"Anyone Can Print": Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication

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ABSTRACT

Broader participation in 3D printing may be facilitated through printing services that insulate clients from the costs and detailed technical knowledge necessary to operate and maintain printers. However, newcomers to 3D printing encounter barriers and challenges even before gaining access to printing facilities. This paper explores the challenges and barriers newcomers encounter when identifying printing opportunities and when learning how to specify 3D printing ideas through observations of stakeholders (n=20) in two university 3D printing shops, and through a focused lab study investigating how to introduce newcomers individually to 3D printing (n=21). We adopt Olsons and Olson's framework for remote collaborations, proposed in "*Distance Matters*", to analyze the sociotechnical requirements for initiating collaborations with 3D printing services. We found that newcomers often require prior guidance towards 3D printing procedures and websites before establishing what to print in collaboration with 3D printing services. Finally, we discuss how future printing processes and computational systems may empower a future where Anyone Can Print.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**.

KEYWORDS

Personal Fabrication; Information Seeking & Search; Maker Culture; 3D Printing; Learning Barriers

ACM Reference Format:

Alexander Berman, Francis Quek, Robert Woodward, Osazuwa Okundaye, and Jeeeun Kim. 2020. "Anyone Can Print": Supporting Collaborations with 3D Printing Services to Empower Broader Participation in Personal Fabrication. In *Proceedings of the 11th Nordic Conference on Human-Computer Interaction: Shaping Experiences, Shaping Society (NordiCHI '20), October 25–29, 2020, Tallinn, Estonia.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3419249.3420068

NordiCHI '20, October 25–29, 2020, Tallinn, Estonia

ACM ISBN 978-1-4503-7579-5/20/10…$15.00
https://doi.org/10.1145/3419249.3420068

1 INTRODUCTION

All 3D printing processes require specification of ***what*** to print, determined through collaboration and negotiation between humans and machines to ascertain ***how*** to print. Specifying printable ideas is not trivial but is necessary for anyone to print, affording broader populations the ability to identify and fabricate a large variety of printing applications to affordably deliver large societal impact: protecting many during the COVID-19 pandemic [1], supporting accessibility for the blind [61], and many other unique applications [5, 30, 32]. While previous work has investigated barriers newcomers encounter ***when*** operating and maintaining machinery within 3D printing facilities, this paper identifies barriers and challenges newcomers face when learning to specify and communicate their ideas with 3D printing services ***before*** seeing or interacting with 3D printing machinery within 3D printing facilities.

While previous research has focused on how digital fabrication may be appropriated by printing–enthusiasts [2, 17, 33, 55] or how proximal printing centers have empowered many to directly utilize these technologies [15, 16, 21, 42], the main focus has been on the *practice* of 3D printing through the direct operation of printers. This practice is learned through trial-and-error, often in co-location with experienced practitioners [15, 21]. However, experienced printing practitioners are not accessible to everyone, but we can imagine a future where anyone can utilize 3D printed products. These products may be made by users with encapsulated knowledge of what can be fabricated through printing services, avoiding the demotivating trial-and-error required for directly operating diverse fabrication technologies. Ideally, such services would only require specifications on *what* clients want to print, insulating clients from the technical details of printer operation and maintenance. Similar to a poster-printing shop, a client could just design a poster and list specifications like material type and resolution. However, many constraints to what can be effectively and consistently produced with 3D printers necessitate collaboration between clients and services to establish *what* can be printed (i.e. the client's role) and *how* to print the client's order (i.e. the operator's role). Even as these constraints are ameliorated by technological advances in 3D printing, barriers and challenges to establish this collaboration will remain.

Olson and Olson's *four requirements* for successful collaboration, presented in *"Distance Matters"* [35], inform the analysis of our two studies: **1)** observations and interviews of "*familiar users*" (n=20) of 3D printing services and **2)** a controlled lab study introducing *newcomers* to printing collaborations (n=21). *Familiar Users* may possess various levels of familiarity and expertise with printing processes, but all possess introductory knowledge of printing opportunities (e.g. where to print) not yet obtained by *newcomers*. **Collaboration Readiness** refers to newcomers' awareness and motivation to begin interacting with printing services, irrespective of prior related experiences [8, 40]. **Coupling of Work** refers to workflow dependencies between clients and service-operators, where co-location and formalizing of printing processes can aid in these collaborations but are not always necessary. **Technology Readiness** refers to clients' awareness of printing processes, and their ability to effectively begin the printing service process. **Common Ground** must be established between clients and services to establish *what* to print (*content*), as a function of *how* to print (*process*) with combinations of software, hardware, and materials that require experience to master [5, 13].

Our results reveal that newcomers are motivated, gain confidence, and obtain the capability to 3D print after a short intervention introducing them to basic 3D printing concepts and helping them practice initial collaborations similar to those in print shops. We first outline related work to current 3D printing processes and to Olson and Olson's framework. Then we describe the methodology for the two studies, and how our observations helped inform the lab study design. We then present our findings aligned with Olson and Olson's framework: (1) newcomers to 3D printing have difficultly identifying introductory 3D printing resources and opportunities on their own (*i.e. collaboration readiness*), which makes it difficult to establish the *common ground* and *technological readiness* necessary to collaborate, and (2) even with introductory resources, newcomers often still face challenges establishing *common ground* about what they wish to print, creating ineffective *coupling of work* and damaged trust when printed products do not match clients' expectations. We conclude with discussion on how computational tools can better alleviate these challenges, broadening participation in 3D printing without requiring direct involvement in the operating and maintenance of 3D printers.

2 BACKGROUND & MOTIVATION

Baudisch and Mueller describe most current 3D printing users as *enthusiasts* who explore the "technological possibilities rather than the applications" [5], early adopters and "*makers*" who hold enthusiasm towards directly operating printing machinery. We outline previous work that describes 3D printing processes and facilities, describing how printing services can help disambiguate specifications detailing printer operation (*process*) from printer function (*content*).

2.1 Future Applications of 3D Printing: Knowing What Can Be Printed is Not Trivial

Eventually, 3D printers may be able to embody the domain- and machine-knowledge necessary to be usable in every home [5]. However, there are many challenges with understanding the present domain of 3D printing, namely how to create artifacts with desired shape, kinematics, statics, and dynamics [5]. Advances in how to make 3D printing more interactive (e.g. *WYSIWYG*), such as investigating how humans can better co-design with machines [23, 25], provoke the tension between designer skills and material-fabrication [51]. These tensions can be alleviated through novel CAD applications that support design with remote mentors [12], design with reusable parts [20, 44], design with better understanding of static forces [11], design to better adapt everyday objects [10], design with code [59], design with better understanding of uncertainties and errors [24], and design with tangible interactions and augmented reality feedback [41, 57, 60]. Translating design intent to machine implementation is another topic of interest, such as automatically optimizing printing products' strength [19, 48, 50], size [28, 53], speed [56, 62], and wasted material [47, 52, 53]. However, each application of 3D printing requires different sets of these constantly-evolving tools and processes. Even if these tools and processes were all readily-approachable and available to the general population, it would take immense knowledge to successfully search, interpret, and apply a set of these tools and processes for each unique 3D printing application. Not all newcomers may be motivated to obtain this knowledge *before* planning to print.

2.2 Motivation to 3D Print: Not Everyone is a 3D Printing Enthusiast

Exploring how future household 3D printers may be utilized, Shewbridge et al. explore how households would log and print items via an imaginary "*faux 3D printer*" [45]. These households wanted to mainly replicate existing objects, but also wanted to create new objects or modify existing objects. Often the 'printed' items could easily be purchased, making 3D printing a utilitarian appliance as much as a creative tool. Many households may not have access to a 3D printing enthusiast, but we can imagine a future where the products of 3D printing can be utilized in every household.

Households of the future looking to replicate existing products may turn to online 3D printing design-sharing platforms, such as Thingiverse. Studies on Thingiverse suggest that many are not there to *innovate*, but to *download* others' works and derive from simple parameterized templates (i.e. *Customizers*) [2, 17, 18, 55]. Many popular designs contain informal operational 3D printing knowledge, but aspects like design creation, functionality, customizability, and printability are often elusive to newcomers [2]. This poses a risk to how people learn 3D printing practices [55], reflected in Blikstein's *Keychain Syndrome*, where the incentives to repeatedly fabricate trivial designs outweigh the incentives to learn more advanced fabrication processes [7]. While repeatedly fabricating relatively-trivial designs may ostensibly be a hindrance towards widespread innovation, enthusiast-focused design tools are not necessary for some users. In fact, Thingiverse's introduction of the Customizer tool led to a rapid increase of new users [17], indicating that many print existing and easily-modifiable designs without necessarily designing novel applications. The 3D printing capabilities of any person can be explained by the composition of tools that they can readily access. Newcomers' printing capabilities can be expanded through experienced practitioners' knowledgable-guidance towards beginner-friendly tools, or through collaborations that reduce the need for more technical printing tasks and knowledge.

2.3 Motivating Broader Participation: Barriers to Newcomers when 3D Printing

Effective methods teaching newcomers to design and print are not sufficient to broaden participation in 3D printing, unless they are paired with effective methods to motivate newcomers to learn. The motivation to utilize 3D printing may be separate from the motivation to learn 3D printing knowledge and skills. Early failures in learning and conducting printing processes can dissuade newcomers from attempting them again in the future [21].

Hudson et al. study how universities, libraries, and schools integrated 3D printing into their existing services, giving insights about how people who are **not** traditional *"Makers"* utilize those printers [21]. These deemed *"casual makers"* are primarily motivated by the product of printing, and face several challenges that are often exacerbated by lack of timely and sufficient support for printing. Newcomers studied in this paper have less exposure to 3D printing than these "casual makers", who this paper would classify as "familiar users". These print centers host 3D printers typically found in Makerspaces, but do not always host proximal printing-enthusiasts to help guide newcomers. Notably, many *casual makers* did not want to visit Makerspaces, because they found it intimidating to approach the 'experts' in these spaces. Additionally, Casual makers often wished they did not have to operate the machines, which most spaces required (e.g. *"I want it to be a black box that's just a service... I'd much rather let somebody else [own the printer], someone whose full time job it is to maintain this device"*). However, 3D printers cannot be presently operated as black boxes, often presenting non-intuitive operational issues, requiring experienced practitioners to successfully maintain and operate [21].

Determining what can be printed (*"printability"*), a "fluid and provisional attribute of the printing arrangement", requires "artful interactions of heterogeneous media systems" according to Dew et al. [13] Experienced practitioners are constantly negotiating print qualities with cost (e.g. money, printing time, and post-processing time), and mitigating risks with experience. Printing technologies are nested within broader embodied and collective sense-making processes. While the focus of the aforementioned work investigates how people learn these processes to directly operate printing hardware and software, we focus on how to learn processes to interact with printing service operators. Easley et al. describe how high-school students may feasible facilitate such a service, focusing on the communication hand-offs needed for the student-staff to collaborate amongst each other [15]. Printing services are feasible in many settings [16, 42], but there remains many barriers that newcomers face to begin interacting with these services.

2.4 Requirements for Successful Collaborations: Lowering Barriers to 3D Printing

For anyone to utilize 3D printing services, successful collaborations must ensue between clients and the service-operators. We present Olson and Olson's four concepts from *"Distance Matters"*[35], which generalize beyond remote collaborations [22, 29, 34, 36–38], to identify challenges to 3D printing collaborations.

1) Collaboration Readiness implies there is information to share and that people are rewarded for sharing. The Olsons suggest to not introduce communication technologies before establishing a culture of sharing and collaboration. For printing services, this implies motivations for clients (e.g. printing without machine-operation) and services (e.g. money). This motivation may be depressed if technology does not support the collaboration workflow, described next.

2) Technology Readiness concerns how habits and infrastructure of collaborators may interfere with adoption of technologies necessary for successful collaboration. It is known that first impressions make a big impact when adopting collaboration technologies ("once burned, twice shy")[35], which is observed in 3D printing [15, 21]. The Olsons recommend that "advanced technologies should be introduced in small steps. It is hard to see far in the future where not only are technologies available, but they fit an entirely new work form". This paper aims to further identify and order the 'small steps" needed to introduce newcomers to 3D printing collaborations.

3) Common Ground is the knowledge and awareness collaborators share about a task and each other, situated in the cues available within a given moment. There is a tension between asking the right question versus finding the answer in common ground. The Olsons suggested that establishing common ground before beginning a task will lead to greater productivity, but recent work argues that sometimes it is more beneficial to breakdown **content common ground** (*know-that*) while accumulating **process common ground** (*know-how*) in certain tasks [29]. Mao et al. claim "the increasing process common ground, in fact, allows the breaking and updating of content common ground to be possible." Failing to build process common ground may lead collaborators to become "frozen" in their established content common ground, be "seized" by information bias, or settle on a "premature conensus" for the discussed problems and solutions. This is not a new idea, as Rittel states: "you cannot gather information meaningfully unless you have understood the problem but that you cannot understand the problem without information about it" [43]. 3D Printing services and clients must establish processes and workflows for collaboration, in addition to establishing what to print.

4) Coupling of Work is defined by the extent and kind of communication required to collaborate. Tightly-coupled work requires more frequent and higher-bandwidth channels of communications, and where loosely-coupled work has fewer dependencies or is more routine. Coupling is dependent both on the nature of the task and the common ground held between participants. An experienced printing practitioner ordering a tested design would be more loosely coupled than a newcomer ordering a 3D design that has never been tested. More tightly-coupled tasks are more likely to succeed if

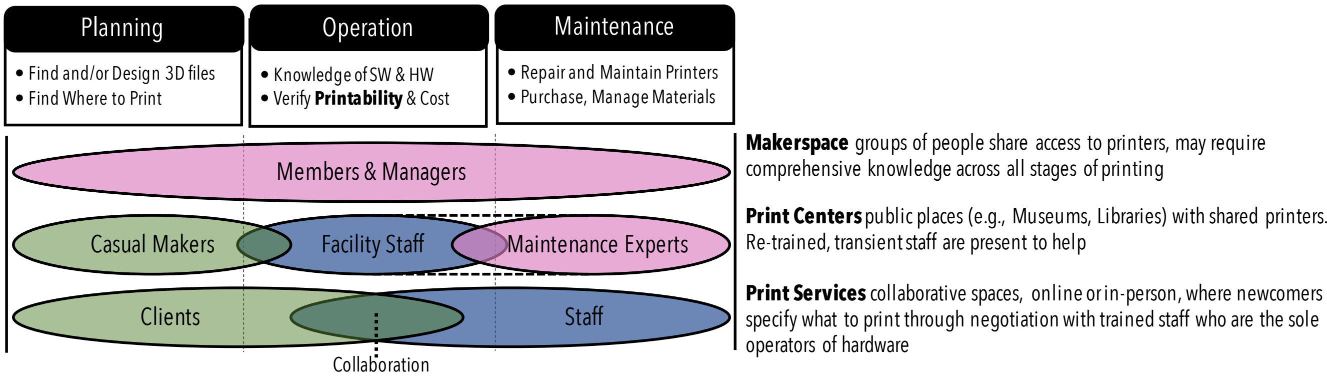

Figure 1: Different options for utilizing public 3D printers. We focus on printing services, particularly Print Shops, where newcomers are insulated from direct operation and maintenance of printers while always receiving collaborative support from proximal staff

collaborators are co-located, and if interactions are more formal. To broaden participation of 3D printing, this paper investigates how to facilitate or differ the tightly-coupled sub-tasks involved in utilizing 3D printing services.

3 METHODOLOGY

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

3.1 3D Print Shop Observations and Interviews: Barriers Encountered by "Familiar Users"

To gain insight into how "familiar users" perceive and overcome barriers to collaborate with 3D printing services, we observed and interviewed stakeholders in two local university printing shops. We observed two printing shops and conducted semi-structured interviews with 20 people: 4 managers, 8 staff members, and 8 clients. Following inductive analysis techniques and a grounded theory approach [9, 49], we iteratively reviewed the researchers' observation notes, semi-structured interview recordings, and associated transcripts to align them with Olson and Olson's framework.

3.1.1 Print Shops are Not Makerspaces. The setting of this study are print shops, which operate differently than makerspaces or purely online printing services (Figure 1); clients can consult the staff and/or have them print out 3D files for a nominal fee based on the material cost and duration of each print (see Figure 4), where the cost of labor is implicitly integrated. The two printing shops are located within a half-mile of each other at the authors' university in a rural location, and are the only print shops nearby. These shops include clients that are not only students and faculty, but external community members. Managers with significant prior 3D printing and fabrication experiences train staff and oversee the shop. The staff, supervised by the manager, help facilitate the service to a variety of clients. Both shops mainly utilize Ultimaker fused deposition modeling (FDM) machines and Formlabs sterolithography (SLA) machines. Both also have high-end printers (e.g. Stratasys DimensionSST), which can be employed for much higher fees. Equipment and staff are largely funded by their respective colleges: Engineering (**E-Shop**) and Architecture (**A-Shop**). Below we denote shop-stakeholders as *A* for A-Shop or *E* for E-Shop, followed by *M* for Manager, *S* for Staff, and *C* for Client. For example, ES1 denotes the first engineering staff interviewed. One limitation of this study is that only "familiar users" of university print shops were observed, not including clients of purely-online services.

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

3.2 Study 2: Focused Lab Study

To gain better understanding of how people with no prior 3D printing experience (i.e. newcomers) perceive printing processes, and how these processes may change after their first time collaborating with a print shop, we conducted a controlled lab study intervention

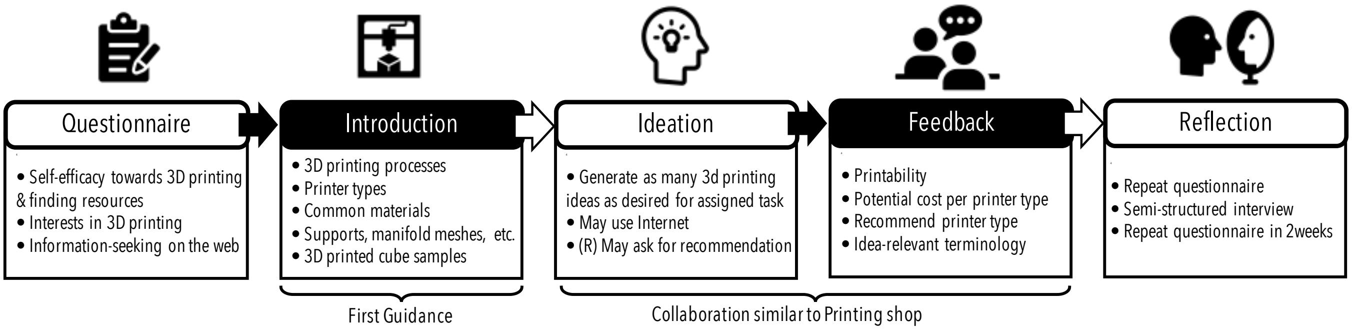

Figure 2: Newcomers, after an introduction to 3D printing derived from the observational study, completed a design-ideation exercise and received feedback emulating print shop collaborations. Some could ask for web recommendations (R) during the Ideation stage.

emulating participants' (n=21, Figure 3 - *left*) first interactions with a print shop. Participants were recruited via email, based on willingness to learn about 3D printing and absence of previous printing experiences. Participants were asked to complete questionnaires before the intervention, immediately following the intervention, and then two weeks after the intervention. The lab study tested the following hypotheses:

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

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

3.2.1 Procedure. The intervention (see Figure 2) was informed from the observational study analysis, where awareness and introductory knowledge motivated and transformed newcomers into clients of 3D printing services. Participants received a brief introduction to 3D printing similar to the introductions that print shop staff give to new customers (~20 min.). Participants were informed about generic 3D printing process, typically involving (i) obtaining a 3D file, (ii) using slicing software to generate printer-specific code (e.g. G-Code), and then (iii) uploading this to the specified printer. Then, participants were introduced to FDM and SLA printing; common printing material options and their properties and costs; approximate size constraints of these printers; and explanations on support material and manifold meshes. Participants were given two sample rounded-cubes printed from high-resolution FDM- and SLA-printers to closely examine, as examination can inform newcomers' perceptions towards material aspects of potential 3D printed products of these print shop technologies [31]. This introduction concluded with description of the two university print shops' locations, contact methods, and a histogram of all print prices for Spring 2019 in the A-Shop. Participants could ask questions at any time and take notes to assure their comprehension. The presentation did not contain any examples of 3D printed products besides the examined cubes, to avoid biasing the participants' ideas of what is printable.

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

3.2.2 Independent Variable: Web Recommendations vs. No Recommendation. Some participants could ask for guidance during the 20-minute ideation session. One of authors, assuming a *facilitator* role as someone experienced in 3D printing, recommended search terms and websites based on their questions without additional commentary (**R**: Recommendations provided, **R#**: denotes participants) to 11 of the participants. In the other condition, 10 participants were given no recommendations from the facilitator (**N**: No recommendations, **N#**: denotes participants). All mentions of *recommendation* below refer to these web recommendations. The distinction between the intervention-types tested *Hypothesis 2*, informing the type and extent of web recommendations that help motivate and initiate printing collaborations.

3.2.3 Questionnaires. The participants first completed questionnaires containing demographic information, open-ended questions regarding what they think 3D printing can accomplish, their imagined 3D printing steps, how they would find 3D printing resources, and inquiring about their prior experiences with 3D printing, with physical design, and with web browsing (see Figure 3). Participants then completed several Likert-scale measures relating to participants' perceptions towards 3D printing and browsing behavior

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

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

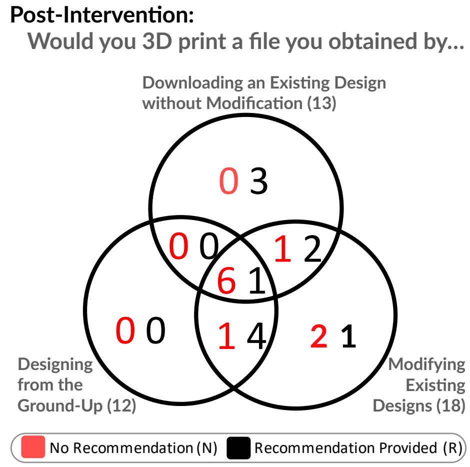

Figure 3: Participants in the lab study were generally well-educated, but did not have 3D Printing experience (*left*). Participants post-intervention considered if they would print files Downloaded from online, Modified, or Designed without modification (*right*)

online: self-assessment on the **1)** attitude and behavior toward careful information seeking on the web [58], **2)** individual interest adapted for both 3D printing and information seeking online [27], and **3)** self-efficacy for finding resources to successfully identify and solve problems in 3D printing, and to successfully print for their work and hobbies [4]. All non-demographic questions were repeated in person after the intervention, and again two weeks following the study via email to help measure participants' changing perceptions towards utilizing 3D printing, finding resources online, and collaborating with print services. The Shapiro-Wilk test showed deviations from the normal distribution, so we ran a Wilcoxon Sign-Ranked (WSR) Test between these before– and after–intervention measures. A grounded theory approach was utilized to analyze the interactions and questionnaire data [49]. A set of common axial codes emerged from open coding of videos, audio, questionnaires, and transcripts.

4 FINDINGS IN FOUR CONCEPTS

To understand how to motivate and facilitate successful 3D printing collaborations, we organize the findings by the following concepts from Olson and Olson's framework: common ground, coupling of work, collaboration readiness, and technology readiness [35]. Each section below describes one concept within the context of our print shop observations and interviews, then presents the relevant results from the lab study.

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

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

4.1.1 Observational Study: Coupling in Consultation and Validation. Collaborations with services can alleviate the needed experience to begin printing, but the extent and type of collaborations vary (see Figure 4). The coupling of work is associated with the nature of the task, requiring differing levels of common ground [35]. Loosely-coupled collaborations require very few interactions, where a client specifies a 3D file and the shop prints it out perfectly to expectations without any iterations of feedback. Tightly-coupled collaborations require many rounds of feedback and advice, requiring higher-bandwidth channels or co-location for success [35]. This section identifies how coupling varies within print shop workflows, and how misidentifications of the workflow result in wasted effort and damaged trust.

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

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

Beginning with Tightly-Coupled Introduction: Those who were allowed to ask questions (**R**) inquired 1-3 questions to the facilitator (median=1), and received 1 to 5 web recommendations (median=2). Questions asked by all R-condition participants include example projects (e.g. "What are some examples of things I can 3D print?"(R3)), printing feasibility of a design idea (e.g. "how do I know which ideas are feasible to print?"(R9)). Participants often informed online queries and ideas based on previous queries. For example, a Veterinary Technology Supervisor (R2) was recommended to search 'otoscope' on Thingiverse, which she found and recorded as an idea (Figure 5). This inspired her to search for a "cell phone ophalmoscope", but realizing that ophalmoscopes are complex to purely 3D print due to the need for an expensive lens, instead focused on other ideas.

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

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

4.2 Collaboration Readiness: Doors to Access

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

4.2.1 Observational Study: Doors to Collaboration. As the Olsons prescribe, newcomers develop readiness to collaborate through developed awareness and familiarity with collaboration-cultures [35]. Lave and Wenger illustrate how this awareness and familiarity are not trivial in their Situated Learning literature about *Access*: an individual's ability to interact with "information, resources, and opportunities for participation" [26]. In this work, common issues in *Access* are depicted in a butcher apprenticeship program, where a door separated butcher-apprentices from the experts cutting the meat, and were effectively relegated to only wrapping the meats. This door denied the relative newcomers access to the knowledge, self-efficacy, and identity to 'become' full-fledged butchers. While they saw the product of the practice, they had no idea how it was made because of a door. This door could be crossed at any point, but the feeling of being an outsider and the lack of awareness about crossing-procedures kept most from opening the door [26]. Similarly, newcomers to 3D printing encounter a metaphorical door even *before* they interact with printing services.

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

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

4.2.2 Lab Study: Google is often a Dead-End. The lab study thus closely examined the door from the perspectives of newcomers who have not opened it yet. We investigated how newcomers found web resources that would aid in collaborations, and found that many newcomers can not find helpful resources for 3D printing without help. Three out of ten participants in the N-condition (n=10) did not look up anything online. Out of the other seven who did search online, only four participants search with terms similar to "3D print",

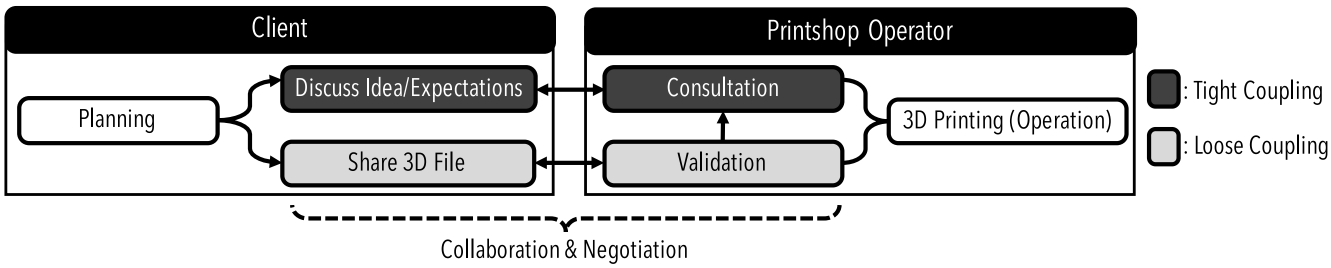

Figure 4: The workflows in *Print Shops* help newcomers learn 3D Printing basics while preventing mistakes. Newcomers' first interactions may be tightly-coupled, but this loosens as newcomers learn 3D printing basics. Sometimes failed validation leads to consultation

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

Even when asking the right questions, the right search queries, newcomers often did not trust search results from unfamiliar domains. Those who received recommendations recollected: "When I first opened google, I didn't know if I could trust Thingiverse"(R4) and assumed "[Thingiverse] was paid advertisements"(R5). Without recommendations and knowledge of printing-terminology, participants mentioned they "feel more confident talking to people than talking [to people] online... because I want to feel confident I'm using the right words to talk to somebody online about what I'm doing"(N8). As printing practices involve articulation of many online tools and resources [13], newcomers should be familiarized with some of these resources *before* collaboration.

4.3 Technology Readiness: Choosing a Printing Process is Difficult

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

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

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

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

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

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

4.4.1 Observational Study: Specifying a File and Material Does Not Establish Common Ground. All interviewed clients had successfully collaborated with the shop, and had learned more about 3D printing during the process. Many clients mentioned that anyone can "*print like you would at any print shop*", and *"I learned with the people who were working here"*(AC3). However, not all collaborations were successful. Often some details of a final print did not match the clients' expectations because common ground was not established. *Process common ground* with printing services is how clients and services exchange information to establish *Content common ground* of *what* to print, not necessarily *how* the printers are operated. Clients are responsible to explain their printing ideas, but need to rely on service-operators to guide the designing process and set expectations on the final product. Similar to Mao et al. [29], establishing elements of process common ground affords collaborators greater ability to establish the needed content common ground sufficient for collaboration. Without process common ground, collaborators may not be able to establish content common ground, because they did not share information pertinent to the particular 3D printing application.

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

Conveying Ideas for Collaboration Participants generated between 1 to 11 ideas during 20 minutes of the ideation task (sum=62, median=2), only 1 to 7 of which followed the assigned task of interacting with a phone to assist with work or hobbies (sum=49, median=1). Participants in the N-condition produced more ideas (38 to 24), but more ideas made by those in the R-condition were relevant to the task (92% to 71%). A large diversity of ideas were generated, from phone-attaching otoscopes (R2: Figure 5) to multi-functioned phone cases for holding test tubes and for aiding in measurements (R1: Figure 5). Only 7 ideas included measurements useful for their design-ideas (e.g. N10: anti pick-pocket phone-attachments). Five ideas in the Recommendation condition wrote website references to YouTube (R4), Thingiverse (R2,R5), and Amazon (R7). Ideas from six participants (N1-2,N5,N8,N10,R7) included details on how to Customize the designs (e.g. earbud inserts made by 3D scanning people's ears – Figure 5:N10).

Establishing Common Ground after the Intervention Many ideas required additional discussion during the Feedback phase of the intervention to explain their design intent (e.g. R1 sketched multiple views of a phone case that has indents to hold test tubes – Figure 5). Participants discussed with the facilitator, which is similar to the consultation in print shops, about all of their ideas, around 4–30 minutes. Drawn designs tended to be more detailed than text descriptions, which aided the facilitator in providing more specific feedback. While visual media better-established content common ground, the written word was the most common way to quickly explain what the drafted ideas represented (44 of 50 ideas). The intervention encouraged newcomers to collaborate with printing practitioners, with 18 participants saying they would visit the print shop in the future. 10 participants mentioned that they'd find someone more knowledgeable in 3D printing. Others highlighted that they would not want to own 3D printers– "owning would require higher education"(R11), even when R11 has a PhD in Psychology and could imagine printing a physical visualization of "Maslow's hierarchy of Needs". Two weeks following the intervention, 8 noted they had seen printers since the intervention. One teacher was looking to buy a printer for her school based on print shop advice, two were actively planning a printing project, and one had completed a printing project (first quote in Section 4.3). Out of the twelve participants who responded, there were significant ($p<.05$) increases in *all* measures via the WSR test compared against before the intervention. The intervention led to many printing within a short time-period, indicating that practice helped foster successful collaborations and sufficient common ground.

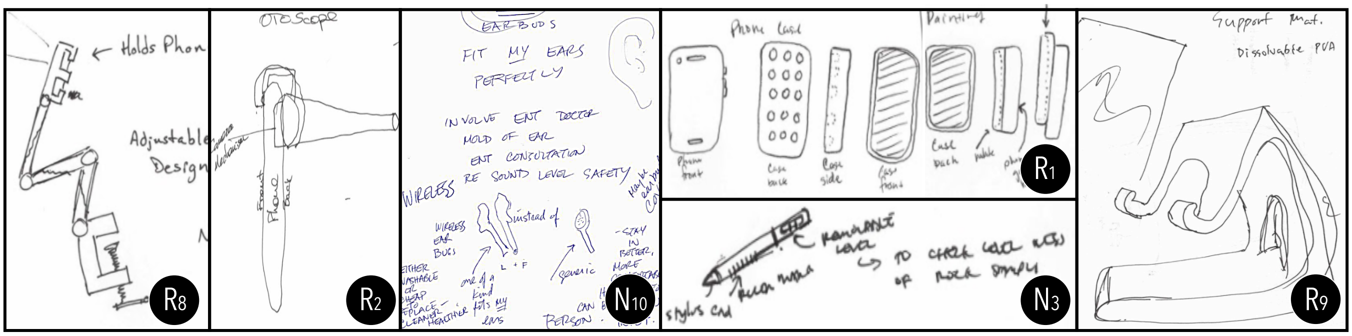

Figure 5: 3D Printing Ideas Generated During the Lab Study. Most participants created drawings of their ideas, some directly referencing how they could adapt existing products (A2) or previously printed designs (D), to help support collaboration with the facilitator

5 DISCUSSION AND FUTURE WORK

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

5.1 Motivating New 3D Printing Users: Opening the Door

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

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

5.2 Successful 3D Printing Collaborations

Newcomers face many challenges towards establishing the common ground required for successful prints. To better ensure success when printing, newcomers could follow formal steps supporting 3D printing collaborations: **1)** obtain 3D files, **2)** give design-specifications to a service (e.g. 3D files and design-intent), and **3)** further specify printing materials and processes in collaboration with the service. Formalizing this process, facilitated through a guided system [39] or other computational systems, could allow for newcomers to better understand the process of printing with services. This also provides distinct steps where clients have loose-coupling with the service (steps 1&2), and where clients may need to collaborate through higher-bandwidth channels in tightly-coupled work with printing practitioners (step 3).

5.2.1 ***Step 1: Obtaining 3D Files (with or without designing)***. Determining what to print can be difficult without some initial guidance. The studied newcomer-participants were capable of determining printable ideas, especially after being introduced to basic 3D printing concepts, websites, and design methods. Newcomers should be given brief introduction to basic 3D printing concepts and terminology, along with information on how to locate 3D designs online. Additionally, newcomers should have knowledge of how existing designs may be modified on their own or with help. Custom Recommender Systems could help newcomers discover potential 3D printing applications (e.g. Thingiverse designs) and design-help (e.g. tutorials or designers-for-hire) that they may not have otherwise searched for immediately. Price estimations could help clients evaluate and learn *what* can be printed affordably.

5.2.2 ***Step 2: Specifying Design-Intent to Service***. Based on *what* the client wishes to print, they need to further investigate *how* to print, constrained by *where* they can print. A directory of online printing services and local printing shops, filtered based on the clients' initial design-specifications, could help them better-establish how they could print. Further, a 3D file's intended function is not always obvious to a service. To help establish common ground, client print-specifications may be formalized by requiring some mechanisms to add required textual fields in addition to a 3D file when submitting, particularly about the prints' intended function (e.g. to withstand force) and appearance (e.g. the color and resolution). Detailed explanations such as each printing service's available materials and fabrication processes should be integrated into these forms. To avoid failing the *Double-Blink Test*, uploaded 3D files should be viewed by the client before being sent to the service. Immediate and reliable automatic estimates of printability and costs

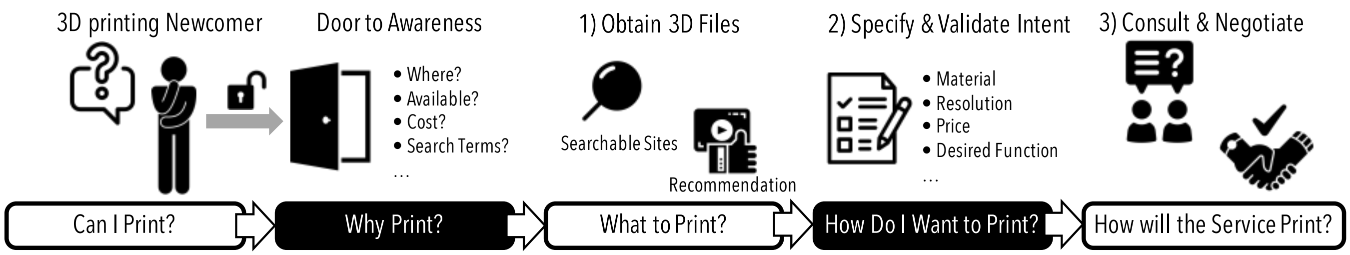

Figure 6: Newcomers can be guided through a series of questions to facilitate 3D printing collaborations. Preemptively delivering answers to these questions may help open the door to newcomers, and help them disambiguate 3D printer *functionality* from *operation*

(i.e. time and money) could help clients interactively develop their printing ideas. Affordances for sketching, utilized effectively by many newcomers in the lab study, could help specify newcomers' prints. Newcomers should be given opportunity to ask questions, and view others' related questions, about service-policies and printing in general. Online forums and question-answer systems [46], informed from online 3D printing data (e.g. [6]), could assist clients specify their ideas before they seek help from printing facilities, where they may be more hesitant to ask others for help [3].

5.2.3 ***Step 3: Personalized Consultation and Negotiation.*** After the design-to-print is specified, now the printing service needs to respond with validation or consultation. Successful validation should always include the services' impression of what is being printed, for what purpose, and how they will print it. More reliable costs should be provided at this time. Validation failures should always provide actionable items to fix. Common validation-failures (e.g. non-manifold meshes) and consultations (e.g. modeling tutorials) could direct clients to online resources where those common questions and concerns are addressed, similar to how StackOverflow functions for programmers [14, 54]. For more in-depth consultations, where a single text-response is likely not sufficient (e.g. a design task), collaborators should communicate with media more-similar to proximal interactions to better afford tightly-coupled collaborations. As trust plays a role in newcomers' willingness to start 3D printing collaborations, authorities and community-members should be able to review and vouch for particular services and online 3D printing resources. Finally, to seed "word-of-mouth" of printing services to other newcomers, both clients and services could connect to popular social media platforms to share their experiences. With awareness of how to accessibly print, groups of new and diverse interests could discover and create 3D printing applications, innovating in directions presently unexplored in the realms of 3D printing practices and research. *Not everyone will become a great innovator, but a great innovator can come from anywhere.*

6 CONCLUSION

Many can presently access impactful 3D printing functionalities, but few are aware about *how* and *what* to print. We investigated barriers and challenges to how newcomers specify their initial 3D printing ideas through two studies: a study observing and interviewing stakeholders of university print shops, and a study investigating how initial 3D printing collaborations shape newcomers' perceptions towards 3D printing. Newcomer-participants were motivated and had the capability to 3D print after a short intervention that introduced 3D printing concepts and practiced collaborations similar to those in print shops. Initial guidance or collaboration is necessary to encourage adoption of 3D printing, because designing or finding solutions to problems is challenging without introductory understanding of potential solutions. Computational–tools and formalized printing processes can support a future where Anyone can Print, supporting newcomers in initial 3D printing collaborations that emphasize *what* they can print without distracting them with detailed technical knowledge of 3D printer operation.

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