

Bandsawn Bands

Feature-Based Design and Fabrication of Nested Freeform Surfaces in Wood

Ryan Luke Johns and Nicholas Foley

Abstract While the rising trend of research in robotic fabrication has furthered the development of parametric or mass-customization concepts in architecture, the majority of these projects are still cut or assembled from standardized blocks of material. Although the use of nonstandard, ‘found’ components provides an additional layer of complexity and constraint to the design/fabrication process, it can compensate for these challenges by enabling more sustainable material practices and the production of unique objects that cannot be reproduced. In this chapter, we illustrate a materially efficient technique for designing and fabricating freeform surfaces within the constraints of irregular wood flitches. The process utilizes a robotically operated bandsaw to cut a series of curved strips which, when rotated and laminated, can approximate doubly-curved and digitally defined geometry. By delimiting the design space by both the ‘machinic morphospace’ (Menges in *RoblArch 2012: Robotic Fabrication in Architecture, Art and Industrial Design*, Springer, Vienna, pp. 28–47, 2012) of the fabrication technique and the naturally defined curvatures and constraints of the flitch, the customized control software and machining processes confer the capabilities of digital fabrication onto materially tailored and operator-informed woodcraft.

Keywords Robotic bandsaw • Freeform surface • Timber construction • Parametric design • Minimal waste

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1 Introduction

Despite the capabilities for customized fabrication offered by digital tools, the vast majority of parametric design-fabrication exercises remain confined to the parameters of standard, industrially produced components. Whether by creating “highly informed” (Bonwetsch et al. 2006) geometry from an additive assemblage of standardized parts, or from a series of subtractive operations upon them, the variable control provided by the generic component (blanks, bars, bricks and sheet stock) is commonplace. While the economy of scale renders this practice practical for many applications, its shortcomings reveal the necessity to explore alternate models of production which engage the complexity of found materials. Rather than transferring material, for example, from a curved tree into dimensional lumber which is then re-machined into curvilinear digitally designed geometry, we take the tree as the starting point for design and move directly to digital fabrication. This leap in the production sequence enables more sustainable material efficiency while simultaneously conferring the natural aesthetic advantage of “beauty’s found geometries” (Enns 2010) (Fig. 1).

In this chapter, we document a technique for designing and fabricating freeform surfaces from live-edged wood flitches. The process utilizes a robotically operated bandsaw to cut a series of curved strips which, when rotated and laminated, can approximate doubly-curved and digitally defined geometry. The thin kerf of the bandsaw blade allows for a tight nesting of finished surfaces, which, through a close relationship between available material and designed geometry, affords practically zero-waste when compared to Computer Numeric Control (CNC) contour milling. This coordination of non-standard material geometries, 3D scanning, parametric algorithms, designer input and robotic control serves to bolster the role of feature-based material intuition in design and “digital craft” (Johns 2014; McCullough 1996).

2 Related Work

The practice of linking 3D surface scanning, tomography, and feature recognition to more efficiently process logs has been present in the lumber industry for quite some time (Connors et al. 1983). This process, however, is generally used as a means to work around defects and irregularities to achieve a higher yield and grade of standard dimensional lumber. In contrast, this project is specifically interested in reading specific and non-standard geometries *from* the irregularities rather than an attempt to embed rectilinear objects within them.

There are a variety of projects which focus upon geometrical nesting of discrete industrial design objects, from Tom Pawlofsky and Tibor Weissmahr’s “7xStool” (<http://www.kkaarrlls.com/index.php?feature=editions,7Xstool>), to Karim Rashid’s “Matryoshkarim” (<http://www.detail.de/daily/matryoshkarim-von-karim-rashid-6307/>),

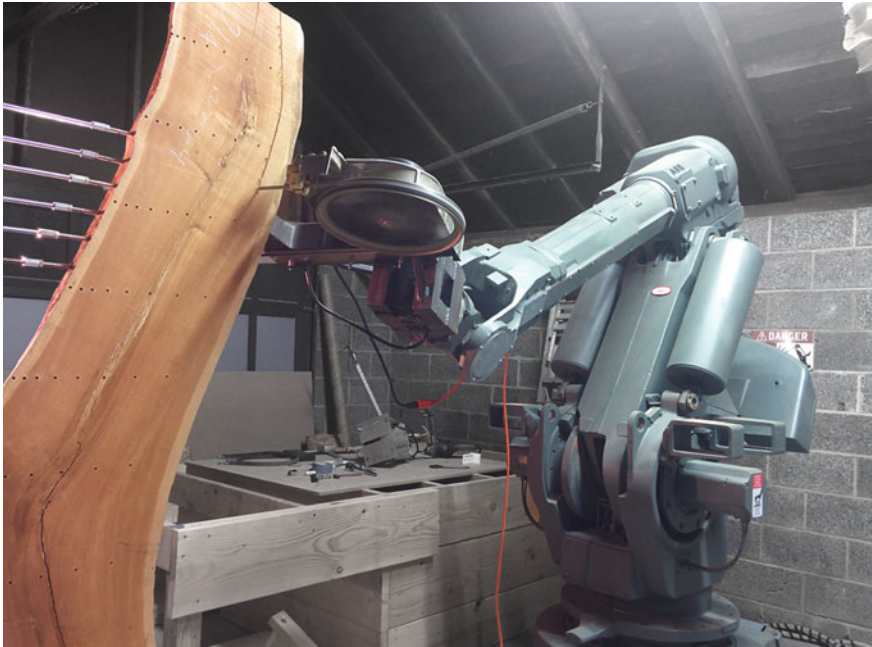


Fig. 1 Robotic bandsawing of irregular flitch

and as far back as Albert Decker’s 1925 patent for “Nesting Furniture” (Decker 1928) (Fig. 2). These types of projects generally create a family of objects which interlock into a standard bounding box (or live-edged, but relatively standard log, in the case of the 7xStool) for simplicity of fabrication, material efficiency or compactness for storage. This object-based approach to packing has powerful implications, but in practice, generally results in several objects with a high performance value (a chair or table) and one or several “remainder” objects with ambiguous functions (a paperweight or footrest). Rather than attempting to solve the difficult problem of packing a variety of discrete objects within a volume, this research focuses on the reorganization and assembly of a found material condition into a single and continuous entity.

Digital fabrication techniques for more efficient freeform surface production have been explored in the CNC-milled “Zero/Fold Screen” by Matsys (<http://matsysdesign.com/2010/02/28/zerofold-screen/>), and made more viable for continuous surface fabrication with the capabilities of 7-axis swarf milling to produce a “single cut...finished surface” (Brell-Cokcan et al. 2009). The comparatively wide cut path and short length of the CNC router, however, prohibits the same degree of surface mating made possible with the bandsaw. For an examination of additional thin kerf abrasive-wire techniques in robotic fabrication, refer to “Processes for an Architecture of Volume” (McGee et al. 2012).



Fig. 2 From *left* Pawlofsky and Weissmahr’s “7xStool,” Rashid’s “Matryoshkarim,” Decker’s “Nesting Furniture”

3 Algorithm and Implementation

3.1 Freeform Volume Nesting

The nesting technique is based upon the premise that the bottom face of each sawn band is a copy of its neighbor’s upper face. The design control software is generated using both *Grasshopper* and *Python* within the *Rhino* modelling software. It operates as a multiple stage process in the following manner:

Flitch-Fitted Surface Generation:

1. The process for creating nested freeform volumes within the confines of a flitch¹ of thickness (t_{flitch}) with volume (V_{flitch}) begins with the digitally modelled live edge surfaces (s_1 and s_2) of the 3D scanned flitch (Fig. 3-1). In this implementation, the scan is achieved using either the Kinect or the robotic manipulator as a digitizer.
2. The freeform surface (S_f) is parametrically linked to the control variables of the available flitch. Specifically, its length must be equal to the length of the flitch, and its width (W_{sf}) will be a factor of the thickness of the flitch multiplied by the number of bands (Eq. 1) (Fig. 3-2).

$$W_{sf} = t_{flitch} \times n_{bands} \quad (1)$$

The edge curves along the length of the surface must generally follow the curvature of s_1 and s_2 , and, for surface continuity, will ideally also maintain tangency.

3. The above conditions provide an infinite subset of permutations which must be navigated by the designer to produce the desired surface, S_f (Fig. 3-3).

¹ Note that it is possible to generalize this process to fabricate surfaces which do not operate within the confines of a flitch, by proceeding directly to step 4.

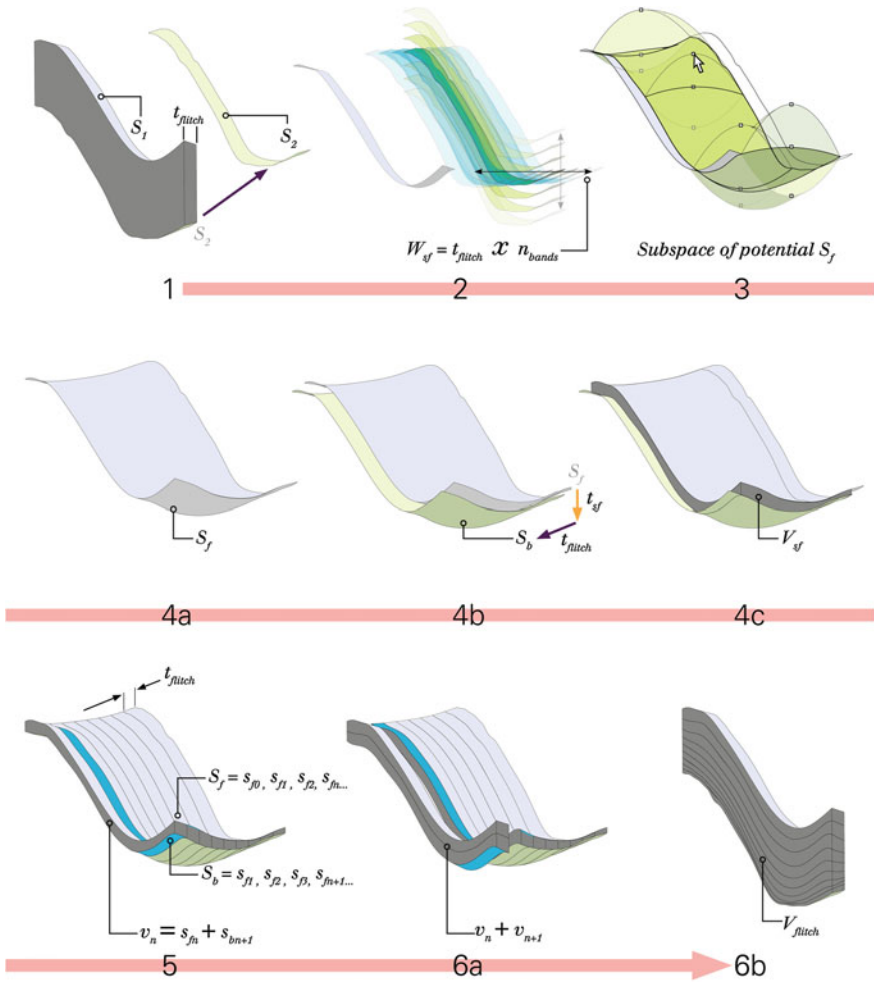


Fig. 3 Freeform volume nesting algorithm

Freeform Volume Nesting:

4. The designed surface S_j is translated horizontally by t_{flitch} , as well as translated vertically by t_{sf} , an amount that will determine the thickness of the final volume created (V_{sf}). The resultant surface is S_b (a translated duplicate of S_j), and the enclosed region between S_j and S_b becomes the boundary of the final volume created (V_{sf}) (Fig. 3-4).
5. The surfaces of S_j and S_b are now divided along their width into a number (n_{bands}) of equally spaced sections (s_{fn}) of thickness t_{flitch} . Because of the translation used to create S_b , any subsurface of S_b (s_{fn}) is the same as the next subsurface of S_j (s_{fn+1}) (Fig. 3-5).

6. The sections of S_f and S_b are now paired vertically, being treated as the upper and lower bounds of a sub-volume (v) of V_{sf} . Each v can be nested beneath the next, collapsing V_{sf} into a fully dense planar volume (Fig. 3-6).
7. The precise value of t_{sf} is determined using a simple binary search algorithm which seeks to set V_{sf} equal to V_{flitch} .

3.2 Initial Studies

As custom end effectors and irregular material conditions can quickly complicate the prototyping process, our initial studies utilized standard dimensional lumber and unmodified tools in order to ease investigation. In these experiments, the robot is holding the work object ($2 \times 12''$ nominal lumber) with a simple toggle clamp end effector, and manipulating the wood through a standard bandsaw (Fig. 4b) and a wall mounted benchtop grinder which has been outfitted with drill chucks such that it may serve as a double sided drill (Fig. 4a). This setup has the advantage of being able to operate as one continuous program, without the need to manually change end effectors between the dowel drilling operation and the sawing operation. This prototypical process, however, has obvious limitations of board length and maneuverability, as the robot must make increasingly large movements when making cuts that are further from its adaptor plate.

These initial physical experiments revealed numerous shortcomings, which were then reprogrammed into the system. For example, we prolonged the life of blades and shortened the duration the cut sequence by programming the robot's cut speed as a value proportionate to the twist and curvature of the cut. Similarly, we added an implementation of the travelling salesman problem (<http://www.psychicorigami.com/2007/04/17/>) to the dowel drilling sequence in order to decrease cycle times.

As these prototypes were not cut from an irregular flitch, their design constraints are limited by the width of the dimensional lumber and the curvature limitations of the selected bandsaw blade (~ 50 mm minimum cut radius). The first prototype emulates a possible found-flitch geometry, while the second works in the reverse direction: beginning with a desired surface and working backwards (Fig. 5). In this instance, we use a Kinect scan of an individual falling in the seated position as the guiding geometry of the surface.

While these initial studies were instrumental in fine tuning the control parameters and in recognizing physical limitations of the tools, they quickly reemphasized the shortcomings of attempting to nest curvilinear designs within rectilinear volumes.

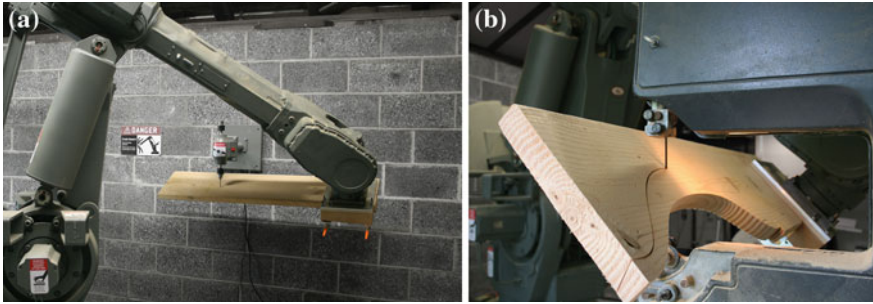


Fig. 4 From *left* **a** Double ended, wall-mounted dowelling drill. **b** Robotic operation of standard bandsaw

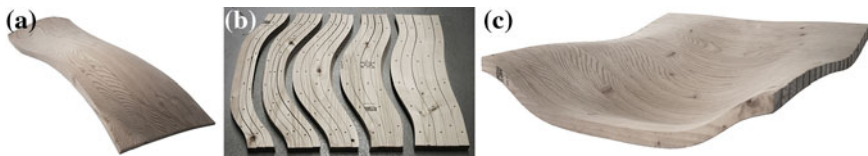


Fig. 5 **a** Freeform surface emulating flitch geometry. **b** Nested bands separated by board origin. **c** Laminated surface

3.3 *Live-Edged Prototype*

In order to optimize the setup to facilitate irregular flitches of various shapes and sizes, the process was inverted such that the flitch is stationary and the robot is holding the tools. For the dowelling end effector, we use a router and closed-loop speed controller to allow us to maintain the high torque at the low RPM's suitable for the 3/16" dowelling drillbit (<http://www.vhipe.com/product-private/SuperPID-Home.htm>). The bandsaw end effector is, quite literally, the standard 12" bandsaw removed from its base, reinforced with a welded steel frame, and mounted onto the robot.

In order to accommodate a variety of possible flitches, we oriented a wooden column within the robot's reach envelope, into which the robot drilled an array of holes for attaching mounting hardware. By using the robot to construct the machining jig within which it operates, we are ensured that the flitch can be oriented precisely within the coordinate system of the robot with little effort in calibration. The robot also drills a matching array of holes into one live edge of the flitch, strategically placing the holes such that they are in the thickest areas of the designed band and to a depth less than the thickness of the band in that region. Wood-screw-threaded studs are then manually inserted into these holes, and become the mechanism for mounting the flitch to the column. In this way, we avoid the use of bulky clamps through which the saw cannot pass, and are able to

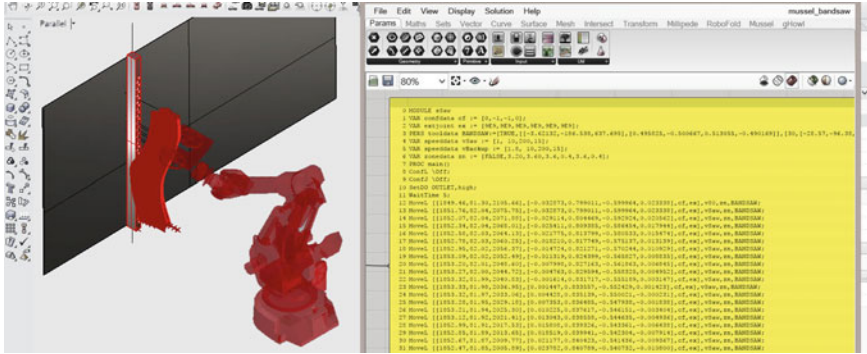


Fig. 6 RAPID code for bandsaw process generated and previewed using the Mussel plugin for Grasshopper

process the entirety of the surface in one operation. These studs can also be later repurposed in the completed surface as connection points to a support structure (in example, the legs of a chair).

The selected flitch for this prototype was chosen with a close consideration of the outlined algorithmic process, recognizing that its edge curvature implied the potential of a chaise longue. Following the design of the surface, the generated drill and cut paths were converted to *RAPID* (ABB’s robotic programming language) using the open-source *Grasshopper* plugin *Mussel* (<http://www.grasshopper3d.com/group/mussel>) and fabricated with the IRB-6400 robot with S4C controller (Fig. 6).

4 Discussion

4.1 Process Benefits

The process allows for a high material efficiency due both to the machining process (the bandsaw has the smallest possible kerf of any mechanical woodcutting method) and the designs being parametrically customized to the workpiece in order to eliminate waste. As with swarf milling (Brell-Cokcan et al. 2009), there is also a high process efficiency, as each cut operation forms two finished surfaces: the bottom of one piece and the top of the next. Similarly, the 6-axis control of the robotic manipulator allows the fabrication of cuts which are not only curved in two dimensions, but (by “twisting” the bandsaw blade) can create three dimensional ruled geometries which, when combined, can smoothly approximate a doubly-curved surface. This allows a much cleaner surface resolution than the traditional terraced geometries arising from laminated 2.5-axis CNC operations.



Fig. 7 *Left* sample flitch, with nested cuts and dowel holes. *Right* in-progress assembly

The technique also holds an interesting position as one of few woodworking techniques which are explicitly not “subtractive” (Kolarevic 2003), but *transformative* (Fig. 7). By parametrically generating the design as a reconfiguration of the workpiece, the process not only enables use of any individual material piece more efficiently, but enables use of more of the complete tree. This form of ‘nose-to-tail consumption’ bears more resemblance to highly efficient and direct-to-consumer automated butchery (Loeffen and Purnell 2006) (<http://www.scott.co.nz/meat-processing/lamb/automated-boning-room-systems>) than to many traditional sawmill operations. Sections which would have previously only yielded small amounts of dimensional lumber due to natural curvature or inclusions can be utilized in their entirety because those features are integrated into the design process. This allows the direct use of widely available and economical “wind fall” lumber, which is frequently not suitable for traditional applications.

4.2 Design Benefits

By fabricating the surface as a reconfiguration of a continuous slab, the final product visually exhibits both the narrative of the source material and the production technique, as traced through repetition and continuities in grain pattern, knots, and imperfections (Fig. 8). This narrative can also be expanded further through the use of multiple sections from one tree, either creating a larger continuous surface (by joining the corresponding live edges of subsurfaces) or a range of related product families. A single “design” can take on subtle permutations which adapt based on the particular tree section chosen, while being united with other pieces from the same tree in general design, woodgrain, and bark conditions. The close association of found geometry and produced artifact ensure not only that each object will be uniquely tailored, but that it also cannot be reproduced. This statement does not hold true for projects which utilize industrially produced source materials (plywood, MDF, EPS foam, etc.): provided that the source code remains, any individually tailored geometry can be replicated. The role of grain, while promoting a specific aesthetic agenda, simultaneously exhibits optimal structural properties: by informing the designed form with the geometry of the live edges, the



Fig. 8 Detail of prototype in cherry

natural anisotropy of the woodgrain is aligned with the cutting operations and final part output in turn.

This more materially efficient process confers the advantage that rarer and more expensive woods can be used in complex freeform surfaces which would otherwise need to be CNC-milled from a block of material many times larger (Fig. 9). Not only a cost benefit, this also eliminates the design constraint of sourcing a large block of material: as most CNC-milled wood projects are presently made with Ash, Birch, or Fir because these materials are relatively inexpensive and available in large dimensions.

4.3 Improvements

The current state of the project has room for an array of potential improvements, in both the design process and its physical execution. Presently, the assembly system relies on the bands being joined with dowels and wood glue. While this process is generally straightforward, it becomes less feasible with large surface deformations. Clamping such geometries without a jig which has been fabricated specifically to the piece can be time consuming (if not impossible). However, the waste associated with the fabrication of such a jig would override many of the efficiencies of the project. A mechanized jig which allowed for a wide array of configurations could be developed, or potentially, some of the dowels holes could be replaced

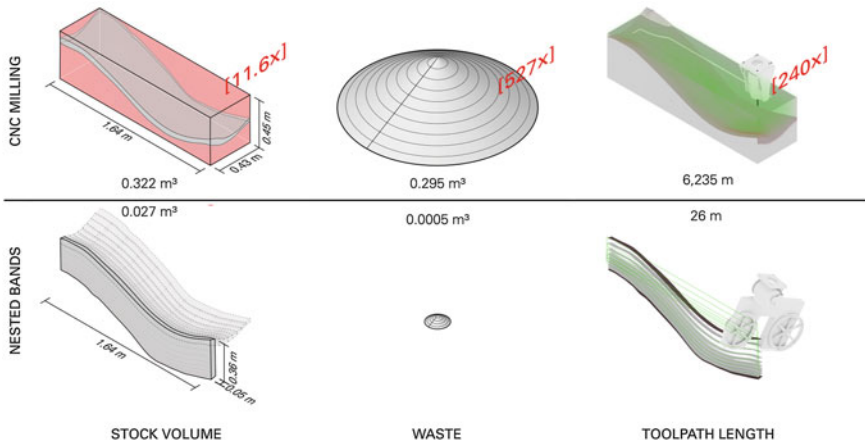


Fig. 9 Comparison between waste, volume, and machining requirements for fabricating a sample surface with CNC milling versus flitch nesting



Fig. 10 Doubly-curved chaise longue surface made from irregular flitch

with through-holes which allow a steel cable to pass through the bands in a post-tensioning system. Each band could also simply be screwed to the previous band. The latter two alternatives, however, have the downside of somewhat limiting the minimum possible thickness of the bands.

The prototypes presented in this chapter rely on as-is lumber for which we have little control of thickness, planarity, or cut plane. Ideally, the process could develop further through a close coordination with the sawmill so that *all* cuts are both digitally, and designer, informed. We imagine a potential future where a library of approximate desired geometries (i.e. a variety of seat shapes) can be cross referenced with the scanned tree using a technique of “fuzzy correspondences” (Kim et al. 2012) in order to isolate potentially fruitful irregularities from the stock which is more suitable for dimensional lumber (Fig. 10).



Fig. 11 Chaise longue assembled from nested bands

5 Conclusion

In this chapter, we present a materially efficient technique for the feature-based design and fabrication of freeform surfaces within the constraints of an irregular wood flitch. The design is therefore not determined solely by the “machinic morphospace” (Menges 2012), but more importantly by the found and organically defined material morphospace, delimited by the edge conditions and dimensions of the flitch and the constraints of the outlined algorithm. The process enables a

unique “cultural performance” (Oesterle 2009) to be pulled from otherwise unusable lumber through a process of materially tailored design. Rather than simply introducing a procedure which is materially efficient, the process is significant in that it makes it necessary to strike a balance between the beauty of the naturally formed, as-is material object and the geometrical demands of the designer, a relationship that is much more prominent in traditional handicraft than in digital fabrication (Fig. 11).





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