating objects that can be customized on-site. However, this capability requires the user to employ a specific modelling tool (*openSCAD*) and build the model in a very specific manner, meaning that only a small portion of the models on Thingiverse had this functionality. Furthermore, these models were not freely customizable and could only be customized in ways predefined by the original author, often making them unappealing to casual makers who had a specific custom need in mind.

Matching Output with Design Intent

Regardless of whether a casual maker created their own 3D model or downloaded a 3D model, they had to first process their model for 3D printing (Figure 2.3). Decisions

made in this step, along with decisions made in what the user modeled (Figure 2.2A) or what the user selected to download (Figure 2.2B), affected the object’s printability.

My interviewees described 3D printers as complex devices, with operation settings that must be configured by the user, including settings such as speed, infill density and temperature. Difficulty evaluating the effects of these settings have been documented in prior work [28] and were not the focus of my study, but I did observe that casual makers had particular difficulty in designing objects that were viable for fabrication. For example, one operator explained how he tried to tell end users that a 3D printer was not a “magic device” that could print whatever he wanted on the screen:

I think when people come in, often the first time they want to print something, trying something impossible is kind of common. They want to print a huge thing the first time, or they want to print a bunch of things at the same time [...] It's usually the first hurdle of understanding, even after the training sessions that we do, that they maybe want to come in and print something kind of crazy. (O8)

As the fabrication experts and operators explained, not all 3D models are easily printable. While 3D printing simplifies fabrication of many forms, it still has constraints that are not easily understood by newcomers. Small changes in geometry or object orientation affect print quality, and whether a print will work at all. For example, one

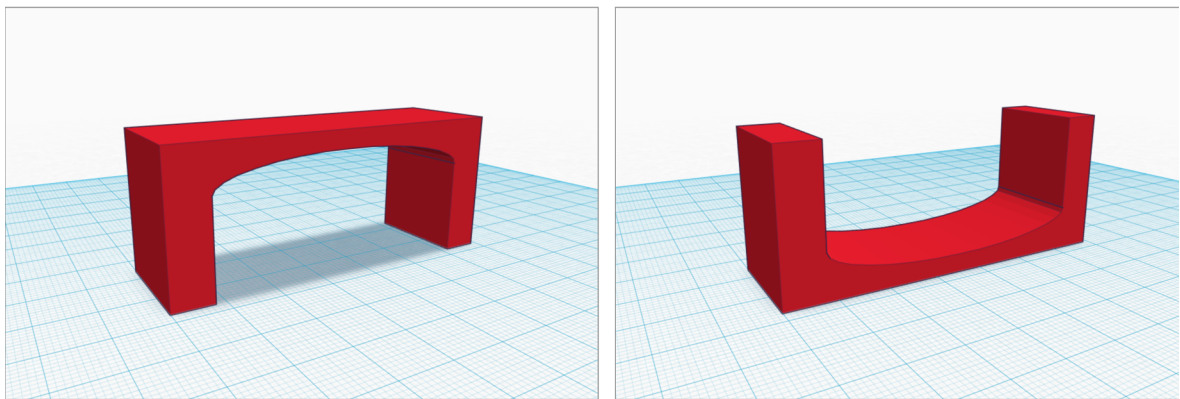


Figure 5: Small changes in geometry affect print quality.

fabrication expert showed us an example (see Figure 5) that the object on the right would print easily and accurately on most FDM printers, while the object on the left would be considerably more difficult. Geometric factors influencing printability included the object's base size, the presence of overhangs or thin sections, and the size of horizontal cross-sections. A new user's lack of a design-for-manufacture mental model resulted in difficulty in understanding printability of even such simple objects.

The most frequently reported difficulty was with *overhangs*, a term used to describe parts of objects that were not adequately supported while printing, as described by one of the fabrication experts:

[FDM] printers can't print on top of nothing – you need something under the bit you're currently printing to hold it up. This means that if you wanted to print a long bridge, or a man with his arms straight out in front of him, it would look really ugly or wouldn't work at all without some sort of support. Short distances are OK, but without something holding up what's being printed it usually won't work. (E2)

The casual makers reported that they had difficulty understanding and designing with these constraints in mind and one of the operators further explained casual makers' interactions:

Sometimes we'll look at their file and say "It might be a good idea to add supports". But the supports and the raft add time, so often they turn them off without really understanding... that can produce a bad print. I'd rather it go over 15 minutes and that they have supports and they walk away happy then have the print go bad. (O5)

FDM printing processes also often leave small blemishes or distortions on printed objects, such as seam marks, layer marks, or warp. While fabrication experts knew to expect these, or used alternate 3D printing processes where appropriate to avoid them, casual makers were often surprised at these surface blemishes on their printed model:

When it prints, the material has to go up, so there's a seam line of where it went up. Sometimes that's an issue for some people. [...] Somebody was printing a little Iron Man that stands about [5cm] big. Then there's a lot of overhangs. [...] It was enough that it was warped a little bit, and [the user] was really unhappy with it. (O9)

With FDM printers, geometric constraints relating to overhangs and base size can be partially addressed using automatically generated scaffolding known as supports and rafts. Operators described a number of difficulties that casual makers faced in understanding when these features would be required. In an attempt to smooth these difficulties, many print centers enforced final check-overs by the operators on users' designs and print settings before printing to reduce failed prints. Casual makers often did not realize that they had made a mistake, and depended on operators for this check-over, and for guidance on how to design more viable forms or choose more suitable print settings:

People forget to add supports to their designs if there are overhangs on them. Then they just fall right to the build plate. They'll be disappointed. Sometimes they'll be here for a while because I'll be on lunch or something and then I'll come back and they'll be like just add supports and it will be fine. They don't want to redo it...(O5)

However, even operators were sometimes not able to troubleshoot due to their limited formal training in 3D printing, leading to difficulty in evaluating printability. In the 3D printing workflows, casual makers often failed to realize that the decisions they made in producing a 3D model (Figure 2.2) would influence their success further on in the workflow. While operators provided some support, their lack of expertise and limited availability meant that casual makers still encountered errors, requiring them to return to earlier points in the workflow and contributing to increased frustration.

Given these difficulties, I asked casual makers if they had tried out online commercial print services (*e.g.*, *Shapeways*⁷). These services allow users to upload 3D models to be printed by professionals using high-end machines, freeing end users from having to learn the mechanics of a 3D printer. However, to my surprise, these services only came up in 1 interview with a casual maker and 1 with an operator. These interviewees cited the high cost of these professional services and long waiting times for printing and shipping (often, over a week) as current deterring factors.

Limitations

Snowball sampling may have introduced bias by oversampling from specific communities. I looked for users who have recently attempted 3D modelling and printing, regardless of whether they were successful. However, users who were not successful may be less likely to come forward. Additionally, my sampling excludes users who were deterred from ever attempting 3D printing due to the perceived difficulty. Future work may look into other recruiting methods in an attempt to capture a wider range of experiences.

Summary

Current research and popular press suggest that consumer-level 3D modelling and printing are challenging, but one contribution of this study is in highlighting where exactly the challenges lie in the casual makers' workflows and how this class of consumers is different from makers and enthusiasts. Furthermore, I show that print centers are different from traditional makerspaces, lacking access to the networks of expertise that have made the latter popular among more experienced users. My key findings suggest that:

- Casual makers rely heavily on social help seeking, depending on operators' expertise and support at every step in the 3D printing workflow, although this is limiting due to the operators' lack of expertise and limited time.

⁷ <http://www.shapeways.com>

- The 3D printing workflow contains many interdependencies, with decisions made at one step affecting a user's success or failure in many others.
- The use of downloaded 3D models to sidestep the complex 3D modelling process is popular, but doesn't match casual makers' highly specific output goals. However, a good empirical understanding of the site did not yet exist leading me to investigate it further as described in the next chapter.

Chapter 4: Understanding Online 3D Model Sharing⁸

As seen in the previous chapter, as an alternative to learning 3D modelling users often turn to online communities such as Thingiverse [8] to download and print community-contributed 3D design files (Figure 6). Thingiverse is the largest online 3D modeling community [69] and allows users to share, download, customize and print 3D designs. Thingiverse contains over 1 million 3D designs, has over 2 million active monthly users, and sees 1.7 million downloads per month [69].

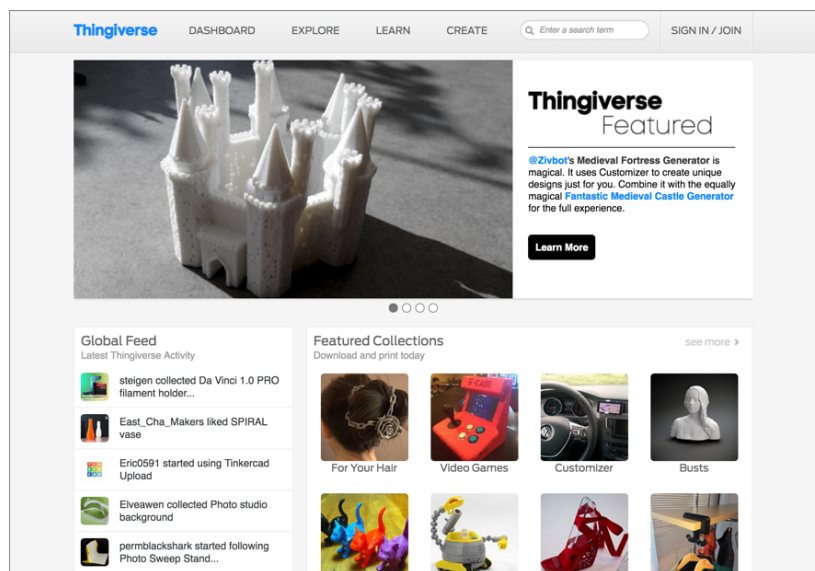


Figure 6: The Thingiverse homepage, showing a number of user-contributed designs

⁸ A version of this chapter has been accepted for publication at the 2016 ACM Conference on Supporting Groupwork [1]. The qualitative work in this chapter is a collaborative effort between myself and Celena Alcock.

Thingiverse provides an embedded social platform (Figure 7) for users to post comments and questions on individual 3D designs. In fact, a quick inspection of popular designs on Thingiverse shows that some designs have drawn over 200 comments within a span of a few days of being shared. However, despite the growing active user community on Thingiverse, we know little about how users actually make use of this social platform in tackling 3D design and printing tasks. Knowing the content of design-specific comments and questions can help us better understand the kinds of challenges that may exist for end users and how community participation could be improved on platforms like Thingiverse.

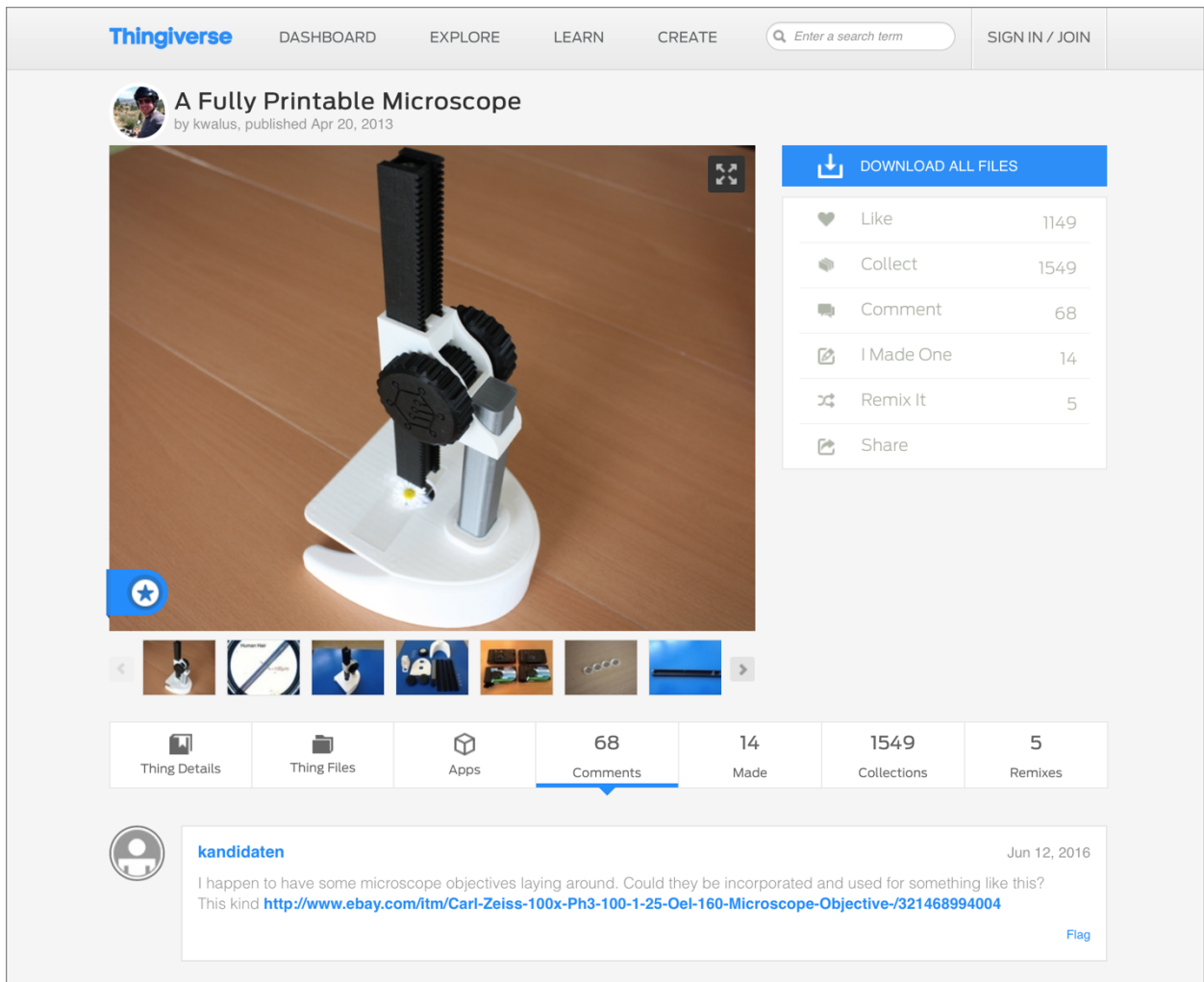


Figure 7: A popular 3D design on Thingiverse for a microscope showing a user’s comment

In this chapter, I investigate users' conversations on Thingiverse to understand their experiences in using, customizing, and printing premade 3D designs. I carried out quantitative and qualitative analyses to systematically explore user activities on Thingiverse and the content of users' questions, comments, and responses. My main findings reveal 4 key barriers that users faced in understanding: 1) how a given 3D object would be used or assembled in real life; 2) how a design could be customized or remixed; 3) how a 3D object would print on a given 3D printer; and 4) how a 3D design was actually created. My findings show that although Thingiverse plays an instrumental role in helping users get started with basic 3D printing, there are many opportunities for designers to provide richer metadata, clarifications, and expert tips to help users succeed in printing objects and customizing existing 3D designs. My primary contribution is in establishing an understanding of the barriers in using, customizing, and printing premade 3D models based on users' conversations on Thingiverse.

Research Approach

To understand users' conversations on Thingiverse, I carried out a study in two parts, as described below.

User Activities on Thingiverse

To get a snapshot of various user activities on Thingiverse, I used their API to download metadata for a sample of 23285 designs, design-specific comments (n=22952) and user profiles (n=21893) of the designers and commenters. I randomly selected this sample from public Thingiverse designs in September 2015 and only considered designs that had been available for at least 4 weeks to ensure that users would have had some time to explore the designs. I looked into the different categories of designs that were uploaded on Thingiverse (Table 2), how actively designers and users were commenting on individual designs, the different file types being shared, and to what extent designs were being customized.

Discussions on Thingiverse

Next, I carried out a qualitative analysis to understand the content of users' design-specific conversations in more detail (this qualitative analysis was completed in

collaboration with Celena Alcock). I used a uniform random sample of 500 designs and the corresponding comments (n=2202) as our dataset, restricting it to Thingiverse uploads that were designed for 3D printing (i.e., excluding designs for laser-cutting) and had at least one comment. To carry out the qualitative analysis, I wrote a custom web application that displayed the comments to be coded in context of the conversation and the 3D printable design, making it easier for us to understand the (often esoteric or complex) designs.

Data Analysis & Classification Scheme

To systematically classify the content of conversations on Thingiverse, I first created a separate random sample of 120 designs with 460 comments. With assistance from my collaborators, I conducted an open coding analysis [56] to look for frequently occurring topics. While studying design-specific Q&A, we discovered a wide range of posts, from praising the designer for his/her work to requesting links to similar designs, to understanding how to purchase materials needed for printing the design. Furthermore, users contributed a lot of miscellaneous information on extraneous topics, such as comparing printers (unrelated to the design), jokes, pop culture discussions, and questions about items that were not a part of the design. Using these observations, we iteratively developed our coding scheme until the researchers settled on a list of 8 codes (shown in Table 4).

To assess the reliability of our coding scheme, I extracted a new random sample of 100 Thingiverse designs with 350 comments, and two researchers individually coded each of the comments. To find the overall agreement between coders I computed the Cohen's Kappa score and found strong agreement in the coding of the Thingiverse discussions ($\kappa=0.82$).

We applied our final coding scheme to the 2202 comments in our sample. In most cases, we assigned only one code to a comment, with the exception of a few longer comments.

User Activities on Thingiverse

Before presenting my main findings on the barriers that users faced in using, customizing, and printing premade 3D designs, I will provide a brief overview of user activities on Thingiverse.

Design Categories Selected by Users

The Thingiverse community is made up of many different types of designs. When designers upload their models to Thingiverse they are required to choose a category that best represents their design, such as art, household, gadgets, 3D printer parts, and tools. In my larger random sample of 23285 designs, I found that the largest number of designs (20.0%) were in the household category, followed by art (14.5%), 3D printing (14.4%), and fashion (9.9%). Table 2 shows all of these categories and commonly shared designs within each category (except the 8.6% of 3D designs that were uploaded to the “Other” category).

Types of Files Shared by Users

Thingiverse users have several options for uploading their 3D design files. Although the majority (84.0%) of files in my sample were 3D models in the STL file format, I observed 197 different file types in my sample, including source code files, 2D graphics,

Table 2: Top 8 Categories of Designs on Thingiverse

Category	% of	Example
Household	20.0%	Toothpaste tube squeezer
Art	14.5%	Vases, replicas of statues
3D Printing	14.4%	Printable 3D printer parts
Fashion	9.9%	Bracelets, keychains, charms
Hobby	8.3%	Parts for RC vehicles
Gadgets	7.2%	Virtual reality headsets
Toys/Games	5.6%	Printable catapult
Models	5.1%	Figurines of characters
Tools	4.8%	Screwdriver handles
Learning	1.7%	Models of human bones

and spreadsheet files. The next most common file types were dramatically less common: *OpenSCAD* .SCAD files (3.7%), *SketchUp* .SKP (2.0%), and *Solidworks* .SLDPRT files (1.2%). This fragmentation puts users who want to customize a 3D model in a difficult place—even if the 3D design’s source file is available, it may be in a format for software that the user is not familiar with or cannot easily access.

Likes and Comments on Designs

Similar to many social platforms, Thingiverse allows users to “like” designs so that they can build up a collection of favorite designs. Overall, a given 3D design attracted an average of 14.8 likes and 1.0 comment (0.3 comments by the designer who uploaded the design file). Objects in the Models and Toys & Games categories attracted the most likes, with 37.8 and 27.6 likes per design on average, while Fashion-related designs attracted the fewest (6.7 on average). Comment length, which averaged 30.4 words per comment, also varied across categories. Users in the 3D Printing category, for example, wrote longer comments averaging 37.7 words per comment, while users commenting on Art designs wrote the shortest comments (16.5 words on average). For more detail, see Table 3.

Remixing and Customizable Designs

Table 3: Likes, Comments and Author Comments by Category (Darker shades indicate more)

Category	Average Number of Likes	Average Number of Comments	Average number of comments by the design's author	Average comment length (in words)
Household	8.8	0.4	0.1	25.4
Art	8.1	0.7	0.1	16.5
3D Printing	15.8	1.6	0.6	37.7
Fashion	6.7	0.3	0.1	22.4
Hobby	17.7	1.5	0.5	33.0
Gadgets	14.1	0.8	0.2	28.6
Toys & Games	27.6	1.2	0.4	31.6
Models	37.8	1.7	0.5	26.6
Tools	12.7	0.6	0.2	29.5
Learning	19.2	0.9	0.2	36.7
Overall	14.8	1.0	0.3	30.4

One phenomenon of particular interest on Thingiverse is remixing, where a new variation on a design can be created to meet a different set of needs or constraints [42]. For example, an uploaded phone case might be remixed to include a sports team's logo, or an uploaded tripod can be remixed to use metric screws instead of imperial. Remixes may be roughly grouped into two categories: parametric and freeform. Parametric changes consist simply of altering the object's existing parameters, such as changing the diameter or width of the wheels on a car [67]. Conversely, freeform changes involve the addition of entirely new elements to the design, such as changing the wheels on the car to tank treads.

While remixes can be created manually by importing a 3D model into a typical 3D modelling application, Thingiverse also offers the *MakerBot Customizer* tool (Customizer, for short), a built-in web application that allows for limited 3D design remixing. This tool allows objects that have been modeled in a specific manner using *OpenSCAD.org* to be altered in parametric ways, such as changing the diameter of a ring, or the text on a nametag [70]. These changes can only be made to existing parameters of an object (i.e., the size of a box or the text on a nametag). These are

known as parametric changes. New freeform changes (i.e., adding wings to a nametag that previously had none) cannot be added using this tool. Furthermore, any parameters that can be customized must be explicitly identified by the designer of the customizable design in the SCAD file. After the designer has uploaded this customizable design, other users can alter these parameters using a simple web interface to generate 3D printable STL files.

I found that the Customizer tool was popular among users: close to half of all designs (n=10613, 45.6%) in my dataset had been generated using this tool. However, I also found that all of these customized designs were derived from a small number of 1298 unique parent customizable designs. Furthermore, my dataset included only 236 designs (1.0%) that could actually be customized using the Customizer tool. This suggests that only a small number of designers were creating Customizer-compatible designs, but, if they did make such designs available, users were likely to generate a large number of derivatives. These customizable designs also received about 6 times more likes (89.4 likes/object) compared to 14.1 likes/object across the whole repository.

User Participation in Discussions

My analysis of individual users who commented on designs revealed that in my dataset these users were highly active on the site, with 89.9% having liked at least one design, and 64.4% having liked 10 or more designs. More surprising, however, was that 84.0% of these commenters had at least one design uploaded to their profile. This suggests that users who participated in design-specific discussions tended to be more experienced with Thingiverse (in fact, 43.8% of commenters had uploaded at least 10 designs).

Based on my qualitative analysis of the 2202 design-specific comments, I have listed the most frequent to least frequent discussion topics within these comments in Table 4. As with activities on other online forums, I observed that people also used the Thingiverse social platform to post miscellaneous comments, insults, and praises. However, I will focus the next section of my results on conversations that were specific to barriers in using premade 3D designs.

Table 4: Classification of Design-specific Comments

Code	% of sample	Example	Top Category
Understanding Object Functionality	26.78	"What makes the watch sit up in the cradle?..."	3D Printing
Understanding Design Customizability	23.94	"Any chance you can post the .scad file so I can modify it?..."	Hobby
Praises/ Positive Reports on Designs	17.13	"it's beautiful"	Models
Understanding Design Printability	14.50	"Would you suggest adding exterior, full, or no support?"	Learning & Models
Miscellaneous Q&A	7.28	"Nothing to do with your part, but I need to vent!..."	Fashion
Understanding Design Creation	6.48	"This is too cool. What did you use to make this?"	Toys and Games
Discussion on License Choices	3.43	"You could make the license include no derivatives, but that is not what you selected."	Gadgets
Insults/ Negative Reports on Design	0.48	"Man, this part is full of mistakes"	Toys and Games

Barriers to Using Premade 3D Designs on Thingiverse

Prior work shows that there are many stages and barriers around creating and printing 3D designs from scratch [8,20] and non-professional users turn to Thingiverse in hopes of getting easy access to premade designs. However, my results show that this path can also present a number of challenges. Below, I highlight 4 key barriers based on users' questions, comments, and requests posted on individual Thingiverse designs. I also discuss the barriers in relation to the categories (Table 2) that users selected to classify their designs on Thingiverse.

Understanding Object Functionality

Before users download a design from Thingiverse to print, they need to understand what the design is, how it functions, and in some cases, how it would be assembled after printing. In fact, I observed that understanding the functionality and assembly of the object being designed was the most frequently occurring code in the classification (26.8%). For example, a common question asked by users was simply:

"I don't get it. It looks cool but what is it?..."

Other users had more specific questions about the assembly:

"I have not built a core xy printer yet so i am no expert but i have to ask about the belt tension. Don't you need a way to tension each belt [separately] to ensure that they have the same tension?"

Although questions about object functionality occurred frequently among all of the categories on Thingiverse, it was the most common type of question in the 3D printing category. In response to the often complex 3D printing tool designs users asked questions such as,

"if I understand how this works shouldn't there be some sort of feedback to the firmware to adjust the bed during print?"

As might be expected, fewer questions about object functionality were seen within the Art and Models categories, which featured more ornamental and less mechanical designs.

Understanding Design Customizability

When users were not satisfied with an existing premade 3D design on Thingiverse, they often asked for a remix or customization (i.e., a change in the design file). In fact, questions about customizing or remixing designs were the second most common theme (23.9%) in my sample. For example, users asked for clarification or made specific requests:

"It looks very nice. Can you please release a version that's just one subcube? I think it would be a lot more workable."

Such requests varied from resizing object parts, adding parts onto designs, or modifying functionality of objects. The hobby and household categories had the largest number of such customization requests.

I also observed that a large number (86%) of customization-related comments were about improving or changing the design's functionality and a small number of comments (14%) were about improving the design's printability. These types of discussions involved comments such as

"Nice improvement on my design! Less print time and less plastic!"

And

"It's too tall for a replicator [printer] so it'd have to be split in 2 parts".

My analysis further revealed that discussions around parametric changes such as changing an object's thickness, length, and adding text to the design accounted for 36% of the comments in remixing for custom needs. These types of requests included comments such as,

"[My] Wife has [a] miniature owl collection - I'd like to print a couple half sized ones. Can you provide scaled down versions[?]"

Surprisingly, freeform changes (which are not possible through Customizer) accounted for 64% of remixing comments. Even if designers were to publish Customizer designs, many of the freeform user needs would still be unmet.

Overall, I found that users only received the customizations they asked for about one third of the time (32%). This was for to several reasons. For example, sometimes users requested designs that were not practical or would not function as well as the original design, with one designer replying to a request:

"I just don't know if it will be stable / wobble free and if I have enough clearance for it to rotate."

Other times designers simply did not have time to follow-up to the request:

"It's not hard necessarily, just tough to make it look nice...I just need to find the spare time to make it."

In other instances, designers simply did not respond to requests or users did not follow up to questions about dimensions or other desired features.

Understanding Design Printability

Another common barrier revealed in the Thingiverse conversations was trouble with understanding how to properly print the 3D design (14.5%). Users often did not know the correct print settings and it was difficult to receive help since different printer models and setups often required different settings. Common printer settings that were asked about included support structures (used to prevent the design from drooping or falling over during printing), infill (the percentage of the model that should be filled in with material when printed), wall thickness, scale, and printer fan speed. For example, one user posted,

"I [am] new to 3d printing and I really like this file. I am still confused on what supporting is and how to do it so that I can successfully print this blade..."

In addition to diagnosing problems and troubleshooting, users asked the designer about what printer they used, what filament was used, and how long it took to slice and print:

"every time I try to print this it starts spitting filament out in the air when it gets past the handle. could somebody tell me what settings they printed this with?"

Designs within the model category received the most questions on printability, and many of them were on support structures. Surprisingly, the 3D printing category overall had the fewest questions on basic printability.

Understanding Design Creation

Although users often turn to Thingiverse to download premade models so that they can bypass the complex 3D modelling tasks [5], my analysis showed that many conversations (6.5%) on Thingiverse were actually about learning 3D design. For example, users were often interested in knowing what software was used for the 3D design ("*...how do you make one of these?*") and some asked for the actual source files for the design ("*Hey, do you happen to still have the model file lying around?*"). Some users described more advanced usage, such as how to extract 3D models from video games, or how to import models into new pieces of software:

"Any tips on how to explode this file in the latest version of Sketchup?"

As discussed earlier, users upload design files in hundreds of different formats to Thingiverse. My analysis further showed that users often do not know the difference between file formats:

"I'm just curious as to why some of the files are ".stl" and some ".obj", or more specifically, why not all files in one format or the other?"

Other comments revealed users' frustration in attempting to modify STL files:

"I don't understand how one is supposed to convert this into a stl (or other 3d printable file). I've tried inkscape, openscad, and a number of others. Anyone with knowledge, please help!!"

These comments were particularly common in the toys and games category.

Summary

In this chapter, I have presented results from my quantitative and qualitative analyses of user activities and users' design-specific conversations on Thingiverse. Among my key findings, I found that Thingiverse was not merely being used to share premade 3D models—in fact, a rich culture of help-seeking and help-giving exists, with discussions revolving around how a design actually functions, how it will print, how it can be customized, how it was originally created and more. This reinforces my observations from Chapter 3 of the social nature of help-seeking for 3D modelling and printing that I saw with casual makers. Additionally, I found that commenters on Thingiverse were not just consumers of premade 3D models and a large majority of them (84%) had uploaded at least one design. However, even these more experienced users tended to face a number of barriers in communicating design intent and understanding how a design object actually functions, how it will print, how it can be customized, and how it can be designed from scratch. These findings help inform the design I present in the next chapter of a system for facilitating in-application social Q&A for 3D modelling.

Chapter 5:

Designing Contextual Q&A for 3D Modelling

As seen in Chapter 3, help seeking in a public print center is a highly social process, with casual makers depending on operators. In Chapter 4 I also observed a culture of help-seeking through online conversations on Thingiverse. However, in both cases this social help-seeking was hampered – casual makers had only indirect access to true expertise, and Thingiverse users faced considerable difficulty communicating design intent. Allowing novice users to more easily seek help and advice can empower these users to more easily create designs that match their own highly specific design intent and streamline their learning process. Accordingly, I decided to investigate how social contextual Q&A might be embedded into 3D modelling tools. Although the primary contribution of this thesis lies in the empirical research found in the preceding two chapters, I wanted to provide an early vision and early exploration of a system that may assist help seekers in the 3D modelling domain.

Motivation

Reliance on External Expertise

In Chapter 3 I observed that almost all of the casual maker participants were deeply dependent on print center operators to bootstrap their 3D printing workflow and to troubleshoot. Given my observations, I believe that this dependency will not easily go away even if we improve the usability of fabrication tools because of the output-driven custom needs of casual makers and lack of interest and time in gaining expertise in the underlying domain. Therefore, we have to view 3D printing for casual makers as a

highly social activity and there may be numerous opportunities along this path to support casual makers' workflows. For example, it may be possible to integrate expert tips, advice, and explanations to applications throughout the printing workflow.

Some recent tools have already started exploring ways of helping users share expertise and learn socially within web-based and desktop software applications [9,30] as well as within programming environments [19]. But, for the population that I studied, the useful information would not just be about troubleshooting software or hardware internals, but also about best design practices and domain-specific nuances and “tacit ways of knowing” [46] that can take years of experience to develop. In particular, since print center operators were lacking the kinds of expertise prevalent in makerspaces and have only limited time to assist users, there may be opportunities for end users to connect virtually and in-context to other end users in need help and advice.

Communication of Design Intent

My analysis in Chapter 4 showed that many Thingiverse users had to resort to asking the designer how the design functioned, was assembled or was 3D modelled. STL files (that are most widely used on Thingiverse) currently lack context on their own, and users were observed to face considerable difficulty effectively communicating specifics of functionality, printability, assembly and more. This suggests that users may benefit from the ability to access details such as assembly and design intent directly from the shared file. Users may also benefit from better interchange file formats or better sharing systems that also communicate their designs' context within the world by including information on the author's design intent or details such as how the design was created.

Problem Scenario

Consider an inexperienced user who is seeking advice or instruction from another more experienced user over the internet. Existing systems for sharing 3D models online, such as Thingiverse or simply attaching the 3D model to an email, require a user to communicate through text separate from the actual 3D file. In order to successfully seek help the inexperienced user will have to describe their design intent and how it relates

to their existing model. However, help-seekers new to a domain often have difficulty effectively describing the problems they face. As I saw with my analysis of Thingiverse, even users experienced with 3D tools had difficulty describing the design intent behind their models. Ultimately, help seekers face a considerable challenge explaining exactly what features of a model they are referring to or what their design intent is when seeking help.

Design Goals

To address these issues, I explored the design of MarmalAid (Figure 8), a 3D modelling tool featuring a novel commenting and Q&A system. MarmalAid is designed to allow novice users to easily communicate within the context of their existing file while seeking help, and allow more experienced users to share richer files and communicate design intent when sharing 3D files with others. These were the three main goals that guided my design:

1) Facilitate Contextual Help Seeking

I sought to support online help seeking by allowing information to be shared within the context of a user's existing 3D model, by allowing users to attach media, links, feedback, questions and explanations to either the model as a whole, or to specific parts of the model in 3D space.

2) Streamlined Sharing

I wanted sharing MarmalAid designs to be as straightforward as possible. I designed the system to be flexible in how designs were shared, allowing users to either share through MarmalAid's built-in email system, or by simply copying a URL.

Unlike Thingiverse or email sharing, which share links to static files, I designed MarmalAid to share links to an online dynamic document so if any user makes a change to a shared document that change is reflected for everyone.

I also sought to make it as straightforward as possible for the receiving user. While most other 3D tools would require the assisting user to have the software already

installed, I sought to create an all-online system to give the assisting user instant access to the shared model and tools to edit it directly from their web browser.

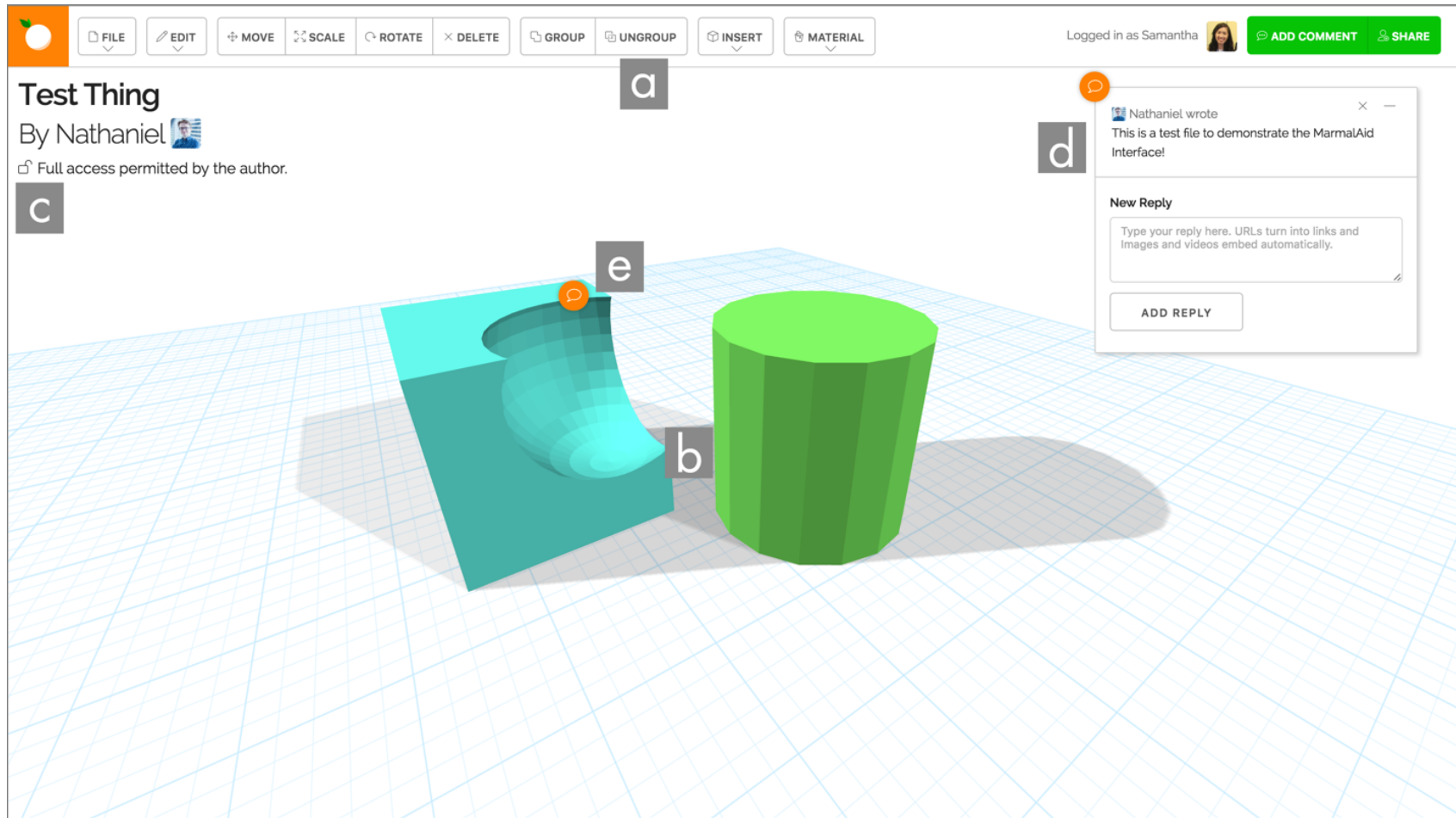


Figure 8: MarmalAid interface overview. a) Toolbar, b) 3D workspace, containing some geometry, c) File information, including file name, author name, and file permissions, d) an expanded comment attached to the entire document and e) a collapsed comment attached to some 3D geometry.

3) Exchange Native Formats

I wanted my sharing system to exchange native formats without loss of information, such that new users can learn from and remix existing designs. Accordingly, I designed my system to share original source files, which makes it easier for users receiving the shared design to remix and modify the design. Furthermore, I wanted my system to preserve and display the document's complete edit history to allow new users to view the document's entire creation process and jump to any point in it.

Features

MarmalAid features a basic constructive solid geometry (CSG) based modelling system by which predefined shapes (such as cubes, spheres, cylinders, etc.) can be transformed by rotation, scaling and translation, and combined in either additive or subtractive manners. Objects are marked as either solid or as a hole by the user, and the resulting mesh is computed when the objects are grouped (Figure 9). MarmalAid's feature set in this regard is very similar to and was informed by TinkerCAD, a popular beginner-oriented 3D modelling tool.

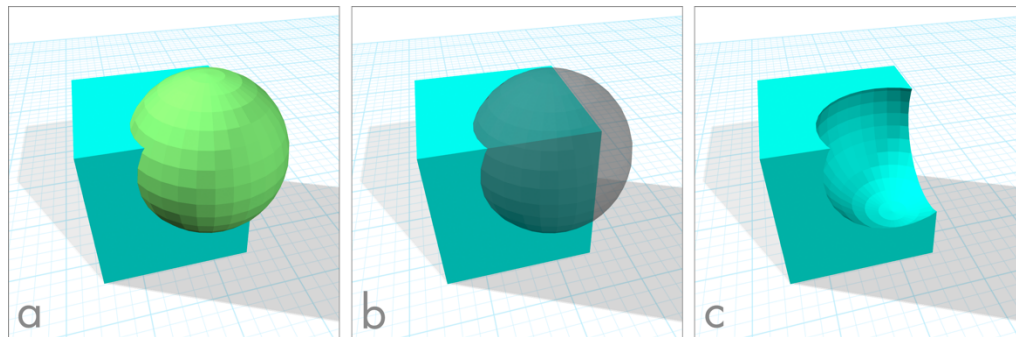


Figure 9: MarmalAid's constructive solid geometry tools. A sphere that intersects a cube (a) is marked as a hole (b) and grouped with a cube to cut the sphere away (c)

MarmalAid's primary novel feature is its comment system. These comments are designed to enable users to better explain their design intent and communicate when sharing files with others. Comments can be added to any point on the model geometry by selecting the comment tool and clicking on that part of the geometry. A comment will then be added to that particular point on the object in 3D space, and remains

attached to that point even if the object or camera is translated, rotated or scaled. These comments will collapse to an unobtrusive icon when not in use, and can be expanded again by clicking on said icon. Replies can be added to a comment by any user using the form at the bottom of a comment. Comments automatically recognize and embed media, such as images and online video when links to them are pasted in the comments (Figure 10).



Figure 10: A new comment is created (a) containing a YouTube link, which is automatically embedded (b), and can be collapsed down to an icon (c)

Comments can also be attached to the document as a whole, rather than any point on the 3D geometry, by clicking on the highlighted area on the right side of the viewport when the comment tool is active.

MarmalAid also saves a user's complete modelling history and allows them to easily jump to any point within it. History is not lost when a file is closed, and is shared along with the file. In addition to supporting standard undo/redo functions, the complete document history can be viewed as a list of steps. This makes it easy for a user who is assisting another to quickly see what steps have already been taken, and makes it easy for the user who is receiving the assistance to see what changes the assisting user has made.

Models can be shared in one of two ways. The user can simply copy their project's editor page URL and paste it into an email, chat message, or any other communication tool. When the recipient clicks on that URL it will open an online editor with the shared object loaded. For more fine-grained control a user can employ the share tool, which allows the user to select a recipient email address and permission mode. There

are three available permission modes: “I want the other user to edit my model for me”, “I want the other user to answer my questions or give feedback” and “I only want the other user to be able to look at or download my model”. These were chosen to match the types of requests and behavior that I observed from Thingiverse users in Chapter 4. When this share tool is used an email is sent to the recipient containing a link with an embedded access key that opens the MarmalAid online editor and enables the appropriate editing permissions.

Example Usage Scenario

Jack is a user new to 3D modelling, and has decided to model a castle to be 3D printed at a library print center as part of a tabletop game he’s designing. The library print center’s operator has given Jack a brief introduction to how to use MarmalAid, but is unable to provide further assistance because they too are inexperienced. However, the operator has given Jack the email address of Samantha, a local enthusiast who helped the library initially set up the print center, for Jack to consult if he needs help.

Jack begins modelling his castle. To keep track of what he’s building, he creates a new document comment containing a link to an image of a simple castle.

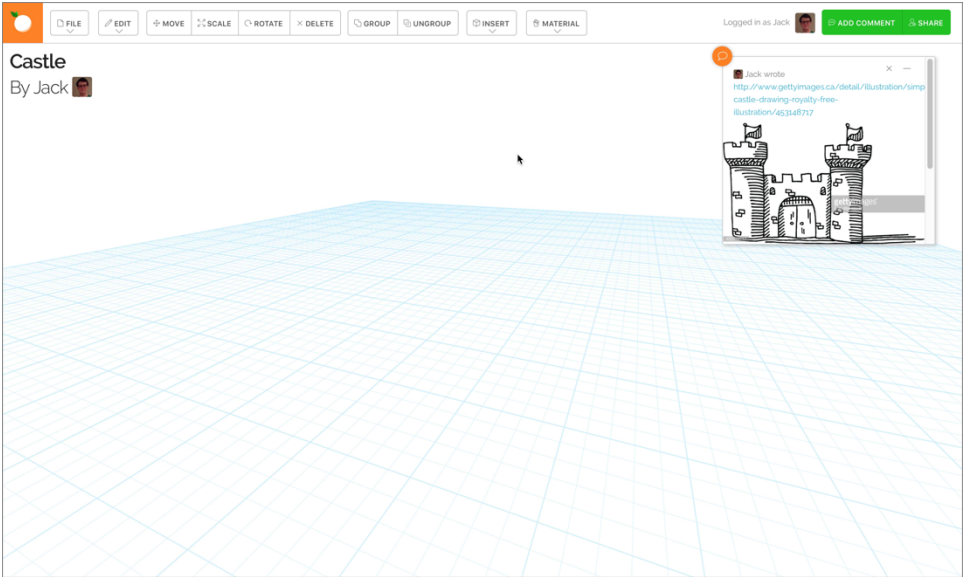


Figure 11: Jack's new document with his document comment

He places a box which he resizes into a wall, and a cylinder for a tower. He then places a number of cubes on top of the castle wall for crenellations. However, Jack discovers that this approach fails for the crenellations on top of the tower, as the cubes stick out over the edges of the tower. Stymied, Jack decides that he'll ask Samantha for help a bit later. He doesn't know the correct term for crenellations, but creates a comment on top of the tower where he describes his problem and leaves a link to a picture of a castle wall with crenellations.

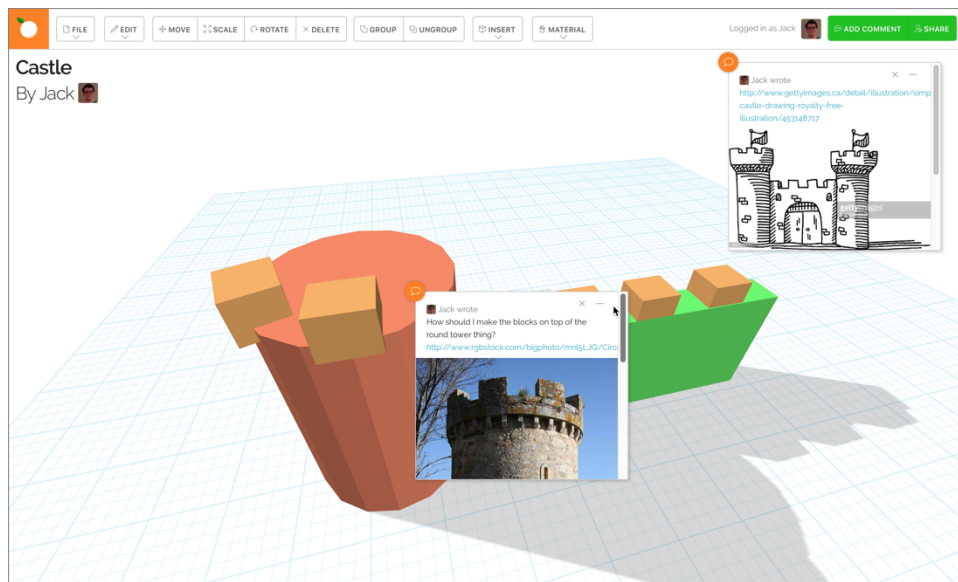


Figure 12: Jack uses a comment with a link to ask a question about his tower

Before Jack asks Samantha for help, he decides to try adding the castle gate. However, he can't figure out how to cut out the doorway shape from the castle wall. He searches the menus for a "cut out" command, to no avail. He leaves another comment on the castle wall he wants the door on describing how he can't figure out how to "cut out" the door, and decides to seek Samantha's help.

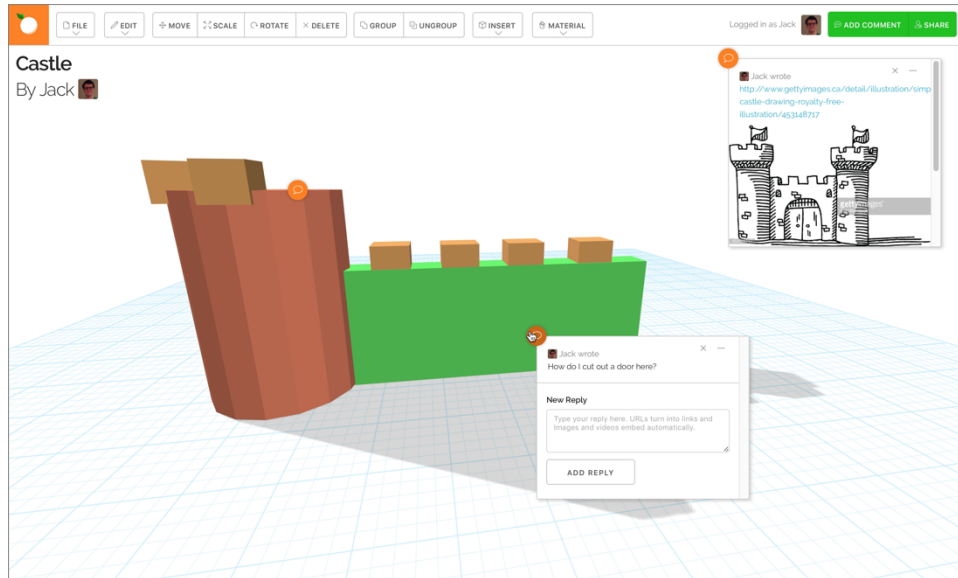


Figure 13: Jack uses a second comment to ask about putting a hole in his wall

He presses the Share button, and enters Samantha's email address. He decides he's experienced enough frustration and doesn't really want to spend any more time than necessary modelling the object, so he selects permissions that allow Samantha to edit his model freely. He then confirms his share and goes off to do other work while he waits for a reply.

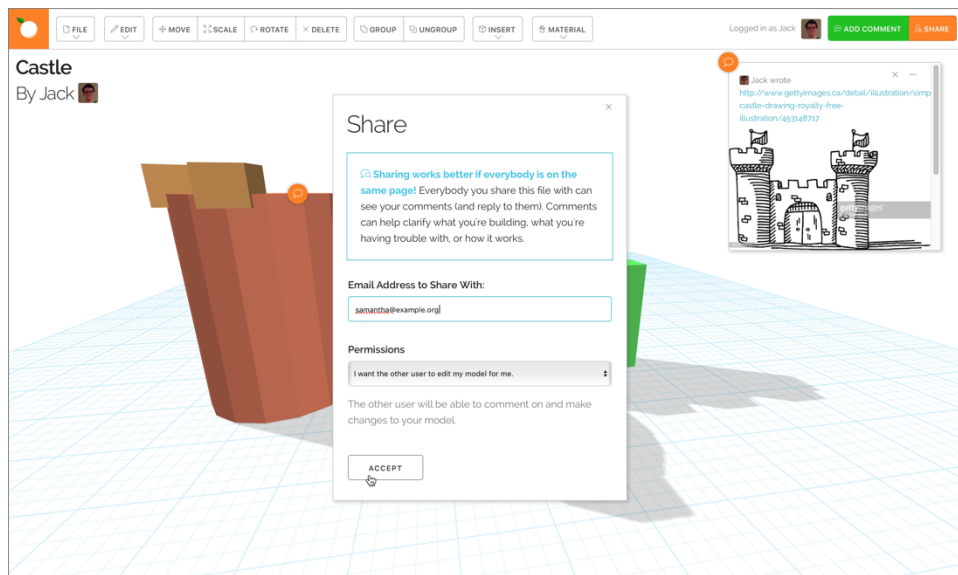


Figure 14: Jack shares the design with full edit permissions with Samantha

Samantha notices the new email in her inbox informing her that Jack has shared a new file with her. She clicks on the link in the email which opens MarmalAid in her web browser with Jack's file loaded. Samantha can see Jack's model as he left it, complete with all his comments. From his document comment she can tell that he was building a castle and roughly how he wanted it to look. She first looks at the comment Jack left on the tower of his castle. Although neither Jack nor Samantha know the correct term for crenellations, Jack's attached picture combined with the comment's position is enough for Samantha to figure out what Jack's goal was. She models the crenellations by subtracting a cylinder and some boxes from the tower. She replies to Jack's comment saying that she thinks she's solved the problem.

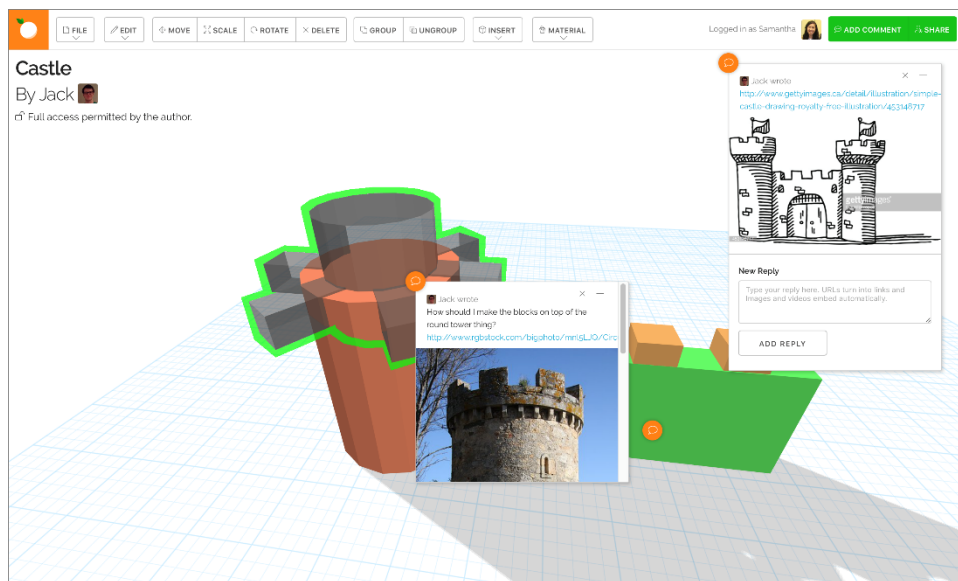


Figure 15: Samantha figures out that Jack was trying to create crenellations using his comments and makes the changes for him

Satisfied, she looks at the comment Jack left on the wall of his 3D model asking about cutting out a door. Although Jack was using the wrong terms to describe his problem, thanks to the comment Samantha is able to quickly determine that he wanted to subtract a box from the wall to leave a doorway, and where on the wall he wanted the door.

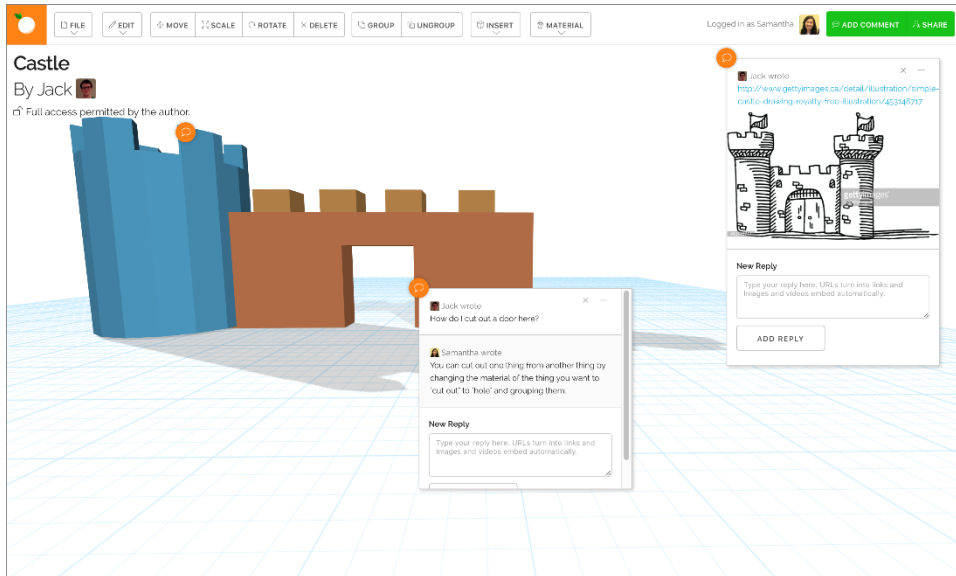


Figure 16: Samantha cuts out the door and replies to Jack's comment

Noting that both of Jack's problems were caused by not understanding subtractive geometry, creates a new document comment containing a link to a video tutorial which describes how subtractive geometry works in MarmalAid, which is automatically embedded into the comment. She saves her changes and closes the document.

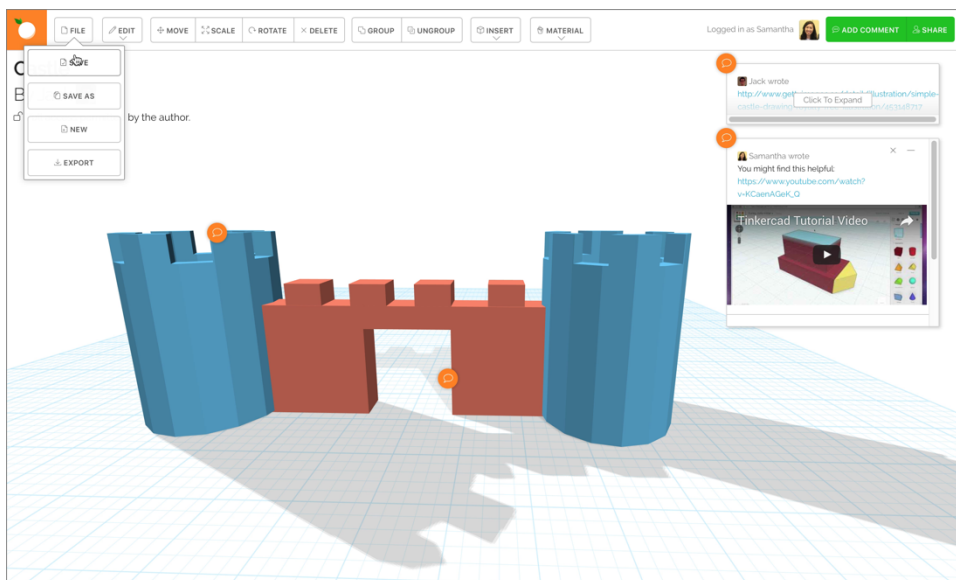


Figure 17: Samantha has made Jack's changes and attaches a tutorial video that she thinks will help him

Jack notices that his homepage on MarmalAid is telling him that his castle model has new changes that he hasn't seen yet.

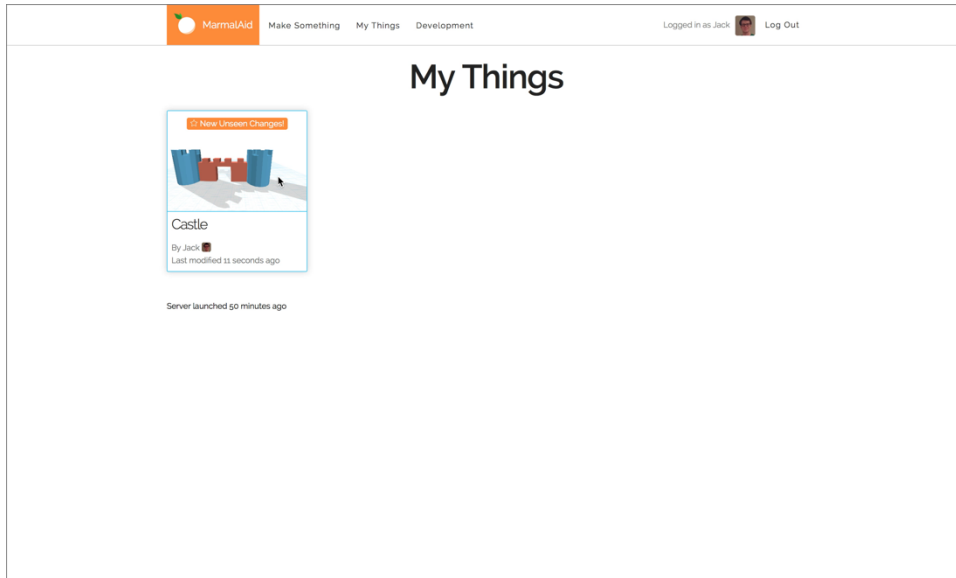


Figure 18: Jack's list of things, with the castle showing new unseen changes

He opens the model and sees Samantha's changes. He's happy with the changes and finds the tutorial video that Samantha added helpful, but is a little curious as to Samantha's workflow. To investigate it he opens up the history window, where he can see all the changes Samantha has made. After stepping through the operations that Samantha took and watching the tutorial that she linked, Jack feels much more confident for his future 3D projects.

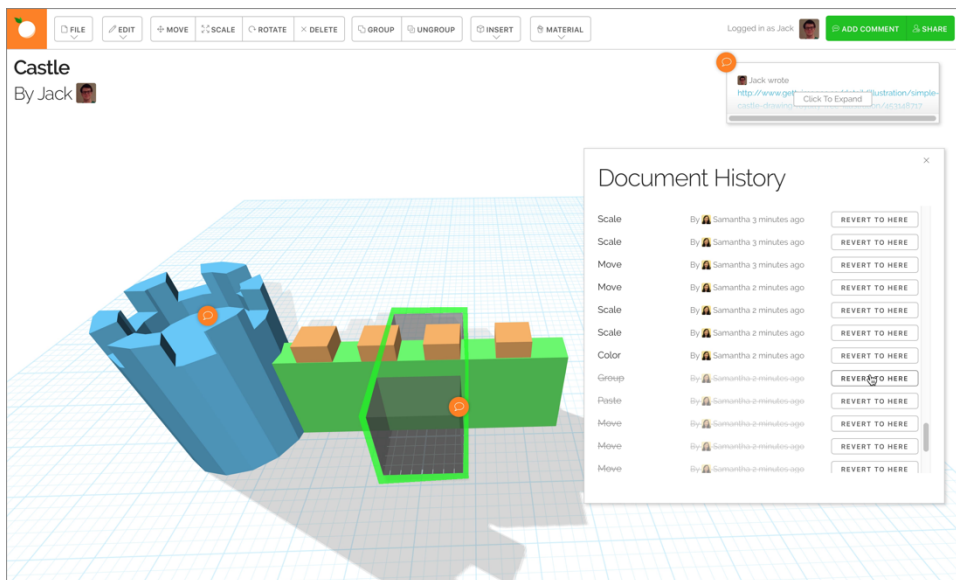


Figure 19: Jack uses the Document History window to explore the steps Samantha took to make her changes

Implementation

The majority of the MarmalAid system is written in client-side JavaScript, and is split into numerous modules each representing a tool, 3D object class, UI widget, and so on that are managed by Require.js⁹, a JavaScript module and dependency loader. The 3D viewport is rendered using WebGL, which allows for modern hardware-accelerated rendering to occur within a web browser. To manage the 3D scene and handle much of the vector and matrix math Three.js¹⁰, a Javascript-based 3D library, is used.

For Boolean mesh operations the CSG.js¹¹ library is used. The algorithm it employs is relatively simple, but works well enough for the purpose of this project. For most of the system's operation 3D objects are stored as triangle meshes. This simplifies rendering and 3D transformations, allowing for smooth real-time drag operations. However, when objects are combined binary space partition trees for both are generated, which are then processed by CSG.js which combines the trees and clips the interior portions of the resultant tree. The output from CSG.js is then converted back into a mesh structure for further operations.

As there are no non-web based client-side requirements, MarmalAid can be ran on any computer with a modern, standards-compliant web browser and a mouse. MarmalAid has been tested in Safari 9.1.1, Chrome 51, Firefox 47.0.1, and Internet Explorer 11.0.

The MarmalAid system has a server-side component written in Python 3.5 using the Flask web framework¹². The server handles functions such as user account management, file saving, file permissions, and email sending. MarmalAid also employs the Yahoo Query Language Platform¹³ to bypass cross site request restrictions and retrieve web page metadata which is used for image and video embed in page comments.

⁹ <http://requirejs.org>

¹⁰ <http://threejs.org>

¹¹ <https://evanw.github.io/csg.js/>

¹² <http://flask.pocoo.org>

¹³ <https://developer.yahoo.com/yql/>

Evaluation Approach

To evaluate MarmalAid's help-seeking approach, I carried out heuristic evaluations with 6 adult users: 3 users self-identified as being inexperienced with 3D design software and the other 3 self-identified as experienced users. Participants were between the ages of 21 and 34, all spoke English as a first language and had been using computers for at least 5 years.

This evaluation was conducted remotely over the internet, with inexperienced users being paired with more experienced users remotely. Users were given a five-minute introduction to the software which gave a brief overview of the modelling tools and showed how to activate the commenting and sharing tools. Experienced users were told to spend 15-20 minutes with the software to become comfortable with the various modelling tools. Inexperienced users were given a sample design scenario (described below) and told to use the software's help seeking tools to seek help if they became stuck, found something that they were unable to model, or felt they were finished with their design and wanted design feedback. The shared files were then sent to the more experienced users with instructions for them to provide help. When the experienced users were finished providing help to the best of their abilities the inexperienced users reviewed the feedback or changes. Finally, both groups conducted a heuristic evaluation of the system following Nielsen's guidelines [39] and a short questionnaire evaluating their experiences.

The scenario inexperienced users were given had them imagine that they were learning 3D modelling for a technology class, and had decided to create an airplane. The type of airplane was not specified, such that help-seeking users would have to make it clear to the help-giver when seeking help. The inexperienced users were also told that they had a friend who was willing to assist should they need help, and given an email address to share the file with. The more experienced users who were providing the help were simply told to imagine that they were providing help to a friend who had recently began learning 3D modelling for a class.

Initial Evaluation

Overall, both the help-seeking and help-giving participants were positive about the help-seeking tools. Help giving users enjoyed the ease with which they could seek help, and also expressed that they felt happy putting less of a perceived burden on the help-giving user: “I really like being able to get [another user’s] help without them having to put in a lot of effort”. Help seeking giving favorably compared MarmalAid’s help seeking tools to more traditional online help-seeking tools, noting that the tools facilitated clear communication: “This is much better than trying to figure out someone’s problems in a forum - way easier”.

Both groups of users requested more advanced social and communication tools. MarmalAid does not currently support any real-time collaboration, prompting some users to request the ability to see new comments and changes show up in real-time. A different user was content with the asynchronous nature of the current tools, but wanted notifications to be instantly sent to their phone when another user had saved a file. Finally, two users requested the ability to sketch simple 2D images or edit existing images directly from the application for situations where they were unable to find an existing image that clearly communicated their intent.

Summary

This chapter has presented the design of MarmalAid, a system that allows users to engage in social Q&A style help seeking directly within the context of their current 3D modelling task. Commenting and sharing features were designed to make this process as simple as possible for both the help-seeking user sharing the file, and the help-giving user who needs to determine the help-seeker’s intent. Although the design presented here is an early vision, user feedback has been positive, with users asking for further social and communication tools, indicating that this is a promising avenue for future investigation.

Chapter 6:

Discussion

This thesis has presented insights into of casual makers including their motivations, workflows and barriers, observations of current user practices and help seeking behaviors sharing 3D models online, and an early vision of in-application Q&A for 3D modelling. There are many ways to respond to the insights gained from this thesis, as discussed below.

The Importance of Casual Makers as a User Group

Previous work [17] suggests that software learnability can be affected by user characteristics, such as level of experience with computers, level of experience with the interface, quality of domain knowledge and experience with similar software. In the context of 3D printing, I also found that these characteristics affected how well newcomers learned 3D modelling software and 3D printing workflows. However, my study further shows that motivation and engagement are important characteristics that differentiate casual makers from other makers and enthusiasts. Whereas makers and enthusiasts are motivated by a desire to learn and experiment with new technology [24], the casual makers that I observed were more concerned with output and were likely to abandon 3D printing if the initial learning barrier was too high and they did not get their questions answered. These casual makers were more likely to give up after false starts and often did not want to make a long-term learning commitment. But, surprisingly, casual makers were still not enthusiastic about simply using premade models or online 3D printing services and showed a strong desire to be able to create custom objects using walk-up-and-use printers. These results suggest that there is a lot

of potential in HCI to better understand and support this emerging user group of casual makers to complement efforts on supporting makers, enthusiasts and professional users.

Print Centers Are Different from Makerspaces

A key observation that I made in Chapter 3 was that the print centers where casual makers went to use 3D technologies lack the strong sharing culture and informal network of expertise of makerspaces. In print centers, users sought help only from operators, who were often not formally trained in 3D printing. Unlike makerspaces, I did not see evidence of sharing completed projects for peer learning in that casual makers were more transient: they completed a project or experimented using the print center and then moved on. Rather than the peer-to-peer community of expertise exemplified by the original makerspaces, these print centers tended to form a much more hierarchical network similar to more traditional help and support structures [24]. Similar observations have been made in online hacking forums where there are tight-knit communities that collaborate extensively each other while others form looser collectives and users come and go without long-term engagement [62].

Shared Models Tackle Only a Part of the Problem

Another one of my key findings in Chapter 3 was that casual makers struggle the most in understanding the 3D domain, and current commercial tools have limited provisions for helping users understand the underlying domain. It is not surprising that we are seeing the emergence of tools (*e.g.*, Thingiverse) that allow users to share and contribute models so that they can bypass the modelling step. But, as explained before, casual makers and operators were not always satisfied by the experience of using Thingiverse as it was difficult for them to understand if a downloaded model would actually be printable on a walk-up-and-use 3D printing station. This illustrates a larger theme in my findings about the interdependency between the different stages of 3D printing workflow.

Supporting Customization

Perhaps the bigger issue that deterred some casual makers from using premade models was the lack of flexibility in customizing models. Many of them had tried to download and customize models, often with little or no success.

In spirit, Thingiverse encourages tinkering and all users to create, remix, and share 3D designs. In fact, the Customizer tool was added with the intention that even non-professional users could create customizable objects [69]. As I discussed in my results, about half of the designs observed had been generated using the Customizer tool. However, I have also shown several issues with this tool that emerged in my studies. For example, Thingiverse users frequently requested remixes that were freeform in nature and not possible through the Customizer tool. Additionally, casual makers' customization needs were often driven by highly specific and idiosyncratic goals for which there may not always be a suitable model available. Furthermore, designers appeared to be stymied by the difficulty of creating for the Customizer platform and shared only a small number of Customizer-ready designs. I observed that Customizer activity was largely driven by a small number of designers who were able to overcome those difficulties.

One potential avenue for research is investigating alternatives to *OpenSCAD's* scripting paradigm that could allow users to create parametric, customizable models through more user-friendly GUI interfaces. This would particularly be useful for non-professional designers who get frequent requests on Thingiverse to generate customizable versions of their 3D models but are not well-versed with complex scripting languages. More generally, there is merit in also exploring how users could more clearly see the level of difficulty involved in creating different customizations for a given design.

Supporting the Interconnected Fabrication Workflow

A key focus in the HCI community has been on making the 3D modelling step easier for end users, which I observed was a key challenge for the participants in my study. Projects as early as *Alice* [10] have worked to simplify how users understand 3D spaces and more recent innovations in augmented reality [64] and virtual reality [23] show

promise in simplifying understanding the 3D space. Sketch-based interfaces (*e.g.*, *Teddy* [21]) and gesture-based interfaces (*e.g.*, *Paper3D* [44]) have also demonstrated progress in ways of expressing 3D forms. However, as discussed above, I observed a strong interdependency between the different stages of the 3D printing workflow in that casual makers often struggled not only in creating models, but also in understanding how the model geometry affected output, or how print settings affected output.

Although recent tools such as *Meshmixer* [51] offer the potential to understand basic qualities of 3D printed output, such as overhang or balance analysis, I did not observe such tools to be in wide use at print centers as at present they still require significant domain-specific knowledge. There has been some exploratory work [13] that uses simulation of fabrication artifacts to visualize fabrication output, or uses interactive guided tools that help end users build more viable objects, such as structurally sound furniture [60]. There is potential in further exploring this space that can help casual makers better connect their design intent to output. Perhaps there could be “preview” techniques built into fabrication tools that would allow end users to actually experience their final printed objects and modify them on the spot. One promising research area is interactive fabrication, where the user’s object is constructed in real time as the user models it, allowing the user to immediately see the relationship between their 3D model and fabricated object, [36,66]. The insights from my study on the behaviors and practices of casual makers can further inform the design of such innovations in connecting digital fabrication workflows.

Augmenting Premade Designs

My analysis in Chapter 4 showed that many Thingiverse users had to resort to asking the designer how the design functioned, what the recommended print settings were, which type of printer was used by the designer, and what software was used to create the design. Other works have also documented these difficulties in terms of understanding print settings [42] and understanding changes to the design [11]. My findings suggest that there is opportunity to augment premade designs with printability and software-related information. For example, 3D modelling software could provide context on how a given feature may appear when printed. STL files (that are most

widely used on Thingiverse) currently lack context on their own—it could be useful for users to access details such as assembly and print instructions through text and pictures. Future research may investigate interchange file types or better sharing systems that also communicate their designs’ context within the 3D printing workflow by including details such as how the design is assembled and what print settings have been used for different 3D printers.

Further Opportunities for Integrating Expertise

The MarmalAid design presented in Chapter 5 is best considered as a first vision of what such a social Q&A system for 3D may look like, and there are many opportunities for improvement. Most notably, the current MarmalAid system does not offer any functionality for connecting novice users to other more experienced users who may be willing to provide help. Future work may further consider how to best enable help-seeking users to connect to other more experienced users who are interested in providing help. Furthermore, while MarmalAid targeted only the 3D modelling phase of the 3D printing workflow, additional opportunities for integrating expertise may exist at all stages throughout this workflow. Ultimately, helping novices take advantage of the fabrication knowledge that experts and enthusiasts have built up over years of experience will serve to lower the barriers for end users to create and solve problems unique to them.

Additional Populations

Future research may also examine groups that were excluded from this research study. For example, young newcomers to 3D modelling and printing (i.e., less than 18 years old) were not included in Chapter 3’s examination of casual makers due to methodological and ethics concerns, but may be useful in informing the design of future novice-friendly tools. Additionally, our sampling methods may underrepresent users who were unsuccessful with 3D printing, and do not include any who did not even attempt it due to perceived difficulty. Future work may seek to examine these groups to gain a more robust understanding of all types of newcomers to 3D printing.

Chapter 7: Conclusion

Current research and popular press suggest that consumer-level 3D modelling and printing is challenging, but this thesis highlights where these challenges lie in the workflows of novice users and how this information may be better leveraged in the design of the next generation of interconnected fabrication tools. In Chapter 3 I have contributed an in-depth analysis of casual makers' interactions with walk-up-and-use 3D printing services, illustrating their typical workflow and highlighting the barriers that they faced in every step of the process. Furthermore, I show that print centers are different from traditional makerspaces, lacking access to the networks of expertise that have made the latter popular among more experienced users. Based on the observed popularity of Thingiverse among casual makers, Chapter 4 examined the emerging practice of sharing 3D models online and how simply making premade 3D design files available to download is not enough for them to be effectively modified or printed by many users. As a result of the social nature of help-seeking observed in public print centers and online conversations on Thingiverse, I introduced an early vision of what a 3D modelling tool with integrated Q&A help-seeking may look like in Chapter 5. Ultimately, I recommend that future fabrication tools consider the interdependencies within the 3D modelling and printing workflow as well as the social nature of learning 3D modelling and printing.

Letters of Copyright Permission

From: **Celena Alcock** celena.alcock@hotmail.com
Subject: **Permission to use co-authored work**
Date: **August 14, 2016 at 12:26 PM**
To: **Nathaniel Hudson** me@nathanielh.com

August 14, 2016

I, Celena Alcock, give Nathaniel Hudson permission to use co-authored work from our paper(s):

- Celena Alcock, Nathaniel Hudson, and Parmit Chilana. 2016. Barriers to Using, Customizing, and Printing 3D Designs on Thingiverse. Proceedings of the ACM Conference on Supporting Groupwork.

for his Master's Thesis and to have this work archived in the University of Waterloo institutional digital repository.

Sincerely,

Celena Alcock

From: **Parmit Chilana** pchilana@uwaterloo.ca
Subject: **Re: Updated version of earlier form**
Date: **August 15, 2016 at 8:36 AM**
To: **Nathaniel Hudson** me@nathanielh.com

August 15, 2016

I, Parmit Chilana, give Nathaniel Hudson permission to use co-authored work from our paper(s):

- Celena Alcock, Nathaniel Hudson, and Parmit Chilana. 2016. Barriers to Using, Customizing, and Printing 3D Designs on Thingiverse. Proceedings of the ACM Conference on Supporting Groupwork.

- Nathaniel Hudson, Celena Alcock, and Parmit K. Chilana. 2016. Understanding Newcomers to 3D Printing: Motivations, Workflows, and Barriers of Casual Makers. Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.

for his Master's Thesis and to have this work archived in the University of Waterloo institutional digital repository.

Sincerely,

Parmit Chilana

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Appendix A:

Interview Materials

The following are the interview questions used in the semi-structured interviews with newcomers to 3D printing and print center operators described in Chapter 3.

Questions for Newcomers to 3D Printing

Briefing:

- Tell them about the purpose of the study, your goals, who you are, etc. for 2 min
- Sign all the consent forms, give them gift certificates (if applicable)

Background

1. Tell me about your current job, role, or what you do in this [lab, library]...
2. What kind of training/educational background do you have?
3. How long you been working with 3D printers? In what capacity?
4. How comfortable do you feel with 3D printers?

Perceptions of 3D printing technology

1. What have you used 3D printing for? Why?
2. Where do you typically go for 3D printing (Home, library, makerspace, online...)? Why?
3. What is your 3D printing process? Think about from the beginning how you start, etc. all the way to printing your desired object.

Perceptions of 3D modelling technology

1. What was it like when you created your first 3D object?
 - a. What did you use? How did you get help?
2. What software do you usually use to model 3D objects? Why? [Can you show us?]
3. What do you like about this software? What don't you like about it? What workarounds do you find yourself using?
4. What other modelling software have you used? Why was that not your first choice?
5. When you have trouble or get stuck, how do you resolve it? What resources or who do you consult? [Probing - friend, online resource, web-based communities]
6. Have you ever shared a 3D model online? Where? How? What? [Show us]
7. Do you use any 3D model repositories? Do you customize, or print as-is?
8. Can you describe how you learned the software?
 - . Were there any learning resources that you were aware of and didn't use?
 - a. Were there any learning resources you tried, but didn't work for you?

Projects - can be worked into previous questions.

1. What's one project that worked well? (Can you show me it?)
2. What's one project that didn't work well? (Can you show me it?)

Questions for Print Center Operators

Briefing:

- Tell them about the purpose of the study, your goals, who you are, etc. for 2 min
- Sign all the consent forms, give them gift certificates (if applicable)

Background

1. Tell me about your current job, role, or what you do in this [lab, library]...
2. What kind of training/educational background do you have?

3. How long you been working with 3D printers? In what capacity?
4. How comfortable do you feel with 3D printers?

Perceptions of 3D printing technology

1. What do you see students/community people using 3D printing for?
2. What is the 3D printing process in your case?
3. What parts of this process are easy for students? What parts of this process are difficult?
4. What kind of challenges do you face in printing a student's file? Why?
5. What would you say are the challenges that new students/ new users face in using 3D printing technologies? [both software side and the actual printer]

Perceptions of 3D modelling technology

1. Who are the typical users of your 3D printers? [department, year, etc]
2. What do the students typically use to model 3D objects? Why do you think that is?
3. How do they typically learn this software?
4. What kind of challenges do students face in printing from some software packages than others? Why do you feel that is?
5. What kind of resources do you offer to students to learn 3D modeling or printing?
 - a. Does your facility offer or direct students to any 3D model libraries?
6. What kind of 3D model repositories do students use? Do they customize, or print as-is?

Projects - can be worked into previous questions.

1. What's one project that worked well? (Can you show me it?)
2. What's one project that didn't work well? (Can you show me it?)