Documented: Embedding Information onto and Retrieving Information from 3D Printed Objects

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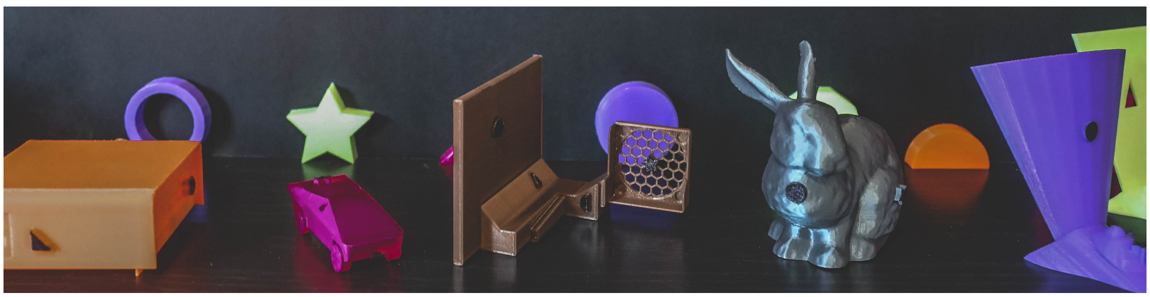

Fig. 1. 3D models of objects printed with tags associated to Documentation information.

Documentation for DIY tasks serve as codified project knowledge and help makers reach new understandings and appreciations for the artifact. Engaging in reflective processes using the documentation can be challenging when it comes to physical objects as the documentation and the artifact exist separately. We hypothesize that spatially associating the documentation information with the artifact can provide richer contextualization to reflect upon the artifact and design process. We implemented and evaluated *Documented*, a web application that helps makers associate documentation to 3D printed objects. Information can be embedded using printed tags spatially placed on the model and accessed using mobile AR. Our study highlights the different strategies participants had for organizing, embedding, and retrieving information. Informed by our results, we discuss how the coupling of the documentation and the artifact can support reflection and identify potential barriers that need further investigation.

CCS Concepts: • **Human-centered computing → Interaction paradigms**.

Additional Key Words and Phrases: documentation, digital fabrication, data embedding and retrieval, self-reflection, reflective learning

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1 INTRODUCTION

Access to tools for making, such as 3D printers and laser cutters, is empowering an increasingly diverse audience to create artifacts [2]. People from different backgrounds and varying levels of technical skills are creating a wide range of projects, such as building furniture, jewelry and smart interactive devices [6]. Makers commonly share their projects and the lessons that they learn with the broader community via online documentation platforms, such as Craftster, Ravelry, and Instructables [12] or through physical zines (e.g., [7]). In such contexts, documentation serves as codified project knowledge. They include information such as the step-by-step procedure that the maker followed to create the artifact, their design decisions, materials list, and a more high-level discussion of the insights gained from engaging with the problem. Knowledge seekers reflect upon these documents either directed by a purpose, or an outcome or both, to reach new understandings and appreciation for the project. Upon reflection, they can learn about the design rationale, recognize values embedded in the object, and identify things that worked during the iterative design process [16, 30].

While makers can benefit from reflecting upon the documentation, engaging in such reflective processes can be challenging when it comes to physical objects. For example, consider the following scenario. Alice, a hobbyist maker, visits her local makerspace during an open house. She picks up and explores objects made by other makers and wants to learn more about how they were made and why certain design decisions were taken. However, she is unable to fully understand the design process simply by looking at the object. In such a scenario, Alice would either have to talk to the creators of the objects or access the companion documentation when available. Since makers typically post documentation for do-it-yourself (DIY) projects on online forums, Alice would have to first search for the information and then mentally map design details to the object in hand to support her reflection process. Such a process would be time-consuming and cognitively difficult [9]. Additionally, to engage in such reflective processes, Alice would also need access to good quality documentation, which is not always available due to the large variation in documentation practices in the maker community [31].

As an alternative to the above scenario, we propose creating an opportunity wherein the objects' creators can couple the documentation with the object and do so in a consistent manner (such as a spatial association). Such coupling can benefit the knowledge seeker to easily access the information and support reflection by exploring the object in the context of the details. In this paper, we present and study a novel tool, *Documented*, with the aim of understanding the benefits and limitations of spatial coupling and richer contextualization for exploring documentation information in the context of digitally fabricated objects.

Benefits of tight coupling and richer contextualization for supporting reflective practices have been previously studied in the literature on Tangible User Interfaces (e.g., [8, 11, 17, 18]) and craft practices (e.g., [21]). For example, researchers have used AR tagging to provide in-situ information about artifacts in a museum [1]. However, such approaches have been typically applied as a post-processing step and do not account for the dynamic authoring of such information when creating the artifact. In the real world, we see such coupling of information in manufactured objects with often explicit information encoded on them (e.g., metrics on a measuring cup). Such encoding is limited by the amount of human-readable information that can fit onto the object without interfering with its function. By extension, barcodes and QR codes are also prevalent and of clear utility, but they do not indicate the type of information they contain or what they pertain to. *Documented* builds on these examples by supporting the encoding of design and fabrication-relevant information directly with the object of interest supported by the fabrication technique, for example, directly 3D printing the information on the object.

We began our research by studying current documentation formats for DIY activities by conducting artifact analysis [14], interviews, and brainstorming sessions with makers. Informed by these insights, we developed *Documented*, which is a web-based application where users can connect text, pictures, videos, and other digital file formats to 3D modelled tags that are then embedded onto a 3D model of the physical object. People can access the information associated with the tags using mobile AR. To evaluate the prototype system, a study was conducted where makers were asked to try out the tool and explore some examples of pre-built projects. Overall, the participants were positive about *Documented*-like tools and highlighted some strategies for using such tools for organizing, embedding, and retrieving information. Informed by these results, we discuss three things that makers reflect upon when creating and interacting with physically embedded documentation: (a) open-endedness versus structured documents, (b) object aesthetics and (c) ways to personalize information sharing. We also briefly speculate and discuss different scenarios we imagine wherein such physically embedded documentation formats can be beneficial.

This paper's contributions include: (1) an expanded understanding of current documentation practices gained by artifact analysis, interviews and brainstorming sessions with makers, (2) a prototype system, *Documented*, that provides a novel approach to interacting with an object's documentation, and (3) the lessons we learned from evaluating *Documented*, that provide insights into potential ways of using digital fabrication to create interactive documentation.

2 RELATED WORK

Our research draws from example projects broadly in the domain of DIY activities such as fabrication, crafts, and physical computing projects, and looks at the different types of documentation that makers create and share.

2.1 Online Documentation

Documentation takes many forms in the online realm, ranging from blogs to project repositories in online communities. One popular online community for sharing documentation is Instructables [32]. On this platform, a typical documentation includes several levels of detail, such as step-by-step textual descriptions that explain the 'how-to', photographs of the materials and artifact, videos that show the construction process and how the object is used, as well as companion digital files to help others replicate the work [26]. Make:Projects [19] is another online platform that is similar to Instructables, but instead of providing makers with a template consisting of fixed input fields, it gives them the creative freedom to write their documentation similar to blogs. A related online platform is Build in Progress which focuses on storytelling rather than instruction [27]. It allows users to create non-linear documentation of their design journey, focusing on delivering a transparent representation of the maker's process over the product. Lastly, even though YouTube is not considered primarily a documentation platform, many makers use it as a way to showcase their projects in a video format. For instance, most of the other platforms that enable sharing of videos usually link to a video uploaded on YouTube. In all of these online documentation formats, viewers can download, like, share, ask questions, and comment to share their appreciations and insights.

Kuznetsov and Paulos [12] who conducted a study to explore the purpose of some such online communities, found that makers are motivated to join them because it enables them to learn more by teaching and sharing with others. However, other studies have pointed out that accessing and using such documentation can be challenging. For example, Torrey et al. [25] who looked at the challenges of communicating the making process through How-To instructions, found that users find it difficult to search for online documentation because makers, especially novices, do not often know the names of the tool, material, or technique used to create the object. Similarly, Wakkary et al. [31] have highlighted that inconsistencies and lack of information in online tutorials make it difficult for people to learn from them. In our work, we further explored these challenges in interviews with makers and studied the strengths and limitations of coupling information with the object for easier access, and identified approaches to structure information to ensure consistency for sharing without necessarily enforcing a template such as input fields.

2.2 Physically Embedded Documentation

Researchers have explored the benefits of physically representing data (e.g., [4, 9]). In the context of digital fabrication, some techniques have been developed to embed data. For example, Travis Rich has demonstrated how data can be visualized using 3D printing and laser cutting in the form of textures, which in post-processing can be detected using a mobile application [20]. While such projects show how data can be visually embedded on physical artifacts, the focus of these projects is not on coupling documentation information with the artifact.

There are two main projects that are relevant to our work, Process Products [29] and Spyn [21]. Tseng and Tsai developed Process Products [29], where they focused on capturing changes across different iterations of a design and visually embedding those iterations into the digitally fabricated objects. In one of their examples, the different iterations of an object are laser cut as different pieces and stacked on top of each other. While this project identifies the opportunity in physically representing aspects of design documentation, it does not expand upon how other types of documentation information (e.g., videos or pictures) can be associated with the artifact. In our work, we focus on exploring ways to embed documentation information without limiting the types or amount of information that is being documented.

Rosner and Ryokai developed Spyn, an application for crafters to embed stories into knitted objects [21]. In Spyn, the crafter uses a yarn with infrared ink to add tags to the crafts, which the craft's receivers can then detect using their cell phones and playback recorded stories that the crafter left for them. Spyn focused on building a communication link between the object's crafter and receiver and enabled the receiver to not only reflect upon the the physical material aspects such as the object's material and colour, but they could also learn more from the attached texts, pictures, audios, and video recordings. Their study found that Spyn prompted greater appreciation for both the creator's efforts and the craft process. Our work is inspired by Spyn's idea of connecting different formats of information with the object. However, Spyn's primary focus was on supporting social relationships that people have with handcrafted artifacts and the people for whom they are made, and it does not reflect on how people might organize and share documentation information.

3 PRELIMINARY DESIGN STUDY

We conducted a formative design study to understand makers' documentation practices, the types of data they capture during the building process, and how they represent the information. The study consisted of two parts: first, an artifact analysis was conducted to study common documentation formats that exist in maker communities; second, interviews and brainstorming sessions were held with professional and hobbyist makers to gather design ideas for tools that support in-situ exploration of documentation.

3.1 Artifact Analysis

For the artifact analysis, we selected four highly viewed examples of documentation (Figure 2), on the assumption that they were more likely to have relatively higher-quality documentation and therefore would be good sources for the analysis. From Instructables, one of Becky Stern's projects was selected, where she builds an RFID ring using metalworking techniques and a small RFID tag [23] (Figure 2a). From the Make:Projects website we selected Clarissa

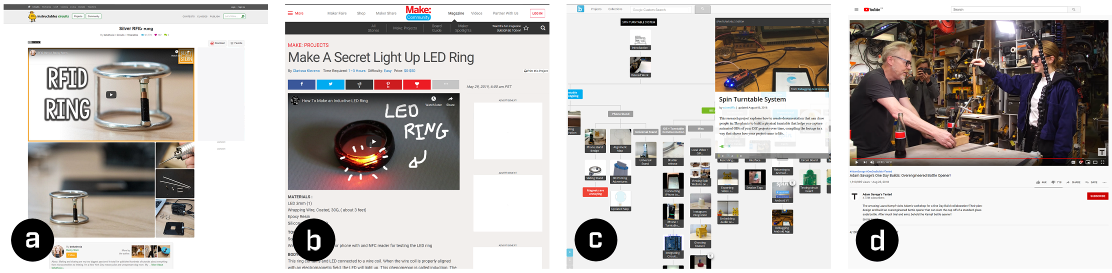

Fig. 2. Screenshots of four selected artifacts: (a) 'Silver RFID Ring' by Becky Stern on Instructable, (b) 'Make A Secret Light Up LED Ring' by Clarissa Kleveno on Make:Projects, (c) 'Spin Turntable' by Tiffany Tseng on Building in Process, (d) 'One Day Builds: Overengineered Bottle Opener!' from Adam Savage on YouTube.

Kleveno's project, where she makes an LED ring that lights up when it is correctly aligned with an electromagnetic field [10] (Figure 2b). From Build in Progress, Tiffany Tseng's Spin Turntable was selected, in which she builds a turntable connected to a mobile phone application and allows makers to create GIFs of their made objects [28] (Figure 2c). Lastly, from YouTube, we selected Adam Savage's projects, where he makes a novel over-engineered bottle opener in collaboration with Laura Kampf, who is another YouTuber and maker [22] (Figure 2d).

We selected an existing questionnaire for conducting the artifact analysis [14] as it offered a wide coverage of what, how, and why questions. From the list of 50 questions, we selected and made minor modifications to produce a subset of 30 questions for analyzing the strengths and limitations of the varied documentation formats, types of media used for sharing information, and ability to access information by an expert or non-expert. The analysis was conducted by the first author, and he answered all 30 questions for each of the documentation examples selected. These answers were then qualitatively analyzed by the first author in discussion with the co-authors.

Overall, we found that it was (a) difficult to directly connect the object to some parts of the documentation information, (b) makers used multiple formats to present information, and there was not much consistency in how the media was used, and (c) lastly, similar to Wakkary et al. [31] we found that finding information was challenging. For example, by simply looking at a picture of the project, we could not easily explain all the design decisions, such as why a particular aspect of the object was designed in a certain way. Images taken using limited camera angles also made it difficult to get a full overview of the 3D object. However, from looking at the images, we could identify the techniques that were used for fabrication in some cases. For example, the metal joint on the ring in the 'Silver RFID Ring' project visually portrays the technique used in the ring's assembly. In all the examples, we found that information about the design process was presented using multiple media formats, including texts, pictures, videos, and digital files (e.g., CAD design files). Issues such as the amount of data presented or the structure of the posts made it difficult to access information consistently, and finding specific design decisions was not straightforward. For example, Becky Stern created a separate video to explain her inspiration for the project, while Clarissa Kleveno used video only to provide a quick how-to instruction on building the project. Similarly, Adam Savage's YouTube no-edit continuous video footage provided rich details, but for a user to find the information they were looking for and engage in an iterative reflective practice, they would have to rewind or fast-forward to specific time stamps multiple times. Lastly, to search for information, usually, there was not an appropriate signpost. For example, Becky Stern's documentation includes step-by-step information regarding the how-to, but we could not easily search for the design rationale.

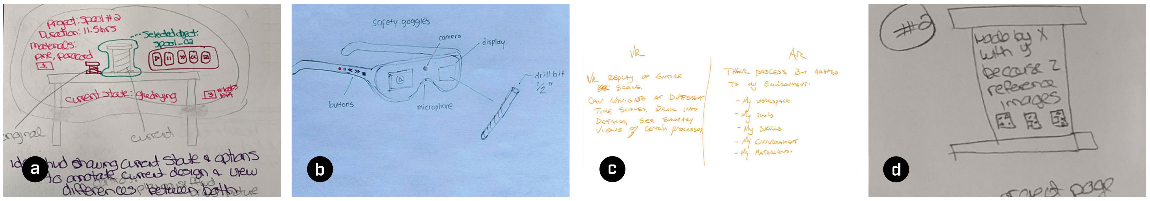

Fig. 3. Ideas suggested by the participants during the brainstorming session.

3.2 Interviews and Brainstorming Sessions

Informed by the artifact analysis, interviews and brainstorming sessions were held with five professional and hobbyist makers (3 male and 2 female). The goal of this session was to generate and discuss ideas for coupling documentation-related information with the physical object. Each participant (P) was asked a series of questions regarding their documentation practice, and this was followed by a brainstorming session wherein the participants came up with a list of data they wanted to capture from their design process, ideas for how they might capture those data points, and how they can be represented in the final built object. Participants were asked to draw a diagram envisioning their ideal documentation tool and how their final physical object would look like if it were documented using their designed tool (Figure 3). During the interview, all five participants mentioned that they often document their projects. They used their documentation to remember how to rebuild their projects (P1), to take note of how they dealt with a specific material that was being used (P2), or to share their process with their friends (P3).

When asked about how participants felt about associating documentation information with the object, four participants stated that associating documentation data in-situ with the physical object could be beneficial and argued that it would help them better understand the documentation. For example, P5 highlighted that *"having the physical object really lets you explore the issue in the way that you would want to view it"*, and found that photos limit their interaction as they only allow people to view the object from pre-decided camera angles. P2 proposed the idea of an *"engraved barcode"* and mentioned that it could enable adding information like the name of the creator or could link to photos that inspired his project. P2 also said that adding such information would allow the user of the object to know who designed the artifact and get a better understanding of why the object was designed the way it was designed.

Regarding the implementation approach to embedding documentation, participants shared two main ideas. First, they highlighted that different people need to have access to different types of information. For example, P1 said: *"not all the data should be shared with anyone who has access to the physical object"*. Related to this view, participants also mentioned that people are usually looking for different levels of details and therefore may need to view and filter information based on some form of high-level categories of information. For accessing information, four of the participants suggested using VR techniques. For example, P4 envisioned an AR system that *"replays the entire [design] scene"* with the ability for the users to *"navigate at different time scales, drill into details and see summary videos of certain processes"*.

A second theme commonly expressed by the participants was that the embedded information should not interfere with the physical object's aesthetic. Participants 1, 2, and 5 proposed using tags that could be embedded in the physical object. In addition, P2 suggested that underneath the object or hidden inside it, we can place *"engraved information about the materials and software tools"*. In contract, P1 suggested that visible tags and their shapes could inform the users about the kind of data they should expect to see when scanning the tags. Lastly, participants added that the tags could be associated with any type of data.

3.3 Design Goals

Informed by the lessons learned from the artifact analysis and the ideas generated by the five participants, we developed a set of design goals to consider for prototyping:

(1) **Support Embedding Information in an Unrestricted Manner** – From the interview sessions, we learned that makers require the flexibility to embed documentation information on any surface of the object. They may decide the spatial location for embedding information based on various factors such as how it affects the look and feel of the object and also based on their assigned weight of importance for that information.
(2) **Allow Multiple Media Formats to be Connected** – We learned from the artifact analysis and interviews that documentation constitutes information shared via multiple media formats such as videos, text, pictures and digital fabrication files. To support a more holistic reflection process, we think that tools for coupling documentation information with the physical object should allow makers to input and map multiple media formats.
(3) **Support for Different Tag Styles** – As identified from the brainstorming sessions, participants value how the objects look and feel and prefer that the embedded documentation information does not interfere with the object's aesthetics. However, participants also highlighted the benefits of embedding information in ways that can be easily recognized. To support such variations, we recommend that embedding information could be supported in multiple ways. For example, the information could be engraved or embossed, it could be represented as abstract patterns that match the texture of the object (e.g., [20]), or when standardization and easy recognition is important, the patterns could look like standard WIMP icons.

4 *DOCUMENTED*: DESIGN AND IMPLEMENTATION

Informed by our design goals, we prototyped *Documented*, a web-based application that helps makers associate their documentation information to the objects they are 3D printing (Figure 4). Data is associated with the model using tags that can be embedded in the print and read using a computer's webcam. The application consists of three main parts: associating data to tags (Figure 4b), placing tags on the 3D model for printing (Figure 4c), and data retrieval (Figure 4d). *Documented* is implemented using p5 and ML5 JavaScript libraries, and the objects were created using the Prusa i3 MK3S 3D printer.

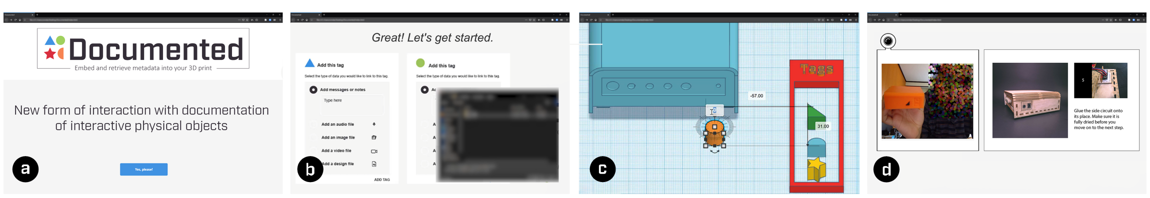

Fig. 4. Documented web interface: (a) welcome page, (b) page for embedding data, (c) TinkerCAD interface for attaching the tags to the 3D model, (d) data retrieval page.

4.1 Encoding Data

As a first step to using *Documented*, users are provided with tags to which documentation data can be associated (Figure 4b). As such, from a computational standpoint, there is no limit on how many tags can be created. However, in the current implementation, it was limited to four with the assumption that people would associate one type of media

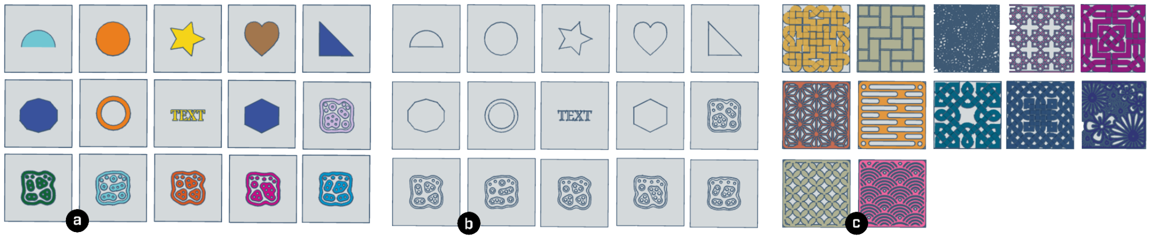

Fig. 5. Tested tag types: (a) embossed simple Shapes (b) engraved simple Shapes (c) abstract patterns.

format (video, pictures, audio and text) to one tag each. Another consideration was that if there were too many tags, then integrating them into the model could begin to interfere with the aesthetics in addition to making it challenging to develop a consistent mental model for retrieving information. To each tag, makers can associate single or multiple pieces of information based on their preferences for organizing information (Design Goal 2).

We intended to create tags that would be both human-readable and machine-detectable (Design Goal 3). Unlike Spyn [21], which uses infrared tags and thus not human-readable, we were inspired by Rich's technique [20] and used 3D printing to create tags. The use of 3D printing to create tags also creates a seamless process since the maker can continue to use the same fabrication machine with which they are creating the object as opposed to introducing a different process such as creating separate barcode labels and sticking them on. Unlike Rich [20] however, we did not use object texture to serve as tags as not all objects use multiple textures, thus limiting the number of unique tags that can be created by the maker. We instead created recognizable shapes and patterns and tested three types (Figure 5).

In the first set, we created simple embossed shapes placed on square pieces of material (Figure 5a). In the second type, simple shapes were engraved (Figure 5b), and we found this allowed more details to be added to the tag. For instance, the text object was more clearly visible when engraved. Finally, for the third type, abstract patterned tags were tested (Figure 5c). However, this attempt was not completely successful due to the limited accuracy of the printer. Of the 12 tags designed, 8 had to be printed on at least 2 cm x 2 cm square tags, unlike the other two types of tags, which could be printed on 1 cm x 1 cm tags.

4.2 Embedding Tags

After associating information to tags, the users are navigated to a 3D modelling sketch in TinkerCAD, a 3D CAD design tool [5], to place the tags on the object (Figure 4c). Users can drag and drop the tags to different locations on the model and can also make them larger or smaller. When this step is complete, makers can export the model in formats appropriate for 3D printing and print the model. The motivation for this step is to help makers plan how they want to organize their documentation. For example, makers may select to document the design decisions by the different parts of the objects and accordingly place the tags on the different model parts, or they may wish to organize by perceived level of importance and decide to place some tags visibly on the surface of the objects and place others on the bottom.

4.3 Retrieving Data

Finally, users can retrieve and reflect upon the documentation by using a webcam to scan the tags, which displays the associated information on the screen (Figure 4d). We used Google's Teachable Machine [15] to create machine learning models to recognize the tags. The algorithm calculates the probability of each match and selects the item with the highest confidence rating.

The three tag types were tested in order to identify which tags would be consistently detected by the webcam. We trained the algorithm using 200 pictures of each of the tags in different lighting conditions. The tests found that the pattern tags could not be consistently recognized. Of the 12 shape tags, four tags were distinct enough to be detected with high accuracy. These included a circle, a semi-circle, a triangle, and a star. Hence, these shapes were selected for the current system implementation. Since this work's focus was not on developing efficient computer vision algorithms, we did not conduct further testing of tag shapes and patterns and is an area for future work.

4.4 Example

In this section, we describe one concrete example of a persona, Brian, using the system. Brian teaches fabrication at a Design School. To show examples of 3D printing to his students, he built a few mini amplifiers that he could pass around the class. He documented his project by making a note of step-by-step procedures. He has audio recordings of his thoughts from the brainstorming phase, pictures of his making process, and many CAD files demonstrating the different variations of the project. He decides to use *Documented* to create an in-situ documentation so that students can read the documentation while they are exploring the object using their hands.

When Brian started to use *Documented*, he realized that he could not simply post all the information he had gathered and had to come up with an information organization scheme. Brian saw that the system had four tags that he could use for organizing his information and so decided to divide his documentation information based on the four main parts of the amplifier model. Using the interface, he attached pictures of the circuit board to the circle tag, an illustrator file for the curved corner to the semi-circle tag, a description of how he placed the power connection to the triangle tag, and an image of the speaker grill that inspired him to the star tag (Figure 4b). Next, he was redirected to a TinkerCAD sketch where he imported the 3D model of his amplifier. In this sketch, he found 3D models of the four tags he had used previously and placed them on the model by their corresponding spatial location, e.g., semi-circle tag containing information about printing corners was placed on the corner of the 3D model (Figure 4c). He then exported his model with the tags as an STL file and sent it to the 3D printer. Finally, on the day of his teaching, he distributed the amplifier models to his students, who then, using mobile AR, read about the documentation information and explored the model in their hand to better understand the design process (Figure 4d).

5 EVALUATION

We conducted a study to learn about how users interact with documentation information embedded into 3D printed artifacts and identify potential advantages and limitations of these artifacts in facilitating a reflective experience.

5.1 Procedure

With ethics approval from our institution, 12 volunteer participants (6 male and 6 female) were invited on a first-come-first-serve basis. These participants were either members of our university or came from local makerspaces. Prior to the study, participants completed a pre-study demographic questionnaire. We found that, on average, our participants had more than 6 years (min of 3 years) of experience in creating projects through woodworking, using electronics to build wearables, product design and creating data visualizations. Two-thirds of the participants documented more than 50% of their projects, with the rest documenting around 10% of their projects.

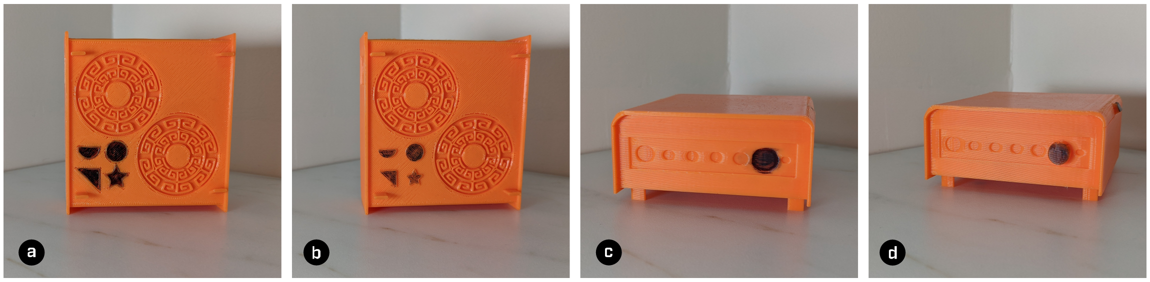

Fig. 6. 3D printed models used in the study.

During the evaluation session, participants were introduced to and interacted with *Documented* via four pre-built objects, versions of an amplifier box with: 1) embossed tags placed underneath the object (Figure 6a)), 2) engraved tags placed underneath the object (Figure 6b), 3) embossed tags placed on different model locations (Figure 6c), and 4) engraved tags placed on different mode locations (Figure 6d).

Participants in the study completed all steps necessary to use *Documented* - selecting tags, assigning information, placing tags on a 3D model and retrieving the information, with the exception of printing new models due to the time-intensive nature of 3D printing. We also provided them access to previously gathered documentation materials so as to use the evaluation time to focus on system use and critique. The materials consisted of 1) audio recordings that verbally discussed critical design decisions that were made during the design process, 2) pictures of every step of the building process, 3) videos of other projects that had inspired this project, 4) digital files containing the 3D model and SVG files, and 5) a text file that contained information about the project's objective, inspiration, background information, tools and materials used, step-by-step instructions for replicating the project, and an evaluation of the final design.

While participants interacted with *Documented*, they also answered a series of semi-structured interview questions regarding the strengths and limitations of the concept and the prototype. Finally, at the end of the session, participants were asked to fill out a short questionnaire on self-reflection. We modified an existing questionnaire that is based on a study on the impact of data physicalization for reflection [24]. The questions primarily focused on asking participants about how the object itself afforded reflection and also how the proposed documentation style supported reflection.

5.2 Data Analysis

Each of the sessions was video recorded for posterior qualitative analysis. The video recordings were then transcribed and analyzed in order to identify emergent themes for participant's responses. We looked for both comments on participants' interactions with the system and those related to the prototype's ability to help people engage in reflection using the documentation information.

5.3 Results

Overall, participants described their experiences using our system as *"insightful"*, *"entertaining"*, *"less intimidating"* and *"meaningful"*. In particular, P2 said that if documentation were this *"engaging"*, they would have gone through more documentation in the past. Similar to Spyn [21], it was found that our participants felt that the association of information with the object helped them better appreciate the product and its creation process. For example, P3 strongly agreed that the system provided rich contextualization as it allowed them to use *"different senses"* to interact with the object, with the *"tactile"* aspect really being helpful.

One common issue highlighted by participants was that they found it quite challenging to use the front-facing webcam on the computer to retrieve information. It was found to be cumbersome, and P9 stated that they felt uncomfortable with the camera pointing at their face.

In addition to these high-level takeaways, the results shed light on a number of strategies people had for interacting with our system, described below.

5.3.1 Data Organization. Participants were asked to consider how they would associate documentation information to the provided tags and to provide a rationale for their decisions. We noted that participants had four main strategies for data organization by: 1) media type (video, photo, audio, and text); 2) design process stages (ideation, iteration, instructional steps, and evaluation); 3) categories based on fields (e.g., engineering and design tasks) and 4) spatial location (i.e., grouping data related to specific parts of the object).

Participants 2, 3, 4, and 10 said that they would prefer to categorize the data based on media type and stated that they currently follow the same structure digitally. For example, P10 pointed out that during their documentation process, they *"put all their documentation into separate folders based on the media"*, and this helps them navigate through the information more easily. When asked which types of tags they would use for representing media type, while P3 was happy with using simple shapes used in the current system, P10 said that it would be nice to have tags that look similar to icons, for instance, a camera icon to represent photos.

Participants 1, 5, 6, and 12 suggested organizing the data based on the different design process stages. Examples of these categories included *"how-to"*, *"inspiration"*, *"testing"*, and *"iterations"*. Again this was based on prior practices, and P6 added that this is the type of data that they wanted to know more about and perhaps others too.

Participants 8 and 11 suggested organizing the data based on fields of expertise. Similar to P1,5,6,12, they saw the overall project creation process as consisting of a number of segments, but rather than focusing on the individual segments (such as inspiration or testing), they had a more abstract high-level task categorization that related to how they approach the project. For example, P11 spoke about two high-level categories that related to the *"engineering"* aspects of the project and the *"design decisions"*.

Although initially participants were focused on finding an organization logic purely based on the data they were provided, upon interacting with the system and noticing they could place the tags on the 3D model, they started considering scenarios where the data could be spatially organized. All participants found that the spatial connection between the documentation information and a physical object could be very beneficial. For example, P7 suggested that: *"if there is something important about the functionality [of a part of the object] or the making process, I want to document about this specific part. So probably the tag will go here [pointing at a specific part of the object]"*. In contrast, P5 and P11 mentioned that they would not be interested in spatial tagging if an object was meant to be used daily and would rather *"hide the tags underneath"* (P11). However, from the perspective of viewing documentation, they agreed that the spatial connection provided them with a *"new"* and *"faster"* way of accessing the information.

5.3.2 Tag Location. Another design decision we experimented with was tag placement locations. In the study objects, participants saw tags located either on the visible surface or the bottom surface of the object (Figure 7). Using this as a starting point, we asked (a) how participants would like to place the tags if they were adding them to a product versus (b) on a model used for the sole purpose of sharing documentation information.

When it came to the placement of the tags on products that might be commercially sold, all participants wanted the tags to be hidden by strategically placing them in a location on the object that will not be visible at first glance. This was primarily motivated by their need to maintain object aesthetics, e.g. P8 said that the tags should not *"clash with the design"*. P12 suggested an alternative idea wherein we might use stickers rather than embedded tags so that the sticker can be taken of the object when the user had completed exploring the documentation.

In contrast, when it came to placing tags on 3D models used for sharing documentation information (as in a scenario similar to our example in section 4.4), all participants wanted the tags to be fully visible and placed at strategic points on the object. Clustering of tags was also a suggested option, and they reasoned that such clusters could help the viewer know how much information was available, e.g., *"there are 4 pieces of important information that they need to know"*.

5.3.3 Reflection Questionnaire Results. Overall, all 12 participants found the experience of using in-situ documentation helpful to different extents. P11, who was supportive of our concept, mentioned that they going forward, would modify their documentation format to emphasize *"some kind of connection"* between the object and documentation information. A summary of the results from the post-study questionnaire is shown in Figure 7.

10 out of the 12 participants agreed that after using *Documented* to explore the object’s documentation, they gained a deeper understating of the object (median 4.2, n=12). P6 noted that the understanding gained helped them to more easily challenge the object and the design decisions made. P3 highlighted that it made it easier for them to visualize the fabrication technique that was used, for example, the laser cut hinge of the amplifier, they felt that this way got a better understanding of "when to use it". Participants disagreed with some of the questions, for example, questions related to critical reflections. P9 commented that the amount of time spent exploring the documentation was limited, and hence they could not comment on if this new approach supported critical reflections.

6 DISCUSSION

From this project, we learned that in-situ documentation could help people reflect on three main aspects of the object and its corresponding creation process.

6.1 Reflections on Documentation Structure

Overall, from the artifact analysis and evaluation, we learned that makers tend to organize their documentation per their own preferred styles. When using online platforms, makers use templates such as those provide by Instructables or create completely open-ended documents such as blogs. However, lack of consistency in how information is shared brings to light issues people may have when they try to access it for engaging in reflective practices [25].

In online documentation, people have the creative freedom to post in a format that they prefer, and users can try to search for things using keywords or look for sign-posts (such as section headings) when they exist. In addition, a single online document presents the reader with all the information in one place, making it easier to navigate without losing the overall context [26]. However, in a system like *Documented*, wherein information from one tag is shown at a time (current implementation limitation), people would have to cognitively stitch different pieces of information together to form a mental image of the entire documentation. In addition, performing a search can be cumbersome as people would have to rotate the object several times while also remembering where specific parts of the information were embedded [33].

In contrast, if the preferred style is not open-ended but instead a more structured format, then we think that physically embedding documentation can perform better. Literature has highlighted that structured documents help

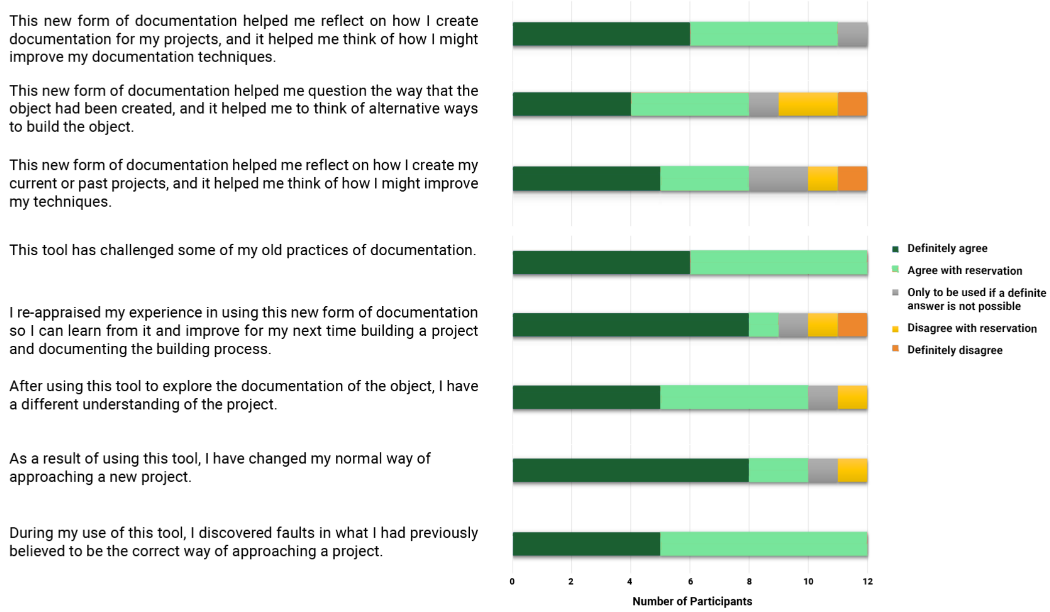

Fig. 7. Results of the Questionnaire on Reflection.

people better reflect on an object or a file [3]. In the case of physically embedded documentation, such structure is implicitly enforced. At the most basic level, this is enforced because the maker has to consciously engage in the task of assigning information to tags before printing the object. Although theoretically multiple tags and therefore multiple categories can be generated by the software and the maker, physically there is a constraint on how many tags can be meaningfully placed on the model, thus requiring the maker to pick an organization format with limited categories. An organization scheme that holds most potential is spatial mapping. As suggested by our participants, the contextual information provided by spatial association can help users hone in to the specific details. For example, if documentation related to a tag embedded in the ear of a 3D bunny said that the creator used increased speeds and reduced filament flow rate for printing, then by seeing the object, the user can verify and reflect upon the effects of such printer settings.

6.2 Reflections on Object Aesthetic

Aesthetics is an important design consideration for professional designers and makers. By embedding information in the form of tags, such aesthetic considerations may be compromised. Informed by this, we recognize that the physicalization of documentation information requires additional features and tools to be developed that help makers consider their aesthetics-related decisions in the light of the documentation information they want to share.

Our participants highlighted that when an object is a commercial product or serves a more professional purpose, they prefer to strategically hide the tags so as to not affect the aesthetics of the object. Partially the issue of aesthetics of tags is a result of the printer capabilities, i.e., higher resolution printers can print better quality tags that can more seamlessly blend with the object's design. Extending this idea, we may look to work by Rich [20] who mapped information to the texture of the object, which can work when objects constitute parts with different textures such as a vase or a hand-tool.

A third option is to print the tags as removable components, which is unlike current online or book-based document options which are permanent entities. With removable tags, documentation could be viewed as ephemeral materials that last only when the person wants to engage in reflection, thereby creating a more dynamic object that can be both information and design rich. Such techniques can also enable the makers to update their documentation information to create a more alive document that can continue to engage people in reflection each time they interact with it.

Interactions with our participants also revealed that in some scenarios, they may prefer to have a separate object just for documentation purposes, and in such cases, they prefer to embed the tags more visibly, placing less emphasis on the aesthetics. A similar observation was made by Tseng et al. [29], who found that objects with physically visualized process information were considered scraps. To facilitate such use cases, several design considerations can be made. For example, building on the concept of documentation as an ephemeral material, we may consider printing documentation objects with recyclable filaments so that they can be discarded. Ideas like this could be useful for educational contexts, such as for an Industrial Design class where students can produce artifacts with embedded documentation information and then recycle the project at the end of the term. Alternatively, when makers would like to keep the object, for example, when a maker or a group of makers would like to build a library of their projects for scenarios such as hosting an open house at a makerspace, objects with embedded documentation can facilitate richer discussions.

6.3 Reflections on Documentation Personalization

As discussed in the previous sections, participants came up with different options for how to categorize documentation data and how to place the tags on the artifact. In addition to that, from our brainstorming sessions, we found that makers also wanted to be given a chance to choose what parts of the documentation to share and with whom. Some preferred to separate what could be visible to the general public from information that should be visible to other makers.

One challenge with offering that level of personalization when it comes to online documentation is that the maker would have to create multiple versions of the same file before sharing the details. Similarly, in static physical visualizations of data [13, 24], the permanency of the data embedded in the objects cannot be changed. In contrast, when systems allow combining physical with the digital, such as the case in *Documented*, we can offer control by enabling the creators of the object to hide and make visible information per their requirements. For example, it is possible to leverage the *Documented* interaction pipeline and add access level controls for tags such that some tags would show full details only to employees of a company or friends and family.

Another aspect related to personalization is regarding the style of tags. As discussed previously, it is possible to create a number of varied human-readable tags. However, as highlighted by P12 during the evaluation, such creative freedom could become a barrier if the users are not provided with a legend, and they mentioned, *"but if that [the tags] is mentioned beforehand, then it probably solves the problem"*. In our current system, people cannot design their own tags. However, going forward, it would be important to consider this aspect and include a step on legend building in the documentation authoring process.

6.4 Potential Usage Scenarios

Through *Documented* we demonstrated an approach where the tangible representation (tags) allows the physical embodiment (3D printed object) to be directly coupled to dynamic bits (editable documentation), thus creating an opportunity for users to interact with and learn from information-rich objects. In this paper, we focused on developing an example tool and demonstrated its implementation using 3D printing. We did not demonstrate the applications of our approach and the use of other techniques for making. While these are directions for future work, in this section, we speculate a few scenarios where we think that in-situ documentation can serve to be useful.

One use case related to teaching fabrication using objects with embedded documentation was previously discussed in section 4.4. An extended use case for teaching contexts is using such objects to support design critique sessions, wherein it is important to look at and explore the objects produced in relation to additional information presented by the authors. However, such critique presentations suffer an inconsistency in information sharing similar to online documentation, making it difficult to compare and contrast different approaches students take to complete an assignment. In such scenarios, instructors can ask students to prepare a presentation using information-rich objects with details attached to all important parts of the model, thereby making it easy to talk about two or more similar objects. Another relevant context is gift sharing as demonstrated by Spyn [21], wherein objects with embedded information can provide more context for understanding the rich technical journey of the creators.

We also think that our approach could be useful for mass-manufactured objects (e.g., IKEA furniture parts or everyday devices such as coffee lids). Products such as IKEA pieces embedded with documentation information can provide in-situ support for tasks such as assembling furniture while also reveal to users insights on specialty design concepts such as modular designs. In everyday contexts, people can pick up objects such as scissors or utensils and learn more about how the objects were designed and by whom. As such, the concept of creating tags and embedding information is not only limited to 3D printing but can be extended to any other digital workflow such as laser cutting or CNC, where unlike additively creating tags using 3D prints, tag shapes and symbols can be formed by subtracting from the materials.

7 CONCLUSION AND FUTURE WORK

In this paper, we explore ways documentation information can be spatially associated with digitally fabricated objects. We conducted formative research through artifact analysis, and interviews and brainstorming sessions with hobbyist and professional makers and gained insights into makers' current documentation practices. Overall, we learned that by spatially connecting the artifact to documentation information, makers can gain more contextualized information, which can help them reflect on the creation process and the artifact. Informed by our formative research, we identified three preliminary design principles for embedding documentation information within 3D printed objects. As an instantiation of our design principles, we implemented *Documented*, which is a web-based application that offers a novel approach to interacting with in-situ documentation information. We evaluated *Documented* and gained insights about the strengths and limitations of our prototype as well as its ability to engage makers in a reflective documentation process. Overall, we found that associating documentation information with physical tags that get embedded in the printed object helps people reflect on three aspects of the process and the object: (a) documentation structure, (b) object's aesthetics and (b) personalization of information sharing and appearance.

As a first step, in this paper, we discuss how people might embed documentation information. In the near future, we are interested in exploring how people might use such documentation styles to support knowledge creation, including developing new skills, building new theories, and evaluating design decisions [16]. After addressing some of the current implementation limitations (e.g., support for collecting documentation data, multiple tag detection and testing other tag styles), we are interested in examining the application of our prototype in varied contexts. We are interested in examining how students might use our prototype in educational contexts to develop and transfer knowledge. We would also like to explore how such documentation might be perceived by users of mass-manufactured objects in the home contexts, for example, by embedding information such as instructions to construct and deconstruct IKEA furniture.

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REFERENCES

[1] Jad Al Rabbaa, Alexis Morris, and Sowmya Somanath. 2019. MRsive: An Augmented Reality Tool for Enhancing Wayfinding and Engagement with Art in Museums. In *HCI International 2019 - Posters* (Cham, 2019) *(Communications in Computer and Information Science)*, Constantine Stephanidis (Ed.). Springer International Publishing, 535–542. https://doi.org/10.1007/978-3-030-23525-3_73

[2] Jeffrey Bardzell, Shaowen Bardzell, Cindy Lin Kaiying, Silvia Lindtner, and Austin Toombs. 2017. HCI's Making Agendas. *Found. Trends Hum. Comput. Interact.* 11, 3 (2017), 126–200.

[3] Peter Dalsgaard and Kim Halskov. 2012. Reflective design documentation. In *Proceedings of the Designing Interactive Systems Conference* (New York, NY, USA, 2012-06-11) *(DIS '12)*. Association for Computing Machinery, 428–437. https://doi.org/10.1145/2317956.2318020

[4] Audrey Desjardins and Timea Tihanyi. 2019. ListeningCups: A Case of Data Tactility and Data Stories. In *Proceedings of the 2019 on Designing Interactive Systems Conference* (San Diego, CA, USA, 2019-06-18) *(DIS '19)*. Association for Computing Machinery, 147–160. https://doi.org/10.1145/3322276.3323694

[5] Tinkercad | Create 3D digital designs with online CAD. 2020. . https://www.tinkercad.com/

[6] Dale Dougherty. 2016. *Free to Make: How the Maker Movement is Changing Our Schools, Our Jobs, and Our Minds.* North Atlantic Books.

[7] Garnetz Hertz. 2014. *Critical Making.* http://www.conceptlab.com/criticalmaking/

[8] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces Between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 1997) *(CHI '97)*. ACM, 234–241. https://doi.org/10.1145/258549.258715 event-place: Atlanta, Georgia, USA.

[9] Yvonne Jansen, Pierre Dragicevic, Petra Isenberg, Jason Alexander, Abhijit Karnik, Johan Kildal, Sriram Subramanian, and Kasper Hornbæk. 2015. Opportunities and Challenges for Data Physicalization. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (New York, NY, USA, 2015-04-18) *(CHI '15)*. Association for Computing Machinery, 3227–3236. https://doi.org/10.1145/2702123.2702180

[10] Clarissa Kleveno. 2019. *Make A Secret Light Up LED Ring.* https://makezine.com/projects/make-a-secret-light-up-led-ring/

[11] Boriana Koleva, Steve Benford, Kher Ng, and Tom Rodden. 2003. A Framework for Tangible User Interfaces.

[12] Stacey Kuznetsov and Eric Paulos. 2010. Rise of the Expert Amateur: DIY Projects, Communities, and Cultures. In *Proceedings of the 6th Nordic Conference on Human-Computer Interaction: Extending Boundaries* (New York, NY, USA, 2010) *(NordiCHI '10)*. ACM, 295–304. https://doi.org/10.1145/1868914.1868950 event-place: Reykjavik, Iceland.

[13] Moon-Hwan Lee, Oosung Son, and Tek-Jin Nam. 2016. Patina-inspired Personalization: Personalizing Products with Traces of Daily Use. In *Proceedings of the 2016 ACM Conference on Designing Interactive Systems* (Brisbane, QLD, Australia, 2016-06-04) *(DIS '16)*. Association for Computing Machinery, 251–263. https://doi.org/10.1145/2901790.2901812

[14] Noah Litvin. 2020. *Artifact Analysis.* http://dlrtoolkit.github.io/artifact-analysis/

[15] Teachable Machine. 2020. *Teachable Machine.* https://teachablemachine.withgoogle.com/

[16] Jennifer A. Moon. 2013. *Reflection in Learning and Professional Development: Theory and Practice.* Routledge.

[17] Claire O'Malley and Danae Stanton Fraser. 2004. Literature Review in Learning with Tangible Technologies. (2004). https://telearn.archives-ouvertes.fr/hal-00190328

[18] If Price, Fides Matzdorf, Louise Smith, and Helen Agahi. 2003. The impact of facilities on student choice of university. 21, 10 (2003), 212–222. https://doi.org/10.1108/02632770310493580 Publisher: MCB UP Ltd.

[19] Make: Projects. 2020. *Make: Projects.* https://makeprojects.com/home

[20] Travis Rich. 2013. Encoding Data into Physical Objects with Digitally Fabricated Textures. https://www.media.mit.edu/publications/encoding-data-into-physical-objects-with-digitally-fabricated-textures/

[21] Daniela K. Rosner and Kimiko Ryokai. 2008. Spyn: Augmenting Knitting to Support Storytelling and Reflection. In *Proceedings of the 10th International Conference on Ubiquitous Computing* (New York, NY, USA, 2008) *(UbiComp '08)*. ACM, 340–349. https://doi.org/10.1145/1409635.1409682 event-place: Seoul, Korea.

[22] Adam Savage. 2018. Adam Savage's One Day Builds: Overengineered Bottle Opener! https://www.youtube.com/watch?v=MxLOoriXkMc

[23] Becky Stern. 2020. *Silver RFID Ring.* https://www.instructables.com/id/Silver-RFID-Ring/ Library Catalog: www.instructables.com.

[24] Simon Stusak. 2016. Exploring the potential of physical visualizations. https://edoc.ub.uni-muenchen.de/20190/

[25] Cristen Torrey, Elizabeth F. Churchill, and David W. McDonald. 2009. Learning how: the search for craft knowledge on the internet. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2009-04-04) *(CHI '09)*. Association for Computing Machinery, 1371–1380. https://doi.org/10.1145/1518701.1518908

[26] Cristen Torrey, David W. McDonald, Bill N. Schilit, and Sara Bly. 2007. How-To pages: Informal systems of expertise sharing. In *ECSCW 2007* (London, 2007), Liam J. Bannon, Ina Wagner, Carl Gutwin, Richard H. R. Harper, and Kjeld Schmidt (Eds.). Springer, 391–410. https://doi.org/10.1007/978-1-84800-031-5_21

[27] Tiffany Tseng. 2016. Build in Progress: Building Process-Oriented. *Makeology: Makerspaces as Learning Environments (Volume 1)* 1 (2016), 237.

[28] Tiffeny Tseng. 2020. Spin Turntable System. http://buildinprogress.media.mit.edu/projects/2330/steps.

[29] Tiffany Tseng and Geoff Tsai. 2015. Process Products: Capturing Design Iteration with Digital Fabrication. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (New York, NY, USA, 2015) *(TEI '15)*. ACM, 631–636. https://doi.org/10.1145/2677199.2687891 event-place: Stanford, California, USA.

[30] Terri Turner and Daniel Gray Wilson. 2009. Reflections on Documentation: A Discussion With Thought Leaders From Reggio Emilia. 49, 1 (2009), 5–13. https://doi.org/10.1080/00405840903435493 Publisher: Routledge _eprint: https://doi.org/10.1080/00405840903435493.

[31] Ron Wakkary, Markus Lorenz Schilling, Matthew A Dalton, Sabrina Hauser, Audrey Desjardins, Xiao Zhang, and Henry WJ Lin. 2015. Tutorial authorship and hybrid designers: The joy (and frustration) of DIY tutorials. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. 609–618.

[32] Eric Wilhelm. 2013. Instructables. *interactions* 20, 1 (2013), 84–87.

[33] Hsin-Kai Wu, Silvia Wen-Yu Lee, Hsin-Yi Chang, and Jyh-Chong Liang. 2013. Current status, opportunities and challenges of augmented reality in education. 62 (2013), 41–49. https://doi.org/10.1016/j.compedu.2012.10.024