# ProxyPrint: Supporting Crafting Practice through Physical Computational Proxies

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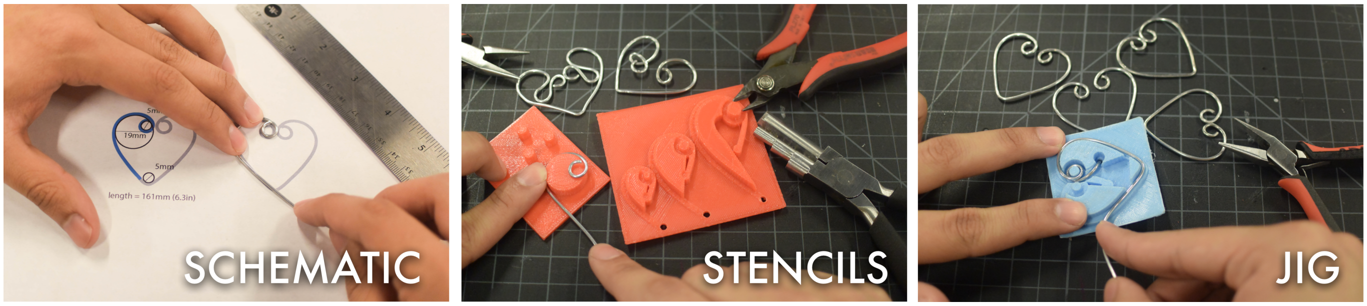

**Figure 1. a) Schematic, an annotated construction proxy used to provide fabrication feedback, b) Stencil, a fabrication proxy that breaks down designs into elementary forms, c) Jig, a fabrication and construction proxy that provides a ritual high-fidelity fabrication process.**

## ABSTRACT

Advances in digital fabrication (DF) technologies are making it easier to produce high-fidelity replicas of digital designs. However, this push-to-print paradigm limits the creative opportunities that arise from the process of "working through a material" which involves risk, uncertainty, and serendipitous discovery. We investigate how DF artifacts can function as static intermediary tools, which we term proxies, to support crafting practice. We focus on the wire-wrapping process where physical wire is bent into complex shapes and build DF fixtures to aid with construction and fabrication. We explore how these proxies can be generated to provide users with different levels-of-assistance and evaluate how these proxies affect the making process. We show that our proxies affect quality and speed and yield different making experiences between novice and expert craftspeople. We derive design principles to inform future proxy design and discuss how approaches such as ProxyPrint that are designed aware of the medium can create more engaging making tools that can embed tacit knowledge, encourage creativity, and sustain crafting practice.

## Author Keywords

digital fabrication; creativity support tools; design; DIY;

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## INTRODUCTION

With the growth of digital fabrication (DF) technology, it has become possible to rapidly manufacture objects in a growing range of materials, including plastics, ceramics, and metal. Today, users can fabricate accurate, physical artifacts from digital designs at the push of a button without the need to master difficult, labor-intensive manual fabrication processes. This technology has clear benefits for both novices and experts. For novices, DF lowers the barrier to entry and expands the range of craft and DIY projects they can execute. For experts, DF facilitates physical prototyping of designs, small run manufacturing, and the production of parts that are hard to manufacture with traditional processes.

However, there are several important trade-offs to the convenience of automated fabrication. By removing manual creation from the process, DF eliminates well-known benefits of making things by hand: Klemmer et al. [17] describe how "thinking through doing" (i.e., engaging directly with the physical world) often helps with problem-solving and learning, which aligns with constructionist approaches to education [21, 25]; makers also tend to feel greater ownership over objects that are physically made [32], especially when the "hand of the artist" is visible [20, 38]; finally, manual creation introduces the risk of making errors, which can lead to "happy accidents" [19] that can shape and even improve creative outcomes. At the same time, while DF machines and interfaces, have moments or surprise and error, this secondhand feedback is more displaced from the material and usually a result of some algorithmic or mechanical error.

Recent advances in human-computer interaction has opened a new hybrid design space that can balance benefits of automation and the advantages of working directly with materials. This hybrid space refers to blended digital and physical practices. Hybrid tools which facilitate this practice have gained traction in domains such as crafts by outsourcing tedious labor to machines [5]. However, several tensions arise around hybrid craft resulting from ambiguities between mediums: traditional crafts are slow and near-at-hand; digital processes are inherently faster (supporting iteration) and can be ubiquitous [15, 22]. Other tensions between digital fabrication and handed fabrication arise from socio-cultural practices such as: a) deskilling the artist by making the craft easier; b) masking the "hand of the artist"', or the distinction that an artifact is hand-made versus machine-fabricated, c) dishonoring the material, such as tacking on other media like electronics [22], and d) failing to listen to the material, such as when a wood knot is not "heard" by a CNC machine whereas a woodworker would detect it and alter the design [5].

### A Proxy-Mediated Practice

In order to address some of these tensions, we explore a new class of hybrid DF tools that combine the convenience of automated fabrication and the advantages of working directly with materials – ProxyPrints is a set of computationally generated physical artifacts that facilitate, inform, and influence the manual creation processes, functioning similar to armatures in traditional sculpture. This gives rise to our vision of a proxy-mediated practice where a user works directly with a material with their hands and tools; this process informs future iterations of a design; a design tool generates a set of specific passive fixtures or custom static tools based on the design; which assist the user to continue working with the material and develop craftsmanship.

Such as practice allows users to still create final artifacts by hand while retaining the advantages of manual fabrication. At the same time, proxies assist users with challenging aspects of the fabrication task by providing more customized design-specific scaffolding than generic tools and be designed to provide different levels-of-assistance based on the goals and expertise of the user (Figure 1), acting in the traditional role of a teacher in a master-apprentice relationship. For example, while novices may want more fabrication assistance to guarantee success, experts may prefer less or more localized assistance that offers the ability to explore interesting variations. Unlike traditional tools, computational proxies can provide this type of design-specific assistance to complement and build on a user's existing skill set.

### Wire-wrapping as Crafting Exemplar

To explore the idea of proxy-mediated practice, we focus on the domain of wire-wrapping, a metalworking medium that involves bending wire into aesthetic forms. Wire-wrapping exhibits many of the characteristics of typical DIY communities: namely, the grassroots innovation in tools and techniques; a culture of shared practice through tutorials and workshops; and the potential for refining craftsmanship. Furthermore, wire wrapping is extremely popular for both jewelers and hobbyists and has been successful in handmade marketplaces ($>$ 300K hits on Etsy). Wire-wrapping has a clear cross over to other 1D mediums and crafting tasks, such as needlecrafts, acrylic bending, basket-weaving, and knot-tying. Thus, wire-wrapping represents an interesting and relevant context in which to investigate how proxies affect DF processes for both novices and experts.

### Contributions

Firstly, ProxyPrint expands the set of computational proxies available to wire wrapping and introduces proxy recipes for *assembling* multiple pieces of wire into a single artifact, *forging* wire to vary its width (and strength), and finally, *weaving* wire to create textured patterns. This expanded set of proxies more holistically supports the medium, and a preliminary usability evaluation suggests that our proxies address these challenges over conventional methods and tools.

Secondly, we address the larger issue of user engagement and innovation with current DF tools and services. Providing the right type of assistance during a user's experience can ultimately determine whether or not a user abandons their endeavor or deviates from a template and begins a new lifelong practice. ProxyPrint introduces the use of *computational scaffolds* to assist users based on their expertise or familiarity with a medium. Here, we identify three types of scaffold proxies (schematics, stencils and jigs) that provide different assistance (Figure 1) and evaluate these proxies in a formal study with novice and expert craftspeople. Our study characterizes the proxies based on metrics from hybrid crafting literature [20, 30, 38]. Our results showed that the making experience with scaffolds differ across expertise and can effectively influence creative deviation and agency.

## RELATED WORK

Recent work has looked at creating more synergistic interactions between maker and tools. Below, we describe work around digital and physically augmented tools, instructional tools, traditional tools, and scaffold design. Lastly, we focus specifically on work that uses wire as a medium.

### Augmented tools

Digitally augmented tools or smart tools combine some digital or computational intelligence with manual usage, and primarily act in the service of providing higher accuracy or fidelity. FreeD, an augmented dremmel tool, provided feedback to users through autoshut off features; notably it provides a "human-overide" mode that allowed users to deviate from the digital model. Peng et al. use common clay coiling techniques, bearing a large similarity to Fused Filament Fabrication, as a way to additively construct and digitally scan geometries at fabrication-time [23]. Enchanted scissors used conductive traces to detect and prevent incorrect cuts [36]. In Hybrid Basketry, Zoran explored how digital fabricated armatures can support and guide the basket-weaving process and influence the final artifact design [37]. Notably, the role of digital fabrication in Hybrid Basketry is not a driving or stopping force, but acts solely as a support structure. ProxyPrint builds on this idea of *passive* assistance and expands the set of computationally-generated support fixtures. Furthermore it explores a new dimension of the levels-of-assistance that is exposed to the user. ProxyPrint looks at DF not for producing final artifacts but for producing intermediate highly customized tools and instructions.

### Augmented practice and materials

Abstracting materials into primitive additive and subtractive processes, such as fusing sand into glass, can omit much of the rich cultural history of people working with a material (e.g. glass-blowing). Several works investigate how the cultural experience of tools, mediums, and their practice can enhance the making experience. Jenkins et al. explored the religious experiences that are associated with crafting practices and created devotional gardening tools mediated with electronic and digital feedback [16]. Rosner et al. explored the combination of clay and digital fabrication, describing the tensions occurring from the displacement of the medium from the ceramist's hand [27]. ProxyPrint complements this previous work; we similarly design the experience of handed practices into our *scaffold proxies*, and work *with* a material by integrating tacit knowledge from current practices into the design of our *material-driven proxies*.

### Design-specific fabrication instructions

Some existing design tools focus on domains that require manual fabrication of the final artifact, such as plush toys [14], inflatable balloons [10], planar cardboard sculptures [12], and customized garments [33]. The output of these tools is typically a set of instructions for how to make the user-generated design. More implicit fine-grain instructions have been explored in systems like Sculpting by Numbers [26] which provides users with a "diff" between forms through a scanning and projection interface, non-intrusively aiding them in evaluating their progress. As we discuss later in the paper, such design-specific instructions represent one type of computer-generated assistance for fabrication tasks. However, the bulk of our work focuses on the design of physical proxies that facilitate manual creation.

### Scaffolds on design

Several systems study the impact of levels-of-assistance on user experience and design outcome. Painting with Bob, a design tool for digital painting evaluates a simple toolset (e.g. an eraser that erases everything under the cursor) against a smart toolset (e.g. an eraser that erases similar color regions under the cursor) and draws from literature in creativity support tools [3]. PortraitSketch provides a set of automatic assistance algorithms for adjusting user strokes while drawing to achieve a certain portrait aesthetic [35]. We similarly study the effects of level-of-assistance under a broader spectrum and in the context of physical making.

### Wire design and fabrication

Some existing commercial products help users create wire-wrapped artifacts. Companies like WigJig and Beadsmith provide kits that allow users to create customized "jigs" by inserting different sized cylindrical pegs into a board. However, the discrete set of peg sizes and positions limits the designs that such kits can support. CNC wire benders such as DIWire have automated the wire bending process, with some tooling limitations. Such machines have been proposed as sites for interaction: Willis et. al. *Speaker* interactively "sculpts" wire based on sound wave forms [34]. In contrast, we are interested in providing a hybrid crafting experience that keeps the user in the loop with the material and propose more flexible, design-specific physical proxies that can support a broader range of designs.

Most relevant to the domain of our work is WrapIt [13], a computational design tool for converting line drawings into optimal wire wrap forms ("wire decompositions") that can be fabricated with the help of a 3D-printed jig. We build on this work in several ways. First, while WrapIt focused mainly on the design problem of converting line drawings into wire decompositions, we concentrate on the problem of fabricating a given design. To this end, we propose several new computational proxies that aid in wire wrapping tasks that WrapIt does not consider (e.g., forging, assembly, weaving). Moreover, our wire shaping jig design offers some important improvements over the original WrapIt jig. We also investigate the question of level-of-assistance, which seems critical for the design of physical tools that aid the creative process of manual fabrication. We validate these improvements with a comparative evaluation.

## OUR APPROACH

Our proxy design approach follows a *style analysis*, or identifying the "constancy, or consistency, in the way an individual, or a group, treats the formal elements of art, or visual culture" [11]. We explored the wire medium not only by its physical affordances (medium-specific) or properties (material-aware), but also through the expert practice and tradition that have already produced conventional uses, meanings, and techniques with this material. For instance, it is a common practice to use coil wraps to connect elements but also to hide imperfections in a design. ProxyPrint develops the tools (proxies) through this medium-aware approach to facilitate these aesthetics and culture to more easily integrate itself with existing practices.

We explore the design of computational proxies along two different dimensions. First, we investigate proxies that facilitate the execution of common wire-wrapping techniques, like wire shaping, forging, and connecting elements together. We call these *material-driven proxies* since they address fabrication challenges that are specific to the material and align with expert craft practice [2]. The second dimension that we consider is how proxies can provide varying amounts of scaffolding for the user. To explore this aspect of the design space, we take the basic elements of our wire shaping proxy and consider design variations that offer different levels-of-assistance. We refer to these variations as *scaffold proxies*.

## MATERIAL-DRIVEN PROXIES

The typical wire-wrapping workflow is to first *shape* one or more wires into appropriate forms, then *forge* (or strengthen) the wires so as to retain or enhance their form, and finally

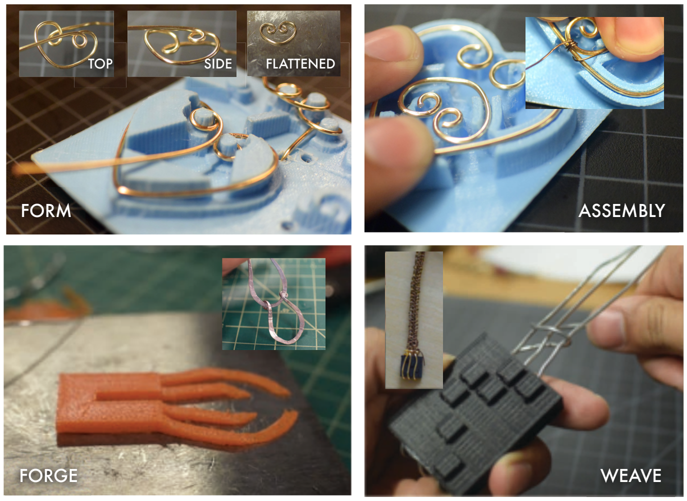


**Figure 2. Material-driven proxies: computationally-generated fixtures assist in common wire wrapping tasks such as forming, forging, connecting, and weaving (enlarged for visibility).**

*connect* separate elements together to form a single, coherent composition. Here, we describe how each of these tasks are carried out with traditional tools and then describe our material-driven proxies that help users accomplish the tasks with higher quality and fewer errors. Figure 2 shows examples of the different material-driven proxies we designed.

## Shaping

Shaping a piece of wire into a desired form is the primary task in creating wire-wrapped artifacts. In general, it is hard to bend wire to create smooth curves that match the proportions of the design. Wrappers employ hand tools and custom-built jigs for this purpose, but using such tools effectively is challenging. For example, different types of pliers heads are best suited for different types of bends: flat-nose for sharp angles, barrel- or taper-nose for curves and swirls, and chain-nose for general bending. In addition, exerting too much force on the wire with pliers can accidentally mar the metal. Finally, experts typically plan the sequence of bends to minimize interference between the wire, pliers and jig(s) as they manipulate the material.

Based on these observations, we derive the following design requirements for a shaping proxy. Most importantly, the proxy should help the user:

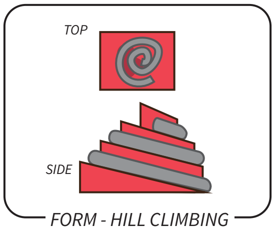
- bend the wire smoothly into the appropriate shape without requiring a lot of precise, plier manipulation.
- clearly convey the bending sequence
- minimize physical obstructions that may interfere with bending interactions

### *Shaping proxy via hill climbing*

The design of our shaping proxy was inspired by the WrapIt jig [13] which has similar design goals. The WrapIt jig includes physical "support walls" around areas of high curvature that guide the shape of the wire to ensure that the resulting form matches that of the input design. While this approach reduces the number of walls and the number of physical obstructions, the wire is prone to falling off the jig since when the wire overlaps on itself it rises above the constraining jig walls. Another issue is that as complexity increases, the ordering of the wraps becomes ambiguous.

The key observation is that support walls are only necessary on one side of the wire (the "interior" or concave side of each bend), which reduces the physical obstructions that may interfere with the wrapping process. However, designs with multiple closely-spaced bends or wire crossings still resulted in interferences between the wire and support walls – a major usability issue with WrapIt jigs. To address this problem, we developed a different type of shaping proxy inspired by a common technique for creating circular jump rings. The method involves coiling wire around a cylindrical mandril, cutting laterally through the coil to create small open rings, and then flattening each ring to create a closed, circular shape. By coiling the wire along the mandril, the user does not have to worry about interferences between subsequent rings.

The main insight here is that *the wrapping process does not need to occur on a single 2D plane*, even if the resulting piece is designed to be flat. Thus, we propose a "hill-climbing" proxy design that creates a supported path for the wire that rises from the start to the end of the path. In cases of overlaps, the lower portion of the path takes precedence ensuring each portion of the jig and wire does not interfere with subsequent wrapping interactions. Moreover, the height of the path acts as an implicit cue for where to start and end the wrapping process. As with the WrapIt jig, support walls are only generated along the interior of each bend. Once wrapping is completed, the user simply flattens the wire into a plane. While the change in elevation may result in a small amount of distortion in the flattened geometry, we did not find this to be a problem in the artifacts that we created.



Leveraging tacit knowledge from wire-wrapping, we designed some additional optimizations for allowing users to shape wire with minimal error. For one, bending ends of a wire is difficult to do without deforming the rest of the design. To minimize this, we extended path ends by length and curvature to "complete the loop". This extra length is easily snipped away by the user. Furthermore, a hole was added at the base of the path; this allows users to thread and anchor the wire. These anchors are necessary to keep the wire in place and allow the user to put longitudinal tension on the wire during wrapping. A terminating platform was added to the end of the path to signal to the user the ending position of the design. Lastly, a flattening phase was needed to compress the design back down into plane. We used a rubber[1] hammer and anvil to flatten large elements and nylon pliers for smaller ones.

## Forging

In addition to designing the shape of the wire path, experts often vary the width of the wire to achieve specific aesthetic goals. Such variations can be used to make the piece look more organic or to add/remove visual weight from certain

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[1] Using non-metal instruments prevents marring of the wire

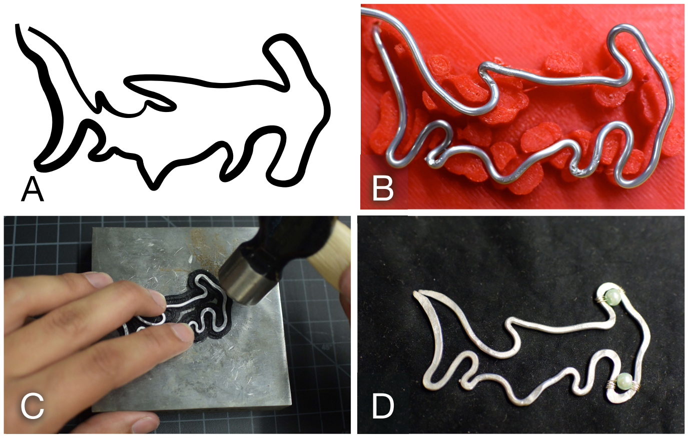
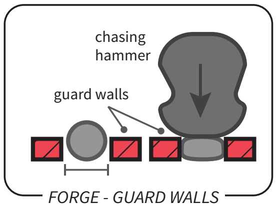


**Figure 3. The forging process: (A) a weighted line drawing is taken as input, (B) the shape proxy is generated and used to construct the basic form; note the uniform width of the wire, (C) using metal-to-metal hammering, we deform the metal; the forge proxy prevents the metal from being deformed incorrectly, (D) two additional pearls are coiled onto the final forged wire piece for aesthetic.**

portions of the design. Changing the width of the wire requires forging (flattening) portions of the material, which also has the effect of making the material more rigid. Forging is typically done by hammering the wire with a steel hammer, but achieving the desired variations in width requires skill and expertise. In particular, accidentally hammering at an angle versus hammering flat can cause unwanted marking.

#### *Forging Proxy through guard walls*



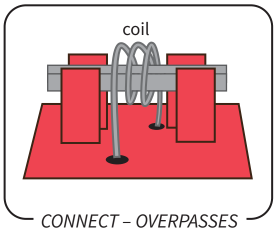
To help users achieve the desired variations in wire width, we developed a forging proxy. Since forging typically happens after shaping, we assume the wire has already been formed into the desired shape. The forging proxy is defined by a channel that holds the shaped wire in place; the user then hammers the wire as it sits in the proxy to create the width variations. "Guard walls" on either side of the channel constrain the width of the wire in two ways: the height of the walls determines how far down the hammer can travel to flatten the wire within the channel; and the gap between the walls limits how wide the wire can become at each point along the channel. We determine the relationship between the height and gap of the walls by fitting an empirical model that relates the lateral strain to the medial strain of the wire. The lateral strain characterizes the width of the compressed wire and the medial strain corresponds to the amount of compression that the hammer imposes.

In order to deform the wire, it must be compressed between two metals (or harder materials). Because of this, plastic cannot be used to compress a metal wire. Thus, it presents a notable challenge to hold plastic guard walls together when they cannot share a common connecting ground. Our approach adds a common substrate across the wire connecting two adjacent guard walls in portions of the path that do not need to be thickened. If an entire path needs to be forged, we select regions at the ends to be connected; a user would have to forge these ends without a guard wall. The minimum height of a guard wall is limited by the minimum layer resolution of the 3D printer; as such thicker gauge wires (<16 AWG) offer a more dynamic and expressive thickening range.

### Connecting

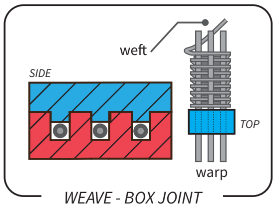
Wire-wrapped pieces are rarely composed of a single element. Typically, several individual elements are assembled together into a single artifact. Connections between elements are typically formed either by wrapping thin coiling wire around elements or soldering the two elements together. With either of these techniques, one of the main difficulties is in holding the various elements in place while forming the connections. In particular, users may accidentally deform the shape of the wire while coiling or soldering, and this can lead to unwanted asymmetries or distortions in the final design.

#### *Connection Proxy*



To facilitate connection tasks, we designed a connection proxy that holds the various wire elements firmly in place while still giving users room to coil or solder at connection points. Similar to the forging proxy, the connection proxy has a channel with guard walls that holds the shaped or forged wire in place. The gap between the walls allows for the wire to be press-fit into the channel. Unlike the forging proxy, the entire channel and walls are lofted above the main plane of the proxy, similar to an elevated highway. The material beneath each connection point is removed resulting in an "overpass". Two holes are added for anchoring the exit points of the connecting wire coil. With this design, users can either coil wire or solder the elements together without worrying about securing or accidentally deforming other parts of the design.

#### *Weaving Proxy*



In some cases, rather than wrapping coiling wire around a single connection point, experts create weaves that bind two or more elements together. In these cases, the individual wires of each element act as "framing wires", or warps, while a thinner gauge wire, or weft, is used to create the actual weave. Holding the framing wires in place when starting a weave is very difficult; usually a rubber-lined clamp is used to position these wires. To help users create weaves, we developed a *weaving proxy* that uses a box joint, a common woodworking joint, to hold wires in place. The teeth of the joint act as a compressive element while the chambers hold and space the wire apart. These teeth can be spaced in different configurations, giving users additional control over the spacing of framing wires. Notably, the box-joint creates two disjoint elements (jaws). This allows for wires which are part of closed elements (with no exposed "ends") to be used as framing wires since the jaws can be positioned anywhere on a design. A binder clip is used to hold the jaws in place while a user weaves.

## SCAFFOLDS OF A SHAPING PROXY

While the previous section describes proxies that facilitate different wire-wrapping tasks, here we focus on wire shaping and ways we can provide different types of assistance, or scaffolds, to assist the user. We design for fabrication assistance, referring to physical assistance with a particular medium such as pliers that provide fine-grain bending control; and construction assistance, referring to the planning of appropriate steps given a set of tools to achieve a given design.

### Jigs (Fabrication and Construction Assistance)

Jigs are proxies that provide the highest level of both fabrication and construction assistance. The hill-climbing shaping proxy described above is one such jig: by indicating where to begin wrapping (the starting hole), how to proceed (continuously rising path), and where to end (terminating cliff), this proxy minimizes the cognitive effort of deciding how, where, and when to bend the wire. Moreover, the act of wrapping itself is constrained to pulling the wire tight against the inner wall, which minimizes the physical skill and dexterity required to realize the design. In this respect, jigs encourages a fairly mechanical, repetitive interaction with the material. While such an interaction may seem somewhat limiting, existing theories of making raise the possibility that even repetitive or habitual creative actions can contribute to the joy of making [20] and that simply engaging in the process of creation has "intrinsic pleasures of creative action" [24]; such self-expression has large socio-cultural benefits [2].

### Stencils (Fabrication Assistance)

Jigs provides a scaffold for shaping an entire design. However, it may be more important for some parts of the design to have an accurate shape, while other parts may be less critical. Moreover, some parts of the design may be much harder to execute than others. Based on these observations, we developed a stencil proxy that only provides scaffolding for specific portions of the design; these portions were manually chosen. For example, the heart design had stencils generated to support fabricating half the heart along the axis of symmetry and supports for creating the arcs that appear at the ends of the design (Figure 1B). These supports are scaled to different size to provide more diverse and alternate forms. To shape the wire, users apply the desired set of stencil components. Since the stencil proxy does not support the creation of every bend in the wire, it provides less assistance than a jig. In addition, users are not constrained to use a single consistent set of stencil components to complete the design; they can choose which combination or subset of components to apply.

In contrast to jigs, our stencil design is motivated by view of making described by Ingold's *making as correspondence*. This correspondence can take the form of a maker who "joins forces' with 'active materials' to see what might emerge"[9]. Latour proposes a similar idea, but notes that agency is not a fixed property of the material or actors but the result of a relationship between people and artifacts [31]. Our stencils act as participants in this correspondence. They provide focused aid for portions of the design but allow for variability in the construction process. In this respect, the final artifact can be viewed as a collaboration between the maker and the stencil.

### Schematics (Construction Assistance)

Both jig and stencil proxies provide some amount of physical assistance with the fabrication process. This assistance necessarily imposes some constraints on how the maker can interact with and manipulate the material. A schematic reduces the amount of physical assistance and instead provides a physical paper with the reference design printed *to-scale* that aids the user cognitively by providing a target design. While schematics are not novel (they act as simple instructions for the maker), they provide a different type of assistance than the other scaffolding proxies. By providing a clear feedback mechanism (evaluating your design as you make it against the piece of paper), schematics aid with a type of making termed "reflection-in-action" and is related to Schön's "reflective practice" [28]. In this view, making occurs between two actors, the user and the materials, and follows the pattern of entering into conversation with a problem, making a move, reflecting on what happened (letting the materials "talk back"), and repeating until convergence. In this framing, schematics enable the user to reflect on how the material responds to bends by evaluating the wire against the reference design. This reflection may produce insights (e.g., a bend needs to initially go past the desired angle to account for the springback of the metal). We provide additional annotations to facilitate the conversation: a) relevant measurements such as the length of the wire and the radii of curves (Figure 1c), b) construction geometries such as the bounding circles of curves, and c) axes of symmetry. By only providing a criteria for evaluation, the maker is free choose their own level of fidelity and workmanship.

## DESIGN TOOL AND PROXY FABRICATION

All of the wire wrap designs and primitives shown in our paper were sourced from artisan handbooks [4] and community forums [2] and encoded as `SVG` drawings. Proxy generation was automated using an annotated SVG path as input. Using our web-based paper.js design tool, we can manipulate paths, specify materials, and add ornamentation (Figure 4). Our tool then produces a heightmap with appropriate walls, holes, and markings as detailed in previous sections to generate a 2.5D model. Proxies were printed using Fused Filament Fabrication (FFF) on a Type A Machine at 0.1 mm layer height using PLA polymer filament. For the proxies that include support and guide walls, we generated the wall geometry by creating offset paths on either side of the original SVG path, giving these offset paths a small constant width, and then extruding them upwards off the plane.

## EVALUATION

We evaluated ProxyPrints in two ways. To validate the design of our material-driven proxies, we conducted an preliminary usability evaluation where participants performed specific wire-wrapping tasks with and without our proxies. We also ran a comparative evaluation between our three scaffold proxies to investigate how novice and expert users respond to different types of assistance.

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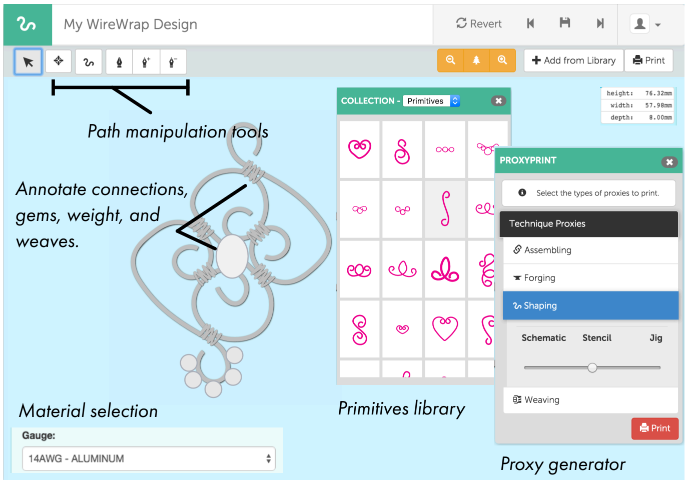
[2] www.pinterest.com



height: 76.32mm
width: 57.98mm
depth: 8.00mm

Select the types of proxies to print.

Gauge: 14AWG - ALUMINUM

**Figure 4. The ProxyPrint digital design tool for wire forms. Users can drag common forms onto a canvas, manipulate paths, specify materials, and add ornamentation and connections. The tool produces a heightmap used to generate a 2.5D printable proxy.**

## Experiment 1: Usability of material-driven Proxies

We recruited four participants through a mailing list and conducted a series of block randomized A/B tests. Each participant carried out four simple wrapping tasks (shaping, forging, connection, weaving) and for each of these tasks answered a series of questions about the usability, perceived speed, and preference of condition, and the preference of the final artifact design.

### *Shape task*

For this task, we gave participants a reference design on-screen and asked them to shape a 16 AWG aluminum wire to match the design. Here, we compared our hill-climbing shaping proxy against the WrapIt jig[13]. Participants were able to complete the design task on average 1.5X faster using ProxyPrint and reported higher usablity and speed; all participants preferred using the ProxyPrint over the WrapIt jig. They also preferred the final 3D wire-wrapped artifacts that were created using ProxyPrint.

### *Forge task*

We then asked participants a shape a wire using a hammer to match a reference weighted line drawing (Figure 3A) with and without our forging proxy. Participants reported a preference for using the hammer without the proxy since it became tedious to reposition the wire in the proxy. However, participants ended up preferring the end artifact created using the proxy, noticing fewer imperfections and a more pleasing aesthetic outcome.

### *Connect task*

Next, we gave participants two heart shapes (depicted in Figure 2B) and asked them to connect them at a specified point with and without our connection proxy (Figure 2). Participants reported a large difference in usability (proxy = 4.5 ± 0.5, without = 1.5 ± 1.0). Without the proxy, participants struggled with accidentally exerting too much pressure on the coil and deforming the wire. In particular, participants worked 1.6X faster and reported higher confidence with the proxy; several participants reported having more control and tighter, cleaner connection coils. One participant expressed a willingness to take on more complex many-connection designs, but noted the limitation that wires need to be shaped precisely in order to fit in the proxy. All participants strongly preferred this proxy.

### *Weave task*

In the final task, we gave participants a simple weaving task: with five frame wires, weave 20 rows of a simple pattern. Participants reported that it was much easier to secure the framing wires and start the weave with the proxy. All participants noted that the most critical stage is the first few rows, however they could not discern a large difference in the quality of their weaves beyond the first couple rows.

## Experiment 2: Scaffold Proxy Evaluation

The main goal of this experiment was to obtain qualitative feedback on how different scaffold proxies affect the making process. We evaluated the scaffolds according to several metrics described in detail below. One of our goals was to compare the responses of novices and experts. We anticipated that the constrained nature of the shaping proxy would conflict with expert practice, while novices would likely prefer the higher degree of assistance. On the other hand, we felt that stencils and schematics would likely coincide with expert practice but provide too little scaffolding for novices.

### Participants

We conducted the study with twelve participants — 6 experts and 6 novices. Expertise was determined from self-reported 5-point Likert values on experience with crafting, metal, jewelery, and digital design tools. Participants with an average experience greater than 3 were labeled experts. Participants were recruited from an internal mailing list at a large software company and the surrounding community via Craigslist. The average age of the participants was 32.3 ± 8 (8 female).

### Procedure

Each session lasted one hour and consisted of a warm-up tutorial, three design tasks, and a post-study interview. Participants were seated at a work table with the following tools: ruler with mm/in, calipers, cutting mat, a rubber anvil and hammer, a permanent marker. Each participant was allowed to choose from three different-color spools of 16 gauge copper wire or 14 gauge aluminum. For each task, the following set of hand tools were made available: a flush cutter and [chain, barrel, taper, bent, nylon] – nose pliers.

In order to minimize newness effects, a small warm-up task introduced each tool and asked used to make an “**S**” shape with no constraint on size; participants were required to cut, straighten, and bend the wire into shape using any of the tools. Lastly, we demonstrated how to use a shaping proxy – specifically how to anchor a wire, follow the jig path, remove the wire, and flatten the final form with a rubber hammer. We then asked each participant to complete the same design task, but varied the type of scaffold proxy that they would be able to use. The ordering was block-randomized. Participants were also asked to reflect out-loud their thoughts on the tools, their design process, and specifically their plans for construction.

The design task was to construct the heart shape depicted in Figure 1. We chose this design since it is a common and recognizable shape that contains a mixture of sharp bends and smooth curves. Participants were allowed as much time to complete each task to their satisfaction. Lastly, each participant was instructed before beginning each task that they could deviate from the design; we only asked that the final design semiotically signify a heart.

### Metrics

Previous HCI research on creativity support has introduced several ways of characterizing how physical tools can support creative practices [20, 30, 38]. We derived metrics from this body of work to evaluate the experience of using scaffolding proxies. We asked participants to rate their experience with each proxy using five-point semantically anchored Likert questions (1=Strongly Disagree, 5=Strongly Agree):

- **USABILITY** – The *proxy* was usable.
- **ERROR** – I made many errors using this *proxy*.
- **TRANSPARENCY** – I was not aware of the *proxy* when I was working with it.
- **CONTROL** – I had control of the wire using the *proxy*.
- **CREATIVITY** – I felt I had creative freedom with the *proxy*.
- **QUALITY** – I am happy with the final design.
- **AGENCY** – Given a *proxy*, I feel capable of making my own customized designs.

Note that **TRANSPARENCY** addresses the awareness of a tool during creative practice [20]. A highly transparent tool (e.g. keyboard) can act as a conduit; a less transparent tool (e.g. high-powered chainsaw) can add risk yet augment the workmanship potential of a craft.

We also looked at **FLOW** which describes absorption with the activity at hand [7] and is a common metric for engagement in games [6]. In design, flow can originate from complexity; the challenge and skill needed to execute a design becomes a source of personal enjoyment [29]. Various methods exist for assessing flow [8]; we focus on one factor of flow – temporary loss of time – which can be measured unobtrusively. We calculated **FLOW** as the difference between perceived and actual completion time. So if a participant completed a task in 11 minutes, and perceived it as 4 minutes, we would have a flow measure of –5 minutes. Lastly, participants were asked to rank the three designs in terms of speed and quality.

#### *Analysis*

We used a 2x3 factorial design with factors **EXPERIENCE** (novice, expert) and **PROXY** (schematic, stencil, jig) within-subjects. Each participant completed the same design using each of the proxy types. The order of the proxies was counterbalanced using a Latin square. Twelve participants completed 3 tasks each for a total of 36 tasks completed altogether. Due to a small sample size and semantically anchored scale data, we look at descriptive statistics.

### RESULTS

Here, we summarize results and findings from Experiment 2. Overall, each session was unique and had widely varying completion times. Several participants deviated from the original design because of an error or took an opportunity to be creative. For reference, the completion time for each task was on average 7.8 ± 3.3 (**SCHEMATIC**), 10.4 ± 3.1 (**STENCIL**), 6.2 ± 2.0 (**JIG**) minutes. We first report quantitative results and then discuss interview responses in the context of specific observations and insights from the study.

#### FLOW, RANK SPEED and RANK QUALITY

For **FLOW**, we found that stencils had a noticeably larger negative effect on time perception[3] than schematics or jigs (Figure 6). This suggests that participants, especially experts, were more engaged and in a flow-state using stencils. Jigs on the otherhand had the opposite effect; experts found these less engaging. When experts used the jig, we also observed a positive effect on time perception, or less flow. Based on subjective responses in Figure 5, this is most likely associated with the higher level of scrutiny (**QUALITY**) that experts had on the near “automated” nature of the jig.

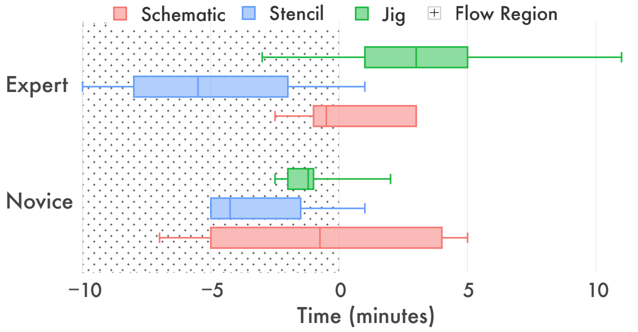


**Figure 6. Flow as a measurement of engagement. The boxplot depict the difference in perceived and actual completion time. Areas in the texture ‘+’ field indicate the participant lost track of time.**

Participants were asked to rank on perceived speed and quality. The results (below) indicate that **JIGS** were consistently ranked higher than the other scaffolding proxies for both factors. Participants reported that their criteria for evaluating quality were symmetry, smoothness, and low marring.

| RANK QUALITY | RANK SPEED |
|---|---|
| **JIG** (1.3 ± 0.8) | **JIG** (1.0 ± 0) |
| **STENCIL** (2.3 ± 0.5) | **STENCIL** (2.3 ± 0.5) |
| **SCHEMATIC** (2.4 ± 0.7) | **SCHEMATIC** (2.7 ± 0.5) |

### Observations and Insights

Our observations of making behavior and user responses led to some insights for future design tools for physical mediums.

#### *Guaranteed success as sites of creativity*

For many, the jig presented a safety net; upon seeing the form they vocalized complete confidence. This was a site for them to explore creative opportunities since they felt they were guaranteed that the base form would “come out”. For those that did not deviate, the amount of guidance the jig gave them changed the narrative of agency. When responding to error, users attributed the error to the jig; whereas in the stencil and schematic condition, they blamed their own skill. One user vocalized that she did not view the jig as a tool:

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[3] Time perception follows a *linear* Weber law with median $k = 0.77$ [1] which suggests that we would still see similar (albeit less profound) trends if we adjusted for perception error.

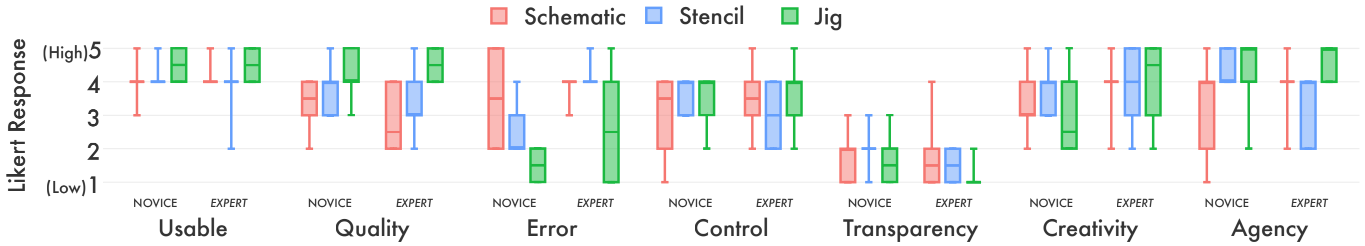

**Figure 5. Scaffolding proxy evaluation responses. A simple design task is carried out by 6 expert and 6 novice participants for each proxy (schematic, stencil, and jig). Displayed are reported values for several creative tool metrics (bottom). Each metric is grouped based on Novice (N) or Expert (E) responses. Note the differences in Creativity using Jigs, Error, and Agency.**

> **Novice #3:** I relied on my hands mostly, not the hand tools. For me, the jig was the hand part.

Furthermore, jig-made designs were subject to scrutiny. Slight imperfections in symmetry were viewed as major flaws, whereas in the other two conditions such asymmetry was embraced as a "handcrafted" look. Notably, experts had higher scrutiny of jig **ERROR** ($\bar{x}$= 2.7 ± 1.7) than novices ($\bar{x}$= 1.5 ± 0.5). This indicates that tools that are designed with more agency in the fabrication process bare the burden of error.

### *Cognitive offloading can support ritual*

Some participants relished the ability to not have to think about how to construct the wire form.

> **Expert #4:** I could just loose myself in the jig. I am totally absorbed in it. I don't have to think; I just do what I tell it to do. I surrender to it.

One participant likened this workflow to the rhythmic mechanical repetitive movement of her hands when knitting garments.

### *Multiple cognitive entry points encourage deviation*

A clear differentiation between expert and novice users was the ability to see multiple paths. For many, the proxies provided to them offered a clear and singular route to achieve the design. We hypothesized that the **JIG** would hinder creativity of expert users since it was so constrained to one design. However we were surprised at how expert users viewed the guiding walls and other superfluous elements as interesting deviation points.

> **Expert #2:** I dislike that I am only given one hole to anchor my design. I want holes everywhere. At the base of the path (Jig) and at the end. I want to start in a completely different place. I want these walls to end more symmetrically, and have gaps exactly the width of my wire, so I can use them in my design.

These participants went "off-the-path" and arrived at serendipitous designs that took advantage of non-design elements of the jig. than their novice counterparts ($\bar{x}$= 3.0 , $\sigma$= 1.3) with **JIGS**. Experts more readily deviated from the constrained design presented in the **JIG** and expressed greater creative freedom ($\bar{x}$= 4.0 ± 1.3). Novices, on the other hand, followed the **JIG** design, expressing less creative freedom than their counterparts ($\bar{x}$= 3.0 , $\sigma$= 1.3). However it was often the case that novices were, if successful, elated at being able to make a professional-looking form. Between both groups, participants expressed the felt the most capable in making future designs (**AGENCY**) with the **JIG** ($\bar{x}$= 4.5 ± 0.9), than the other proxies ($\bar{x}$= 3.6 ± 0.9), **SCHEMATIC**; ($\bar{x}$= 1.2 ± 0.9), **STENCIL**).

### *Expert behaviors: Forethought and tool-switching*

Many novice participants needed to match each construction step to visually approach the final design. As such, if an element was accidentally misplaced, it would immediately be corrected. This behavior was most noticeable using the **SCHEMATIC**. Since the schematic was to-scale, many participants bent wire directly on top of the schematic and used it to frame and "sanity check" their design. When accidentally displacing an element, users found that they had more confidence in returning it to the correct form. Participants using this proxy constantly verified form and felt higher risk working with their hands. Several participants expressed a similar sentiment for deciding when to stop, likening the wire to becoming stale.

> **Novice #1:** I always worry about the symmetric part. Thats when I didn't have control. I was particularly intimidated by [hand tools]. Hand tools are so free form. The jig I could handle. I just had to follow the form. With the hand tools [schematic], I didn't know where to begin. I realized that I had to minimize the amount of contact I had with the wire.

We noticed a delay in this match-step behavior with expert participants. Notably, experts were more prone to make movements meant for making fabricating the shape easier:

> **Expert #3:** I'm not going to worry about that now. I know that I can make it look fine in the end; I need to focus instead on these end loops first.

From think-outloud transcripts, we noted general differences amongst proxies over the type of thinking participants exhibited. Participants using the **JIG** exhibited passive thinking, succeeding agency to the jig.

> **Novice #1:** I'm just going to go around and around the jig, letting it guide me to where I need to go.

Conversely, **STENCILS** elicited in-the-moment thinking, or responding to events as they happened. This was evident in the amount of tool-switching that occurred as participants varied their working style based on the current state of the wire. Lastly, **SCHEMATICS** elicited more active, forward thinking, or planning actions based on anticipated outcomes. Forward-thinking was primarily observed when participants realized that they had to achieve symmetry without any aid. Only then did we see behaviors that purposely started with the crease in the heart design, before moving onto the curves and loops on the ends of the wire.

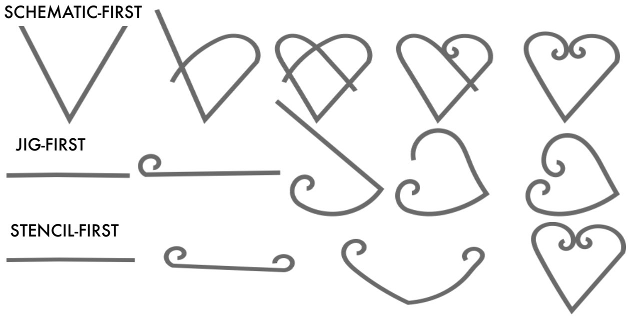

**Figure 7. Construction patterns were highly dependent on the first scaffold that was presented to participants. Schematic-first users moved with step-wise similarity, jig-first followed a linear progression, while stencil-first compartmentalized forms – an expert trait.**

### *Novice behaviors: Construction fixation*

We observed high variability in how users constructed their design in the **SCHEMATIC** condition, and detail some notable construction patterns depicted in Figure 7. Participants who started with the schematic condition moved closer to the final design with each step. However, if a step did not bring the design closer to the desired form, these users would become more apprehensive and stop manipulating the wire as freely. Participants who started with the jig followed a linear construction pattern, often being unable to allocate enough material to successfully achieve symmetry. Lastly, participants who started with the stencil compartmentalized their construction, creating the complex loops before creating the bend thereby minimizing the amount of interaction between different components of the design. This approach had a higher chance of achieving symmetry. This priming effect suggests a construction fixation, or a cognitive bias that limits a person to construct a design in a prescribed way. This presents a unique opportunity for the design of making tools: *construction methodologies can be influenced by computational proxies to encourage expert best practices*.

## LIMITATIONS

Our study targeted the fabrication phase of a simple design in a limited time frame. While our evaluation metrics provided a profile of the making experience, we recognize a need for assessing how embodied skills and experiential pleasure develop. The study does provide insights into the onboarding phase of design tools — a critical phase for novice users getting acquainted with a process.

## DISCUSSION

Future tools need to be able to incorporate the user back into the design cycle in order for users to develop an understanding of the material and engage users to deviate from templates. Our approach strikes a subtle balance of handed and digital fabrication; we show how this balance can promote exploratory behaviors through stencils, encourage design deviations using ambiguous entry points, communicate tacit knowledge through ordering. ProxyPrint offers an alternative trajectory for DF tools, specifically one that foregrounds making intermediary tools that aid users in fabrication.

In the case of maker communities that openly share designs, the room for deviation for novices is dependent on the familiarity of the tools available to them. Scaffolding is especially relevant to empowering novice users to create their own designs. To encourage deviation, we found it necessary to explicitly mark alternative forms and visualize ambiguous designs. For instance, a parametrized STL model of a vase can "ghost" its design space, indicating to the user the multiplicity of forms that can exist.

The level of automation in a scaffold is particularly important to how makers might assess their work. As we saw in ProxyPrint, providing too much fabrication assistance shifts the burden of error to the machine, whereas when the error is shared by the maker and the machine a "handed" synergy exists. Providing consistent feedback is important for novices who we observed had less of a basis for evaluating whether their construction patterns are "correct"; providing a guaranteed success can mediate this initial experience as evaluation criteria develops. In this context, design tools can present a task with a ground truth for users to compare against during their initial experiences with a material. While frustration is common in the design process, certain areas of a design can purposely be made to instill pleasure. We found that ritualizing an action, or offloading cognitive effort with a repetitive manual task, can support crafting practice.

We showed that with a medium-aware design that takes into account the unique properties and cultural histories of materials, we can make proxies that assist, enhance, and extend the wire-wrap medium. Other domains can benefit from such passive proxies, for instance, a ceramics proxy practice might involve stencils that form lathe bits for use with a pottery wheel. Because of the *passive* nature of proxies, participants found value in a proxy's non-intrusiveness and proposed a practice which follows: sketching an idea and "wrestling the material"; converting interesting forms into stencils; and refining this into a final artifact. It is imprudent to disregard the new cultural histories that are arising from DF machines; works such as *Filament Sculptures* [18] that creates 3D forms from a 3D printer's characteristic extrusion demonstrate the gray area that exists between what is a tool and what is a material.

## CONCLUSION

In ProxyPrint, we expanded the expressibility of computational wire-working through forging, connection, and weaving proxies. We identified that proxies can exist on a spectrum of support and design three scaffolding proxies (schematic, stencil, and jig) that capture points along this spectrum. We characterize these proxies through common measures in hybrid crafting, and evaluate them in a formal user study. We show that our supports impact quality and speed, and differ between experts and novices. We contribute design principles for facilitating both expert and novice practice and engaging users with the medium.

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