Digital Joinery For Hybrid Carpentry

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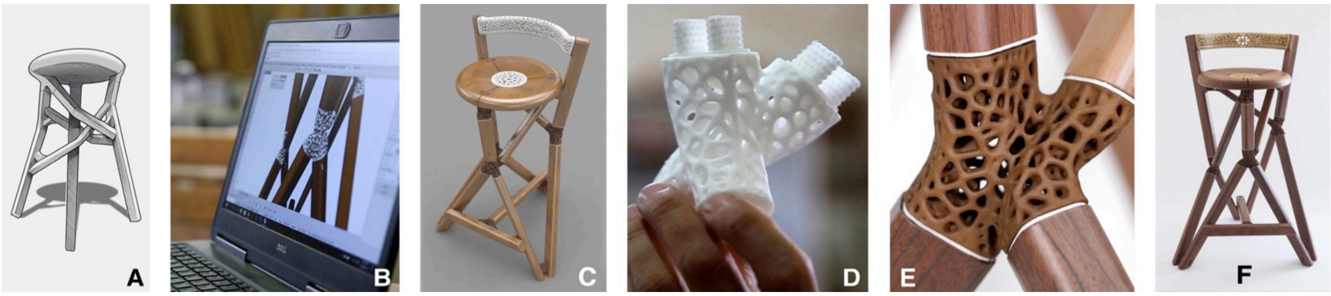

Figure 1 Digital Joinery and five development stages of a hybrid stool. (A) An early sketch of a stool design relying on Digital Joinery; (B) using the *Generative Joinery Design Tool*, the software generates digital joints; (C) a rendering of a complete stool with digital joints; (D) a 3D-printed (by selective laser sintering) Nylon-12 joint with its anchors; (D) a closeup photograph of a dyed and assembled Voronoi diagram skeleton joint, connecting four wooden beams; (E) a photograph of the finished stool (by Daniel Shechter).

ABSTRACT

The craft of carpentry relies on joinery: the connections between pieces of wood to create multipart structures. In traditional woodworking, joints are limited to the manual chisel skills of the craftsperson, or to capabilities of the machines, which favorite 90° or 180° angle joints with no more than two elements. We contribute an interactive design process in which joints are generated digitally to allow for unrestricted beam connectors, then produced from Nylon-12 using selective laser sintering (SLS) 3D printing. We present our *Generative Joinery Design Tool* and demonstrate our system on a selection of stools. The paper exemplifies the potential of *Digital Joinery* to enhance carpentry by incorporating a hybrid and interactive level of design sophistication and affordances that are very hard to achieve with traditional skills and tools.

Author Keywords

Design; Carpentry; Woodwork; Joinery; 3D printing; Hybrid; Digital Fabrication; Computer-Aided Design.

ACM Classification Keywords

H.5.2. User Interfaces: User-centered design.

CHI 2018, April 21–26, 2018, Montreal, QC, Canada © 2018 Association for Computing Machinery. ACM ISBN 978-1-4503-5620-6/18/04...$15.00
https://doi.org/10.1145/3173574.3173741

INTRODUCTION

> *Good joinery... is difficult to design and even more difficult to execute. It should be thought of as an investment, an unseen morality.*
>
> George Nakashima [22]

The craft of designing and implementing wood joints has a long-standing and important role in all traditional woodworking practices [22,23,28]. Joints are the elements that transform lumber into a practical artifact. They are fundamental to wooden artifacts and are probably the most technologically advanced elements in woodworking.

The complexity of the joinery craft applies severe constraints on carpentry, limiting the design possibilities of wooden artifacts. It is difficult to master high-end joinery craft as it requires to control free-hand chisel techniques and the design of non-trivial joints. Thus, common joinery restricts design possibilities to flat or right angles between pieces of wood, rarely connecting more than two pieces in the same joint. In our work, *we are motivated to liberate contemporary woodworkers from this limitation* and enable new design affordances using generative design and additive manufacturing (AM) of plastic joints.

Digital Joinery contributes a new type of design freedom and construction affordances to furniture making. For instance, a maker who wishes to design a complex joint posits the 3D lumber plan virtually and selects all of the surfaces that need to be connected. A parametric design procedure helps in generating a Voronoi diagram skeleton, which acts as a bridge between the wooden surfaces. Our tool allows for parametric control over the characteristics of the joint, such as density, thickness, and style. After structurally evaluating the design, the user 3D prints the joints in Nylon-12 through selective laser sintering (SLS).

In addition, we contribute new designs for 3D-printed anchors, which are virtually added to the generated joint before printing. These anchors, which do not require special woodworking skills to assemble neither glue, are the locking mechanism between the joint and the wood.

In the following section, we review related work, then discuss wood joinery. Then we turn to detailing the technical aspects of Digital Joinery, including the anchors, our *Generative Joinery Design Tool* (GJDT), and a design workflow. We present a design case featuring three stools. Before concluding, we discuss feedback we received from makers regarding the future potential of Digital Joinery.

RELATED WORK

Digital Joinery brings new design affordances to carpentry, like other *hybrid design* projects that mix traditional craft with digital practice [1]. Hybrid design is a blooming research territory in HCI, featuring new hardware [37] and software tools [6], aesthetics and creative procedures [4,12,13,29,34]. In general, the hybrid practice aims at extending the creative spectrum of makers, going beyond the secure boundaries of autonomous fabrication [35].

Today, designers rely on hybrid practice in diverse ways [6,14,17,21,26]. For example, in [33] Zoran demonstrates a process where plastic structures are designed digitally and 3D printed, then manually reinforced with organic woven fibers. *Hybrid reAssemblage* features an alternative process, where broken ceramic elements are restored by 3D scanning and printing to create a new type of aesthetic [36].

With respect to craft, digital design can produce complex patterns that are hard to make manually [25]. These patterns, such as the Voronoi diagram that we use in our work, can resemble organic structure [11] and are common in many CG projects. For example, Lu et al. introduce a minimal-weights optimization tool, utilizing the Voronoi diagram to compute irregular volume tessellations [18]. Martínez et al. study procedural aperiodic microstructures inspired by Voronoi foams to enable 3D printing of flexible structure [19]. A newer work discusses a foam-like printed material that adapts to uneven load scenarios, featuring structures that are generated by a stochastic process [20]. In addition, the idea of modifying 3D forms to achieve a new aesthetic is also common in CG, where 3D CAD objects are virtually modified to allow for surface decoration [2,31].

Recently, several projects have explored the application of parametric and generative design to both joinery design and furniture making. Zheng et al. have developed a parametric joint generation tool for 2D laser cut assemblies [32]. *TrussFab* is an integrated end-to-end system that allows users to fabricate large-scale structures [16]. Yao et al. present a tool for designing furniture joints with user-controlled graphics [30]. *SketchChair* is an application that allows novice users to control the entire process of making their own chairs [27]. Fu et al. present a computational solution to support the design of a network of joints that form a globally-interlocking furniture assembly [7]. Meanwhile, Garg et al. present software to support the interactive design of reconfigurable furniture, featuring tools that resolve infeasible configurations [8]. Yet these projects have grown out of an academic landscape, while many joinery developments are happening in design studios and professional woodworking workshops.

WOOD JOINERY: FROM TRADITIONAL TO DIGITAL

In *The Joint Book*, Terrie Noll reviews joint techniques and orientations [23]. Achieving a joint between pieces on *two* different planes is very difficult and therefore rare. Several beam and board orientations are common: *parallel* and *I* orientation (boards joined by their edge or end to end to increase width or length); *L* and *T* orientation (90° connectors); and *crossed* or *angle* orientation (modification of one of the orientations to change the joining angle in *one* axis to anything other than 90° or 180°).

There are numerous techniques to implement the joint itself. One can use glue, nails, screws, or other fasteners to attach one piece of lumber to another. *Dovetail* joints are interlocking joints with great mechanical strength. They are constructed with an angled male part shaped like a dovetail that fits into a similarly shaped female socket. *Mortise-and-tenon* joints are also very common, having a tongue (tenon) that fits into a hole (mortise). In many traditional practices, such as Japanese carpentry [28], skilled craftpersons mastered dry wood (no glue) joint techniques that are reversible and feature several complex wooden parts, enabling sophisticated locking mechanisms.

Recently, as digital fabrication devices have became more common, a growing number of projects have featured computer-aided design (CAD) joints. Jochen Gros has presented 50 digital wood joints, designed using CAD and fabricated by a computer-numeric control (CNC) milling machine [10]. In addition, several projects explore the use of 3D printing in fabricating plastic joints, mostly to allow for modularity in their construction [3,5,9,15,24].

DIGITAL JOINERY FOR HYBRID CARPENTRY

Working in the same realm, and implementing 3D-printed plastic joints for woodworking, we aim at adding an *interactive* stage to the joinery design process. Our work allows users to create *unique and specific solutions to complex conditions*, rather than generic ones. Our digital joints comprise two parts: the joint body and anchors, both printed in Nylon-12 $[(CH_2)_{11}C(O)NH]_n$ (PA12) a durable, low-cost material with good mechanical properties, which enables production of hollow and latticed structures.

The *joint body* bridges all of the wood surfaces that need to be connected, and is generated with our software. In order to save material costs and weight, a sparse Voronoi skeleton makes up the body, which also contributes a distinguished style. The *anchors* are set manually, as the designer chooses the type of anchors she or he would like to use and adds them virtually to the joint body prior to printing.

Our *Generative Joinery Design Tool* allows makers to specify unique joints for custom design furniture. Using our portfolio of anchors, the 3D-printed joints can be assembled easily with no need to master manual chisel work or have special CNC machines. We now review our custom anchors prior to discussing GJDT. (All of these files can be downloaded from the project website[1]).

Digital Joinery Anchors

Anchors enable easy assembly of strong and stable furniture. The anchor is an element of mechanical *dry* connection (without adhesive). To prepare the wooden parts to receive the anchor, only manual tools are necessary, as opposed to only using CNC. We conceptualize different methods to implement the anchors, and present below the final four anchor designs we use in our work. CAD models of these anchors are available from the project website.

Anchor 1 relies on friction in a 6 mm-diameter cylindrical structure 16 mm in length with one-directional 1 mm serration (see Fig. 2C). To ensure anchor efficiency, seven different models with varying teeth angle/quantity were evaluated. All of the models underwent a pulling test to see if they would move out of place under stress (see Fig. 2D). The tests showed that the quantity of teeth is less significant than tooth angle. We observed that a decisive 25° angle provides maximum durability when an anchor is pulled. Optimal results were received from model 20/25, which could withstand a maximum pulling force of 29.25 kg.

Anchor 2 (Wedge) relies on Anchor 1 (serrated structure) with a wedge that locks the anchor when the joint reaches its final location (see Fig. 2D-E). Unlike Anchor 1, which resists insertion (as friction makes it extremely difficult to achieve an optimal tight connection), Anchor B can be inserted smoothly and easily. In our proposed structure, Anchor 2 can withstand a maximum pulling force of 65.62 kg, double the amount of Anchor 1. One limitation of this anchor is that it requires access to the joint from both sides of the wood, thus it is not suitable for every situation.

Anchor 3 (Nails) relies on Anchor 2, but instead of using a 3D-printed wedge, we used steel nails inside the anchor (see Fig. 2D-E). When the anchor is pushed into the wood, the nails remain inside the anchor's body. The nails reinforce the plastic anchor with a metal structure; hence, withstanding a maximum pulling force of 101.83 kg.

Anchor 4 (Jumbo) is a jumbo anchor (see Fig. 2D-E). Unlike the previous models, this anchor uses the latticed body of the joint to set in a 2.5mm screw that holds a tenon. As the screw is tightened, the tenon retracts the anchor, which is pushed forcefully against the wood. This joint reinforces the anchor with a metal structure and can withstand a maximum pulling force of 35.98 kg. It should be noted that this anchor never failed a test, as the anchor never collapsed, although the nylon body began to stretch.

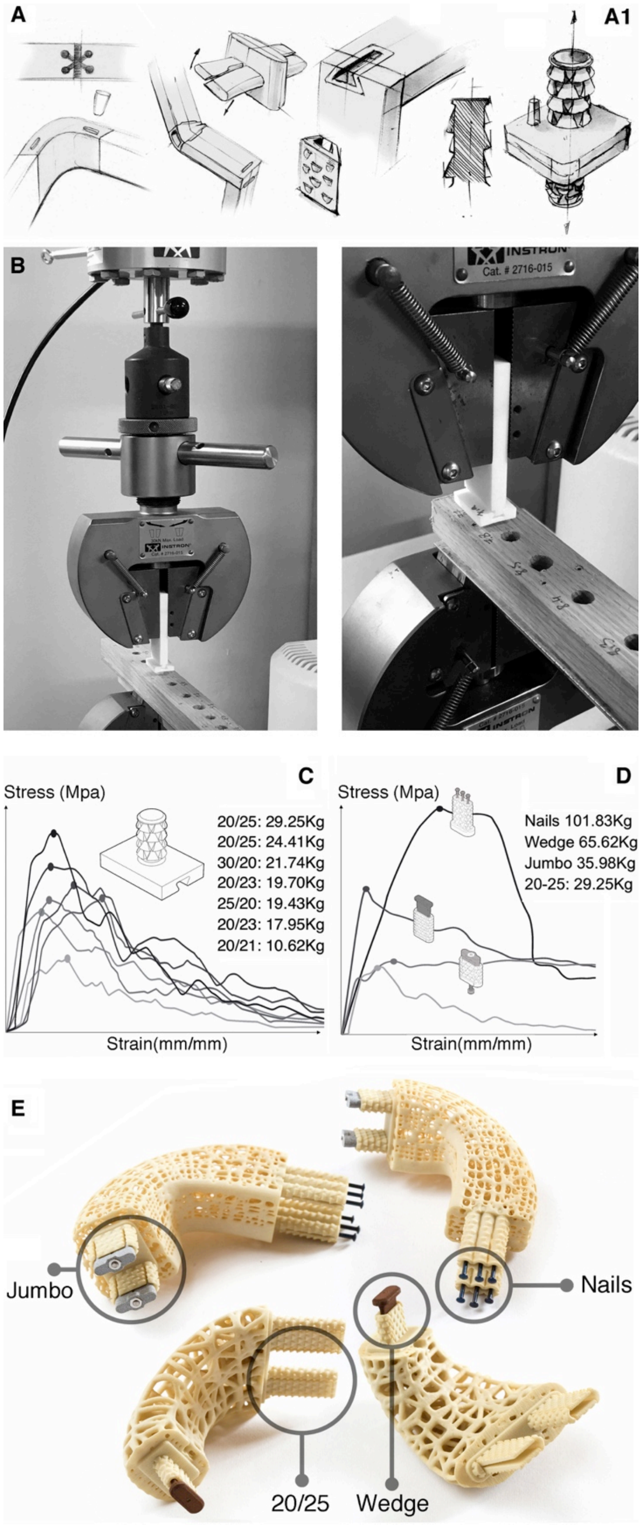

Figure 2 Digital Joinery anchors. (A) Initial sketches for anchor concepts, and (A1) the selected solution. (B) Physical stress-strain evaluation and (C) the results as a function of teeth angle/quantity of a cylindrical anchor. (D) Improved designs with anchors utilizing different locking mechanisms (nail, wedge, jumbo and flat 20-25). (E) The collection of different anchors we used (Photograph by Daniel Shechter).

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[1] http://www.amitz.co/DigitalJoints.html

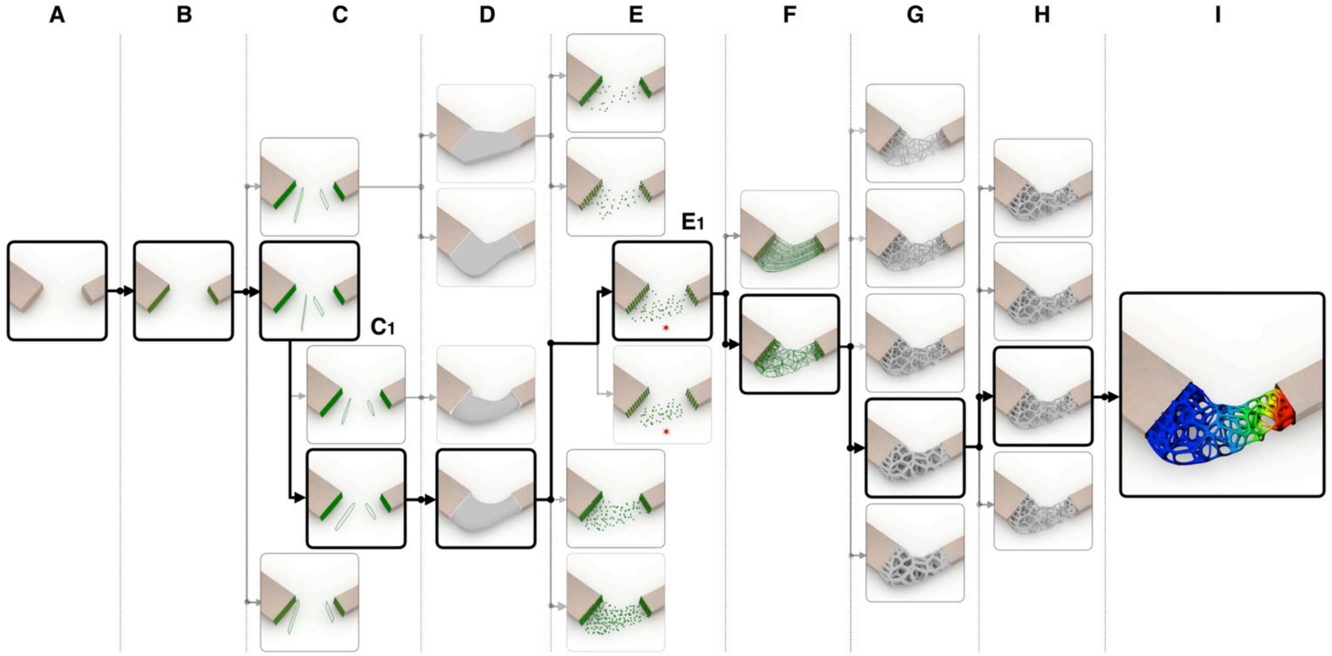


Figure 3 The interactive procedure and workflow of our Generative Joinery Design Tool (GJDT). (A) Specifying lumber position in Rhino; (B) selecting surfaces to be joined in GJDT; (C) defining the position and orientation of the supporting contour curves, (C1) and controlling their fillet angles; (D) applying a loft function between the surfaces to create a watertight solid object; (E) populating this object with random points, or (E1) using attractor points; (F) generating a 3D Voronoi diagram with or without isocurves; (G) creating a solid 3D Voronoi skeleton in the arm thickness defined by the user; and (I) outputting the design for external structural validation tests.

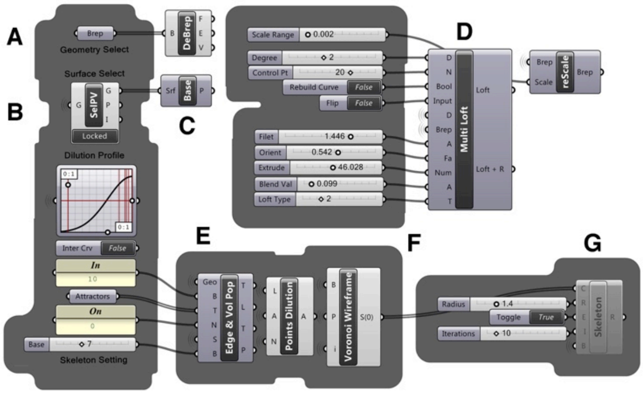
In the *Design Case: Stool Collection* section we present a set of stools that demonstrate the use of all the anchors described here. In real-world applications, we extend the length of the anchors up to 25 mm if the thickness of the wood allows. Before examining this work, we outline the main interactive and technical principles of our GJDT tool to design joints.

Generative Joinery Design Tool (GJDT)

Using Grasshopper, a parametric design plugin for Rhino, we developed GJDT to allow users to customize joints. Where the design consists of several joints, the designer will need to process each of them separately. The generative design procedure is as follows (see Fig. 3 and 4):

1. In Rhino, the user specifies the lumber position in 3D space, or imports a design made elsewhere. The user can use as many separate wooden parts as he or she wishes, as long as the surfaces that need to be connected are flat and rectangular (see Fig. 3A).
2. In GJDT, the user selects the wooden elements and their surfaces S_i (where i is the surface index) that need to be joined (see Fig. 3B and Fig. 4A-B).
3. GJDT generates contour curves C_i for S, and a set of curves C_i^* that offset C_i^* by distance d (the user's input parameter) in the corresponding normal direction n_i, such as that $C_i^* = d \times n_i + C_i$ (see Fig. 3C). The user has parametric control over $C_i^{Total} = \{C_i, C_i^*\}$ corners, filleting, and the angles of C_i^* (see Fig. 3C_1).
4. GJDT lofts each set of $C_l^{LoftSet} = \{C_i^{Total}, C_j^{Total}\}$ to create a solid object ($0 \leq j \neq i <$ number of surfaces), such that $SO_l = \mathrm{Loft}(C_l^{LoftSet}, \mathit{control\_param})$. Lofting can be challenging, and sometimes Rhino's manual loft function operates better than the function in Grasshopper, allowing more control options. Therefore, if the lofts do not satisfy the user, they can be redone manually (see Fig. 3D). In both cases. the user can choose the type of loft function to use (*Loose*; *Normal*; *Straight sections*; *Tight*; *Uniform*).
5. GJDT applies boolean union U on all SO_l. Sometime boolean operations in Rhino and Grasshopper fail due to numeric conflicts; this is solved by re-scaling each SO_l by different frictional factor.
6. GJDT populates U with points inside and on the boundary surfaces. The user controls the number of points to populate. The surface bases are populated with a dense grid of points to stabilize the connection to the wood (see Fig. 3E and Fig 4E). The user can implement an attractor to create an uneven distribution of the points, in order to change the local resolution of the joint skeleton (see Fig. 3E_1).
7. GJDT generates 3D Voronoi curve skeletons based on the population points. GJDT creates Voronoi 3D solid objects, produces curves based on the corners of these objects, and deletes duplicate curves. The user can decide whether to add the original isocurves of U to the skeleton (see Fig. 3F and Fig. 4F).

8. GJDT generates a volumetric skeleton based on *U* curve structure. The skeleton *SK* bones radius is set by the user (see Fig. 3G and Fig. 4G).
9. GJDT applies Laplacian smoothing on SK^s = *LaplacSmooth* (*SK*,*iterations*), when *iterations* is set by the user (see Fig. 3H and Fig. 4G).
10. The joint SK^s is finished. The user can evaluate it aesthetically and structurally (using an external FEM tool; we used the Scan&Solve Rhino plugin) and review alternatives (see below and Fig. 6). A future GJDT version may include internal (built-in) topological optimization abilities.
11. In this stage the joint body is ready. The user now adds the anchors she or he wishes to use in the design and generates a STL mesh file for print.



Scale Range 0.002
Degree 2
Control Pt 20
Rebuild Curve False
Flip False
Filet 1.446
Orient 0.542
Extrude 46.028
Blend Val 0.099
Loft Type 2
Inter Crv False
In 10
Attractors
On 0
Base 7
Radius 1.4
Toggle True
Iterations 10

Figure 4 The Grasshopper interface of GJDT. GJDT's main components are: (A) 3D object import; (B) surface selection; (C) generating supporting curves; (D) lofting between surfaces to create a solid watertight joint body; (E) population of the object with random points; (F) generating a 3D Voronoi diagram; (G) creating a smoothed, solid skeleton body. Initial settings are in the center of the sliders' ranges for ease of use.

The Hybrid Design Process and Workflow

The hybrid design workflow is subject to personal design preference and habits. We can only suggest a recommended workflow we used and executed, as demonstrated in the following section and later demonstrated on three stools.

As in many design processes, the maker starts by sketching concepts and exploring alternative solutions to the project requirements (see Fig. 7). The maker is free from traditional carpentry restrictions and can envision designs going beyond traditional shapes. For example, multiple-beam joints and unusual angles are now possible, and new types of organic aesthetics (as influenced by the Voronoi diagram style) may suggest decorations and new patterns influenced by the 3D printed work. The maker can select the preferred anchor for the specific application. A color treatment and material bridge may be needed to aesthetically link the printed plastic with wood. See Fig. 5 for varying types of printed and assembled joints, and Fig. 8 for examples of the impact of the joint on the overall stool design.

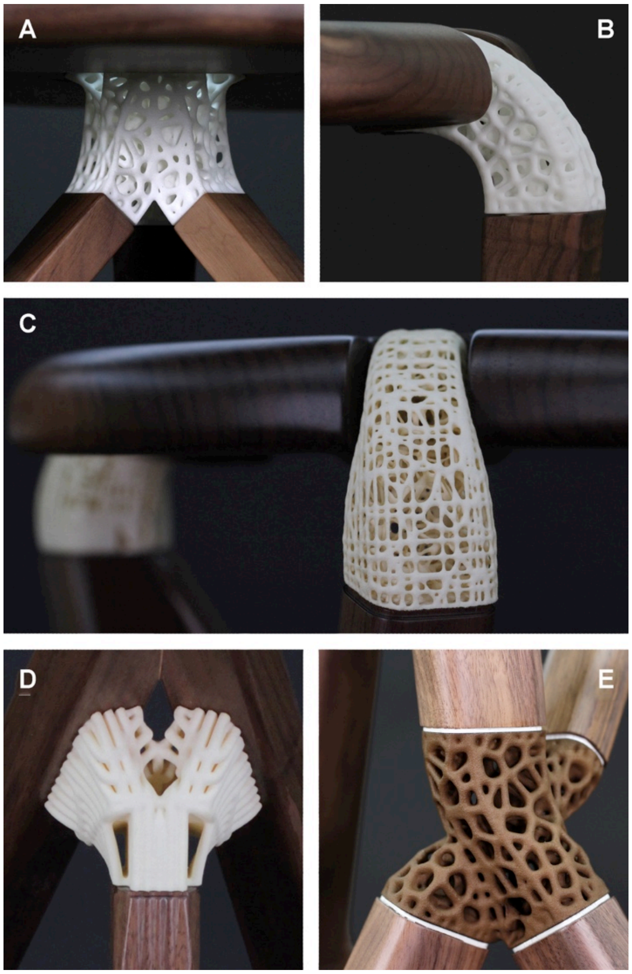


Figure 5 Five different photos of printed joints with varying finishing colors and visual styles in the bodies of the joints. These joints demonstrate a small sample of the potential for stylistic variety in GJDT.

When the maker is satisfied with the sketch, she or he models it in Rhino—largely by positioning wooden beams and boards in the 3D CAD space. Then, joint-by-joint, the designer creates digital joints using GJDT. For each solution, the designer can consider alternatives, taking into account varying parameters such as structural analysis results (finite element analysis, FEM, is not yet an integrated part of GJDT), printed price and weight, and the aesthetic style of the joint. Anchors are then added to the design, and the work is sent to print.

Meanwhile, the maker manually produces the wooden parts. Upon receiving the printed joints, she or he assembles the work and finishes it using any accessible, useful technique and process. One of the main principals of Digital Joinery is that the construction can be dry (no glue) and does not require any special CNC work and/or chisel skills. This makes the furniture assembly reversible and easy to accomplish for non-professionals.

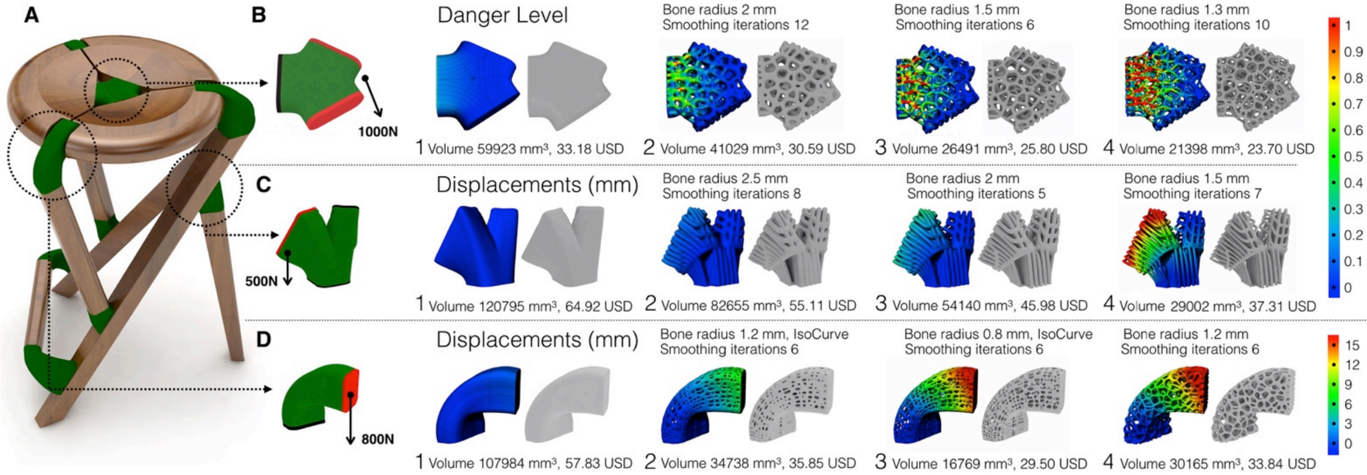


Figure 6 (A) A CAD model of a stool, and different Digital Joinery alternatives for joints (B-D). The user can consider structural analysis evaluation (here done in the Scan&Solve plugin for Rhino), cost, weight, and aesthetics: (B) A three-surface joint and its danger level simulation; (C) A three-surface joint and a displacement simulation; (D) A two-surface joint and a displacement simulation. Cost calculated from www.shapeways.com website in May 2017.

Figure 7 Concept designs, sketches, and investigations. (A) Initial sketches of concept designs for hybrid stools that require Digital Joinery for construction, and (B) several 3D-printed miniature stools to evaluate design ideas.

DESIGN CASE: STOOL COLLECTION

To personally evaluate Digital Joinery and demonstrate its capabilities, we designed and built a collection of hybrid stools. The first model constitutes our initial attempt to fully complete the design and construction of an object that merges woodcraft with digital practice

T1 model The first stool is a 120° radial symmetry stool (see Fig. 8A-B). It consists of a central joint joining three sections of the top together, and three sets of two joints connecting the three legs to the top. During the production of the joints, we learned that connections made at multi-faceted junctions have multiple advantages over those made at connection points where one face is joined to another.

T1 is based entirely on Anchor 1. In the process of creating this stool, we discovered many design principles that helped in the following designs. The joints were fastened together with friction, thus the degree of precision needed between the holes in the wood and the printed anchor parts was extremely high. Precision to the tenth millimeter is required to enable the anchor to enter without damaging the 3D-printed plastic and to lock the part into the wood. The printed parts suffer from imprecision due to production accuracy and the placement of each anchor in a different vector on the printing tray. Additionally, as the printed material absorbs moisture after printing, its dimensions change. These factors all make the connection points slightly loose, which causes a sense of instability when a user sits on the stool.

Visually, the meeting point between the wood and the printed Nylon-12 creates an aesthetic unease. The visual challenge raises several design-related concerns about how technologies are sacrificed for each other; hence, this was a main consideration for the subsequent developments.

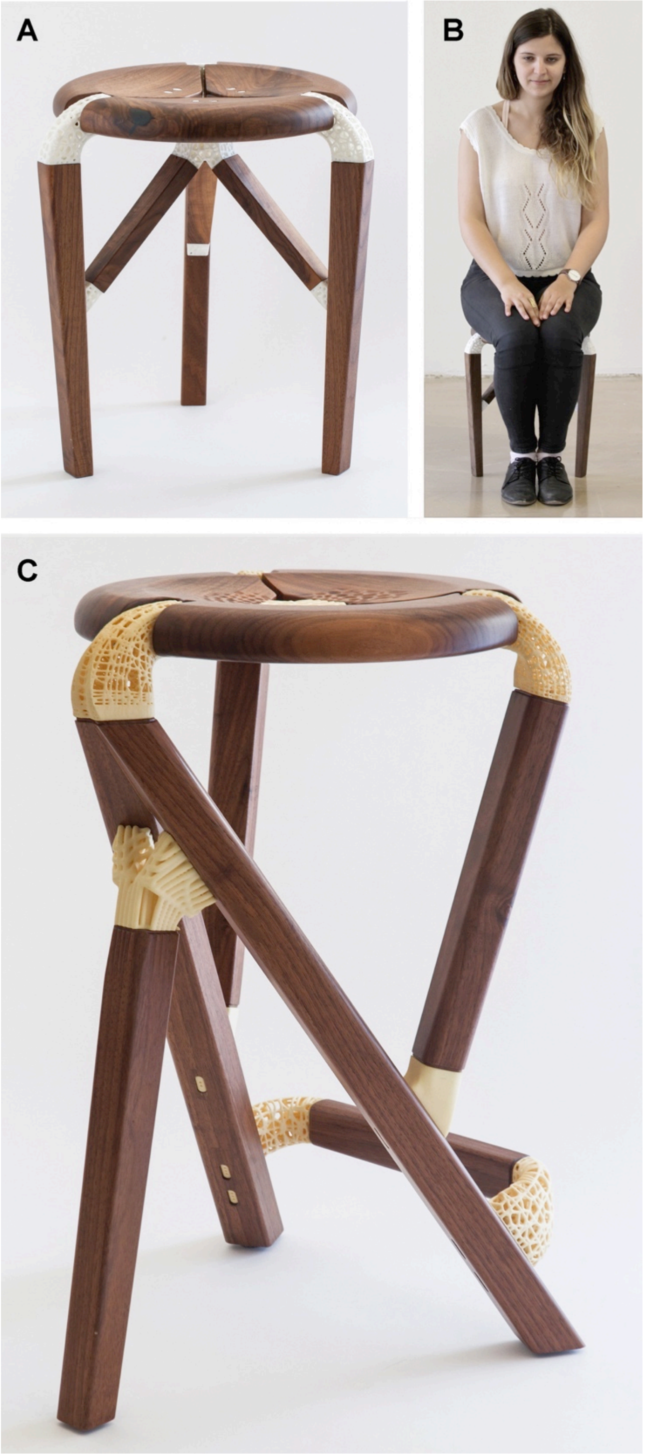


Figure 8 The two first hybrid stools in our collection. (A) T1 model with no load and (B) with load, and (C) T1 model with off-white dyed anchors. Photograph (A and C) by Daniel Shechter.

T2 Model In this second model, different types of joints were generated (see Fig. 8C). Here our design purpose was two-fold. First, we aim at exploring varied aesthetic possibilities received from GJDT. In addition, this stool allows for examination of the joints' maximum mechanical ability to bear a load, compared with FEMs (see Fig. 6).

The range of styles resulting from GJDT enabled a wide variety of possibilities, as the user-controlled parameters in GJDT result in joints with rich aesthetic characteristics (see also Fig. 5). In addition to stool T1, here we considered for the first time how manual woodwork could welcome the plastic joints with better visual integration. We colored the joints using a special paint solution, and explored how manual carving can reflect some of the joint patterns in the wooden elements (in Fig. 5D, for example, note the decorative pattern in the wooden beam below the joint).

The use of Anchors 2, 3 and 4 allowed for easy and quick construction. The required precision of the joint placement was made possible with zero tolerance in the connection points. Given that the form chosen for the joints bearing the seat was one that has lattice strips with a thickness of 0.8 mm (see Fig. 6D$_3$), which in the preliminary analyses revealed extensive areas of failure, the stool top becomes springy and soft. This contributes an additional quality in our Digital Joinery: the ability to use FEM to predict and design the *dynamic* behavior of the joints.

T3 model The last model was inspired by the aesthetics of the Voronoi diagram implementing the joints. This model demonstrates a stool design with a structural style unique to the technology. It reveals the design potential that can be achieved using our new process, which allowed the creation of a complex geometric structure that cannot be achieved using traditional technology. Digital Joinery allowed relative ease in the design, production, and assembly of the resulting structure, which is both stable and unique.

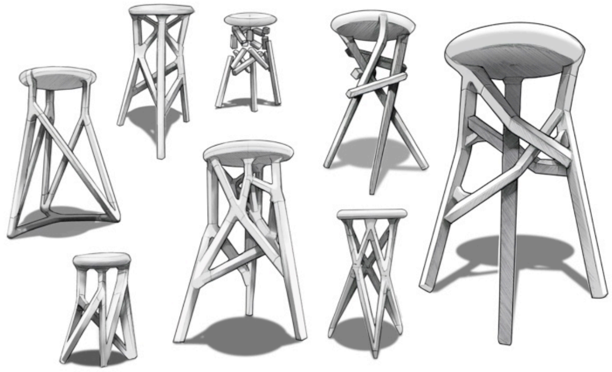


Figure 9 Eight sketches of 3D Voronoi-diagram inspired stools, an early stage in designing stool T3.

In this model, most of the joints were locked using Anchor 4. A latticed structure resulting from Voronoi diagrams (see Fig. 9) enables joint precision using screws that are almost invisible, yet provides an excellent degree of structural strength (see Fig. 10). We used CAD work to create stylish 3D printed parts in the backrest and the center of the seat (such as in Fig. 10B), colored to compliment the aesthetic of the wood. This creates an additional visual link between the wooden parts and the 3D-printed parts. A thin white ring was painted on the wooden beams near the edge that meets the joints to stylize these contact points.

EVALUATION

One can easily see how our work evolved from the first stool to the last, and how we refined our hybrid craft skills while we worked on the three stools. The design evolution we experienced hints at the full aesthetic potential of hybrid furniture with Digital Joinery. Only in the last design did we really start to free ourselves from traditional carpentry constraints, limitations, and habits, and to fully explore the design freedom we now have at hand. Thus, we see the stools collections as an initial step towards exploring hybrid carpentry in depth.

To gain some perspective on how professional designers and carpenters would value Digital Joinery, we engaged in meetings with four carpenters and three designers. However, our study participants did not have a great deal of time to invest. The design and fabrication of each of our stools took two to three weeks from sketch to completed furniture; this is not a process we can compete in short evaluation meetings. Moreover, not all of the participants are skilled in CAD. Hence, we used these evaluation meetings to learn more about design potential rather than GJDT usability, focusing on concept design rather than production of real furniture.

We had a single meeting of approximately one hour with each of the participants, in his studio or workshop. In each meeting, we presented our work, the capabilities of Digital Joinery and our portfolio of stools. We asked the carpenters and designers to share any feedback they had. Furthermore, we asked them to draw some ideas for future objects they would design using this technology.

Overall, we received positive reactions. None of the professionals we met with failed to understand or support the contribution of Digital Joinery. Yet, as we were aware that these responses might be biased or incomplete, we put more emphasis on the drawings and visions participants expressed about how they might implement these new design and construction capabilities in their own work. Fig. 11 shows a collection of drawings we made based on the rough sketches we collected from the designers and carpenters who examined our work.

Roughly speaking, it seemed that the carpenters, who in their daily practice largely produce designs made by others (such as architects or designers), value Digital Joinery as a tool for efficiency or for labor-saving. Fig. 11C, for example, shows how one carpenter envisions a printed joint replacing part of a chair he makes, thus freeing him from the most demanding part of the job. This perspective was repeated in the open discussions, as the carpenters we met value automation and computers as labor-saving technologies, not necessarily as design or innovation tools.

Figure 10 (A) The last (T3) stool, (B) a decorative, 3D-printed part and (C-D) digital joints. Photograph (A) by Daniel Shechter.

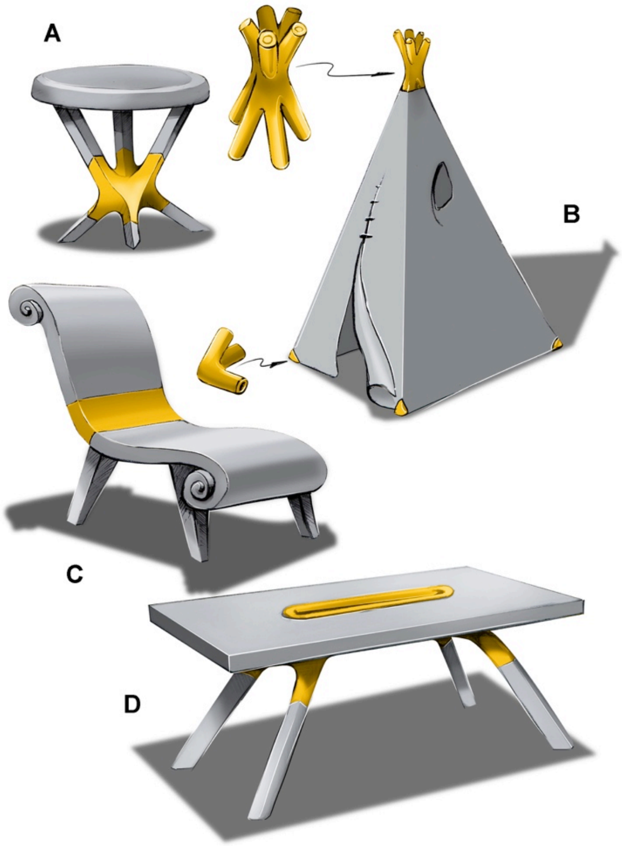


Figure 11 Four drawings based on sketches made during the evaluation stage by external carpenters or designers. Hybrid Joints are in yellow. (A) a coffee table uses Digital Joinery in a manner that resembles our stools; (B) a toy tent allowing for many shapes enabled by Digital Joinery; (C) a traditional chair design whose most demanding craft section is replaced with a 3D-printed joint; and (D) a table with a central structural joint that becomes the most important design element of the work.

On the other hand, the designers we met, who are used to computational design in their daily practice and do not manually operate machines or master woodcraft, envision new design affordances enabled by Digital Joinery (see Fig. 11A-B, D). As this group of designers is familiar with 3D printing and CAD, they were excited to consider new possibilities for design agency. For example, one designer imagined the use of Digital Joinery in fabric toys, and another considered pieces of furniture with a large, central joint that would serve as a structural base for all elements, holding the furniture together.

Our overall impression was that while the carpenters we met with value the traditional craft, they were unable to demonstrate design creativity related to CAD practice, as they are simply unfamiliar with CAD capabilities and design potential. In other words, they were a bit conservative compared to the group of designers.

On the other hand, designers easily integrate Digital Joinery into their conceptual work. Although our pool of participants was too small to draw further conclusions about the division of skills and design intent, the concept of hybrid practice seems easy for makers who are already familiar with computational design to accept.

Nevertheless, CAD designers are not necessarily part of the community of makers who work in woodshops. This means that our motivation to liberate traditional carpentry from some of its technical limitations will not develop fully with CAD practitioners. Thus, we argue that our innovation will be the perfect device for a third type of makers, *hybrid makers*, who explore a wide spectrum of traditions and technologies, and use manual and physical craft together with digital fabrication and CAD. This community of makers is still small, but increasing (see [35] for a wider discussion on hybrid craft).

CONCLUSIONS AND FUTURE WORK

In this paper we presented Digital Joinery, a woodworking design paradigm aiming to liberate carpentry from traditional construction limitations. We contribute a new joinery design software tool that supports new types of connectors, to let multiple pieces of lumber meet at unconventional angles, manifesting a new type of aesthetics and structure for furniture. We demonstrated our tool in a collection of three stools, each of which illustrates a different aspect of new joints for stool making.

Our work aims at reinforcing the bridge that has already started to pave the way for makers, designers, and researchers to merge computational practices with craft [26,29]. In doing so, we continue the lines of prior work [36] aiming to keep computational design open and allow for some sort of manual freedom to encourage makers to explore the full potential of the hybrid medium.

In addition to the technical work presented here, we discussed our work with professional carpenters and designers. The designers seemed a bit more open-minded about the affordances of such technology, envisioning a new type of human-computer interaction via the furniture design process. Yet, as our work aims to assist craftpersons as well as designers, we believe that hybrid design tools may be most fruitful in the hands of hybrid makers. Otherwise, a broader introduction is needed to expose traditional craftpersons to digital design and fabrication prior to training them to use Digital Joinery.

Considering future work, digital joinery can be extended to serve as a connecting agent between other ready-made artifacts (not just wood). Moreover, we would like to extend the deployment of Digital Joinery to a diverse community of makers wishing for hybrid design prosperity. We envision future craftpersons equipped with manual and digital machines, mastering handwork and computational work. While this community of professional hybrid makers already exists, more tools and technology for hybrid practice is required, and our work aims at this need.

Finally, and on a slightly different track, we would like to learn how Digital Joinery could personalize mass furniture manufacturing. For instance, given a warehouse with a huge amount of lumber in a finite set of dimensions and types, how can consumers interact with parametric and generative tools to customize their furniture? How can we optimize the use for this collection of raw material, yet maximize the design freedom of the end users?

For example, let us assume a warehouse includes 4 cm x 4 cm wooden beams in lengths of 80 cm and 50 cm. When a customer requests a chair that will support a load of 100 kg, or a table in a specific dimension, the software will be able to generate an optimal or semi-optimal (using a minimal amount of wood) solution enabled by 3D-printed joints and an optimizing design algorithm. In addition, the user can specify a finished style and other details.

This vision require extensive research on (1) finite-set catalog selection mechanisms integrated into generative design software; and (2) extended generative design procedures that optimize full furniture architecture for production, considering wood costs, 3D printing costs, and the system's abilities. This will be the topic of our future research, and hopefully will interest other researchers in the HCI and CG communities.

ACKNOWLEDGMENTS

We would like to thank all people who supported and helped in finishing this work, including the Hybrid Lab group at HUJI; the external advisors in Bezalel Academy of Arts and Design, Jerusalem; Raanan Fattal; Chia. L. Evers; Tal Levi; Lior Uri; Oz Banderman; Hai Phalach; Nimrod Shamia, Ronen Dor; and Alon Greber, and others who helped by allowing the use of their technical facilities. The work was partially supported by the Israeli Science Foundation (ISF).

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