Homage to Charles O. Perry

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Abstract

Perry's "Topological" ribbon sculptures are analyzed based on their border curves and skeletal graphs. All sculptures studied turned out to be based on planar graphs. Starting from three simple symmetrical, non-planar graphs with low complexity, new sculpture-maquettes have been designed in the style of Perry's ribbon sculptures.

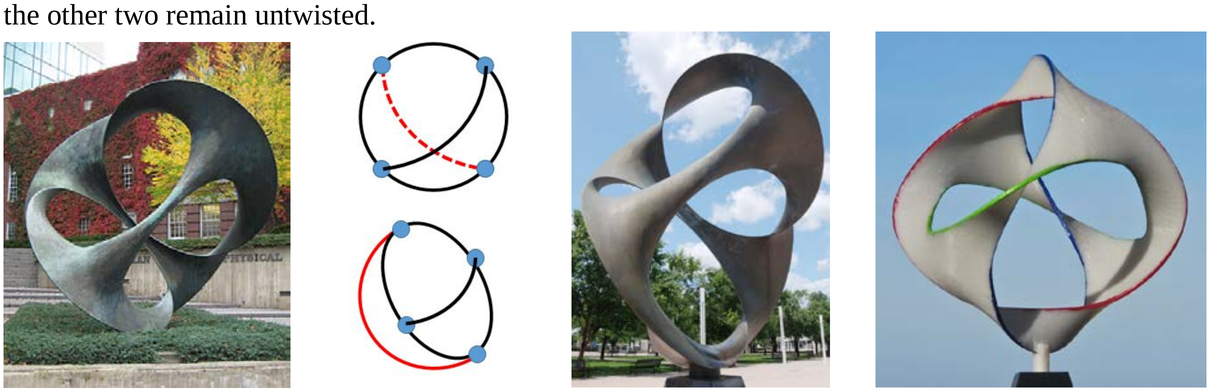
Introduction

Charles O. Perry (1929-2011) is one of my sculptor-heroes. He was a very versatile artist, who not only created a vast number of amazing metal sculptures (Figure 1a), but also invented puzzles (Figure 1b), and designed jewelry (Figure 1c) as well as comfortable, stackable chairs (Figure 1d).

(a) (b) (c) (d)

Figure 1: *Perry creations: (a) sculptures; (b) puzzles; (c) jewelry; (d) chairs.*

On Perry's website [4], his sculptures are grouped into four different types: *Ribbed*, *Planar*, *Solid*, and *Topological*. In 2010 [3], I studied Perry's Ribbed sculptures [8]. In this paper, I now focus on a subset of his *Topological Sculptures* [7] – those that can be seen as simple graphs in which the edges are realized with curved and twisted ribbons. If one skeletonizes the edges of Perry's sculpture "D_2d" (Hanover, NH, 1975) (Figure 2a) into simple linear 1-manifolds, one obtains the edge graph of a tetrahedron (Figure 2b). The same is true for his *Tetra Sculpture* (Louisville, KY, 1999), which is a thick 2-manifold bordered by four interlinked circles (Figure 2c). Four of its edge are realized with ribbons that twist through 180°, while the other two remain untwisted.

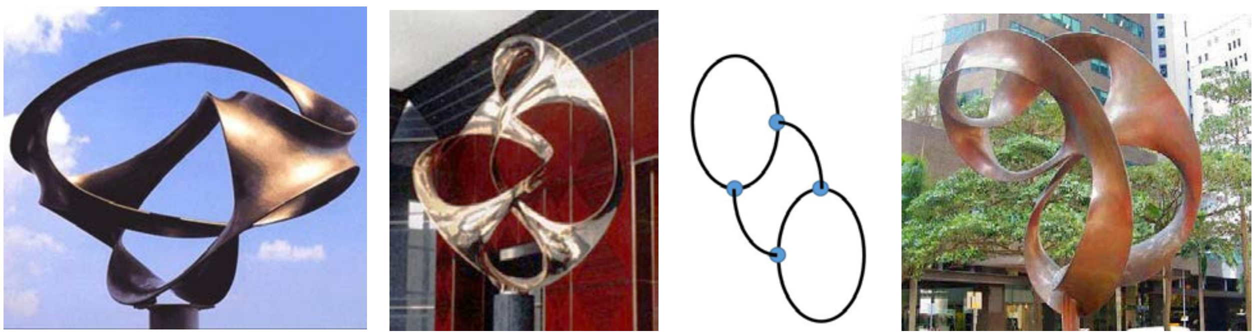


(a) (b) (c) (d)

Figure 2: *(a) "D_2d"; (b) skeletal graph. (c) "Tetra"; (d) my single-sided variation of "Tetra."*

In Bridges 2015, I showed that by changing the amount of twist given to some of these ribbons, one can change the interconnectivity of the border curves and obtain a wide variety of topologically different 2-manifolds – but all are still based on the edge graph of a tetrahedron [11]. By twisting all six edges through 180°, I obtained a single-sided surface with only three figure8-shaped border curves (Figure 2d).

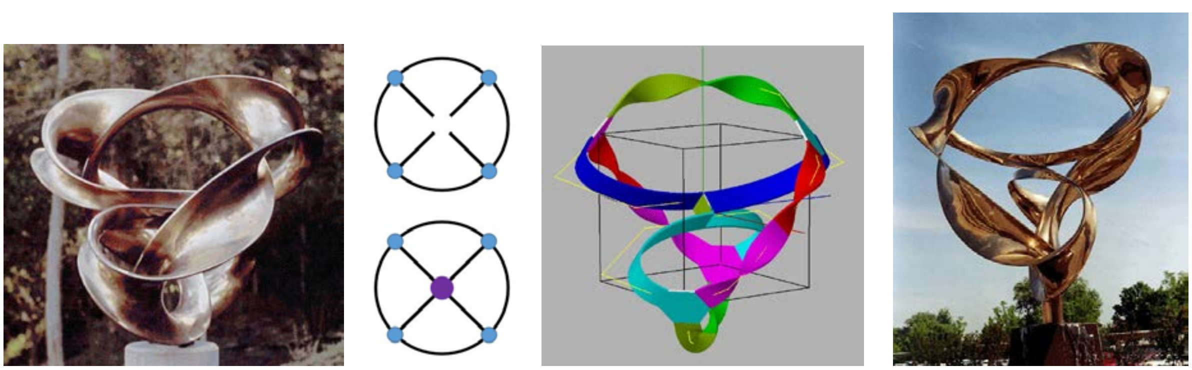
Duality (Greenwich, CT, 1986) (Figure 3a) and *Duality_2* (Jacksonville, FL, 1990) (Figure 3b) also have just four 3-way junctions and six ribbons; but there is a different underlying graph. In this case, it is the edge structure of a 2-sided prism; a graph that can also be drawn as two loops joined by two arcs (Figure 3c). In addition, Perry shortened one pair of opposite edges to the point where two pairs of 3-way junctions almost merge to become 4-way junctions (Figure 3a). The same graph structure also defines *Dual Universe* (Singapore, 1994) (Figure 3d), but now the two loops are no longer interlinked, and the arcs that connect them are much longer.



(a) (b) (c) (d)

Figure 3: *(a)"Duality"(1986); (b)"Duality II"(1990); (c) skeletal graph; (d)"Dual Universe"(1994).*

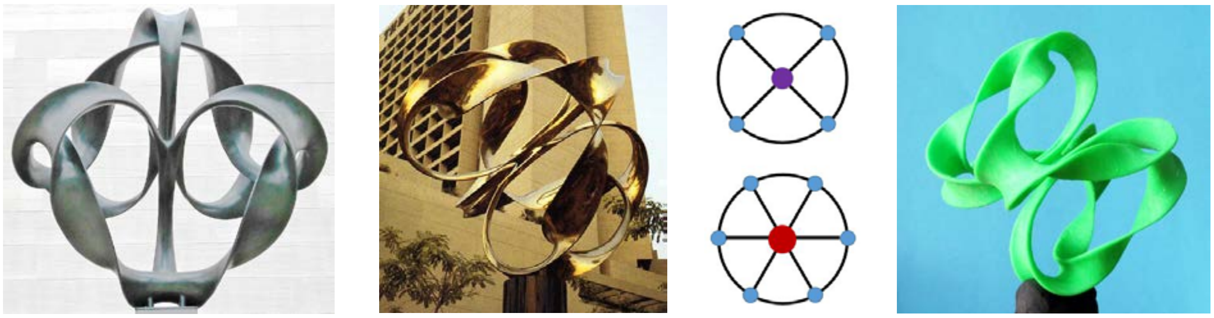
Double Knot 1 (Sydney, 1967) (Figure 4a) and *Double Knot* (Taylor, MI, 1991) (Figure 4d) are more difficult to understand, because these sculptures are more compact, and because in the few images on the Internet many parts of these sculptures remain hidden. Eventually, I started to understand these two sculptures as a modification of a tetrahedral frame, in which one pair of opposite edges has been cut in the middle (Figure 4b, top), and the four resulting stubs are then routed towards the center, where they join to form a biped saddle (Figure 4b, bottom).



(a) (b) (c) (d)

Figure 4: *(a) "Double Knot" (1967); (b) skeletal graphs of tetrahedron and of "Double Knot" (1967); (c) schematic CAD model; (d) "Double Knot" (1991).*

My interpretation was confirmed by analyzing *Continuum* (Washington, D.C., 1976) (Figure 5a) located in front of the Aerospace Museum in Washington, DC. While the *Double Knots* exhibit S_4-glide symmetry around the major symmetry axis through the central saddle, *Continuum* has the same basic structure but with S_6-glide symmetry around a central monkey saddle. Perry made another version of this sculpture, which he called *Triple Knot* (Singapore 1986) (Figure 5b). The geometry of this sculpture can also be understood as a zig-zag-y hexagonal wheel in which the six spokes join in the center to form a narrow monkey saddle. This sculpture still has a planar skeletal graph (Figure 5c, bottom).



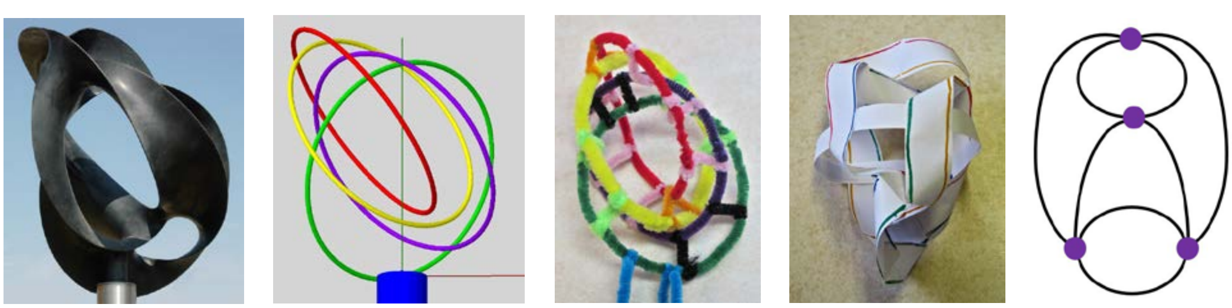
(a) (b) (c) (d)

Figure 5: *(a)"Continuum"(1976); (b)"Triple Knot"(1986); (c) skeletal graphs; (d) my 3D-print.*

"Four Orbits" – An Enigma

For quite some time I did not pay much attention to Perry's *Four Orbits* sculpture (Oklahoma City, 2004). I did not have a clear understanding how the four dominant ribbons were connected to one another, since I had only two somewhat unclear images (Figures 6a, 7e). Even though I had the coordinates of *Four Orbits* (35°28'38.0"N 97°30'50.3"W) [10], I could not find it with *Google Street View* to get a better look at it; – new construction in that area had displaced it.

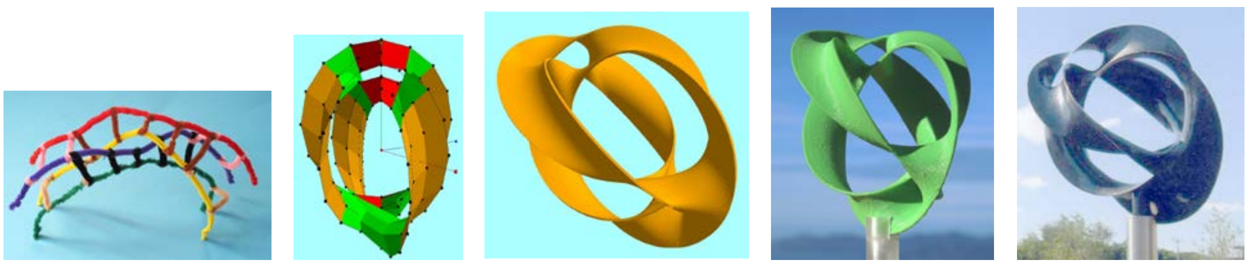
The one attribute that was undisputable was that this *Topological* 2-manifold was defined by four perfectly circular border edges and that the four dominant ribbons were formed by connecting two adjacent half-circle borders. I thus assumed – a little too hastily – that this sculpture was not too different from Perry's *Tetra* or *D_2d* sculptures, and I guessed that the underlying skeletonized graph might be again a pair of circles, coupled in some way as shown in Figure 3c. To obtain a better understanding of what is going on at the two "poles" of *Four Orbits*, where the four dominant ribbons join together, I built a CAD model that allowed me to interactively place four circles into a configuration (Figure 6b) that could be matched up with the visible edges in the photographs (Figures 6a,7c). Based on this, I also built physical models from pipe-cleaners (Figure 6c) and from paper strips (Figure 6d). Imitating Perry's construction process for his topological ribbon sculptures, I added a dozen lateral connecting pipe-cleaner segments to represent the geometry of the curled ribbons between the circular border edges (Figure 6c). By working my way towards the two poles, I tried to figure out, how the dominant ribbons might split and then rejoin again with the ribbons coming from the opposite side to form proper cross-overs at the poles without introducing any additional border lines.



(a) (b) (c) (d) (e)

Figure 6: *Four Orbits: (a) Perry's sculpture; (b) the defining border curves; (c) pipe-cleaner model; (d) paper model; (e) skeletonized graph.*

After some unsuccessful first guesses, I constructed a larger pipe-cleaner model (Figure 7a) of four circular arches passing through one another near the upper pole, as implied by the photos. Eventually, I realized that there was an elegant and compact way to split and rejoin the four dominant ribbons by forming a pair of closely spaced biped saddles. This was a somewhat surprising configuration. Perry had used such a biped saddle a few times in isolation, as, for instance, at the center of *Double Knot* (Figure 4a). Such a saddle corresponds to a valence-4 node in the corresponding skeletal graph. With a better understanding of the interlinking of the four circular border curves and of the topology of the resulting 2-manifold, I could now construct a parameterized CAD model (Figure 7b) of this sculpture using Berkeley SLIDE [12] and NOME [13] [2]. After fine-tuning its parameters it resulted in a smoothed model (Figure 7c), which was then fabricated on a 3D-printer (Figure 7d). It matched closely with the photographs I had (Figures 6a, 7e) and also with five images found on pages 32 and 33 of a gorgeous book [9] that I obtained a few weeks before submitting this paper. It turns out that the skeletal graph of *Four Orbits* also is planar (Figure 6e).



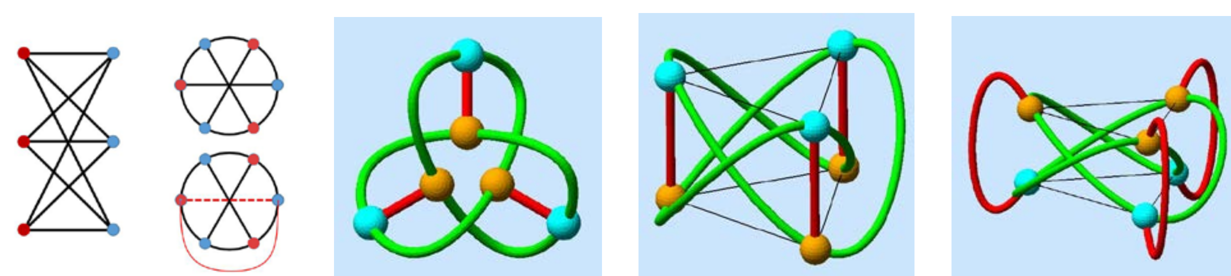
(a) (b) (c) (d) (e)

Figure 7: *"Four Orbits": (a) larger, detailed pipe-cleaner model; (b) parameterized CAD model; (c) smooth surface model; (d) 3D-print; (e) another view of Perry's sculpture.*

I gained some key insights through this analysis of *Four Orbits*: A different interlinking of four circular borders can lead to a quite different and more complex ribbon structure. In *Tetra*, the four circles each interlink with only two of the other circles, forming a 4-member ring-chain. In *Four Orbits*, every circle interlinks with all the other circles, forming eight separate ribbon segments which all split at both ends and rejoin in different pairings. However, it is surprising that the resulting skeletal graph is still planar. All of Perry's topological ribbon sculptures thus seem to be based on planar graphs. Would a ribbon sculpture based on a non-planar graph look substantially different? This prompted me to start with some simple non-planar graphs and to try turning them into sculptural models in the style of Charles O. Perry.

"Utility Trefoil"

The simplest non-planar graph is the *Utility Graph*. This is the bipartite graph $K_{3,3}$, representing the trenches needed to connect 3 residences (red) to 3 utilities (blue), e.g., power, water, and gas (Figure 8a). This graph can also be drawn as a regular hexagon enhanced with three diagonals, which do <u>not</u> join in the center (Figure 8b, top). Redrawing the edges, we always end up with one crossing (Figure 8b, bottom).



(a) (b) (c) (d) (e)

Figure 8: *(a) Classical Utility graph; (b) alternate depiction of this non-planar graph; (c,d,e) trefoils with differently placed cross-connections.*

A more interesting depiction is a trefoil knot with three cross-connections. I started from a loose, 3-fold symmetrical embedding of a trefoil knot. There are two ways to turn this into the *Utility Graph* while maintaining 3-fold dihedral (D_3) symmetry. One can add three connector segments between the points of maximal and minimal radial distance from the center (Figure 8c), thereby creating the six branching points that are the nodes of the graph $K_{3,3}$. Alternatively, one can place the connectors at the three crossings seen in a projection of the trefoil knot along its main symmetry axis (Figure 8d). Both of these schemes can be turned into attractive ribbon sculptures by sweeping a skinny rectangle along the edges of this graph. Quite a range of different results can be obtained by giving the ribbon segments different amounts of twist. Figure 9a is based on the graph 8c and results in a 2-sided surface with three borders. Figure 9b is based on the graph 8d and results in a single-sided surface with a single border.

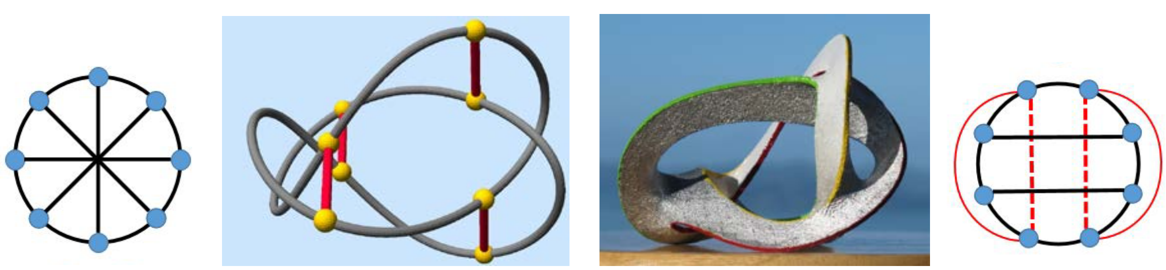
(a) (b) (c) (d)

Figure 9: *"Utility Trefoils": (a) model resulting from graph 8c; (b) model resulting from 8d; (c) model resulting from 8e; (d) "Utility-Trefoil" realized in the style of Charles Perry.*

However, none of these models looks like a true Perry sculpture. The ribbons in his sculptures typically exhibit some lateral curl. Thus, I replaced the simple flat profile, employed to sweep out the ribbons, with a 3-segment cross-section forming a "_/"-shape, which can be adjusted interactively in width and in depth. Moreover, the large flat Y-shaped, 3-way junction, representing the nodes of the graph, rarely appear in Perry's sculptures. He often turns these areas into T-junctions, where the "stem" of the "T" curls over the "horizontal" ribbon and connects to its far-sided border. To integrate this feature into the utility trefoil, I used the basic graph embedding shown in Figure 8e; I reduced the undulations in the trefoil and let the cross connectors act like clamps that grab the trefoil from the outside. In Figure 9c, I connected these clamps to the outside rim of the trefoil ribbon. In Figure 9d, I connected them to inner ribbon edge, thus realizing the curled T-junctions that Perry used in *Continuum* (Figure 5).

Wagner Graph

If we add a fourth diagonal connector through the center of the circle, we obtain the next more complicated non-planar cubic graph, called the *Wagner Graph* (Figure 10a). Inspired by the construction of *Utility Trefoil*, I aimed to create a *Wagner Graph* by placing four connecting ribbons at the cross-over points of a 4-fold symmetrical embedding of the Figure8-knot (Figure 10b). The resulting ribbon sculpture looked appealing; but it turns out that its skeletal graph is still planar (Figure 10d)!

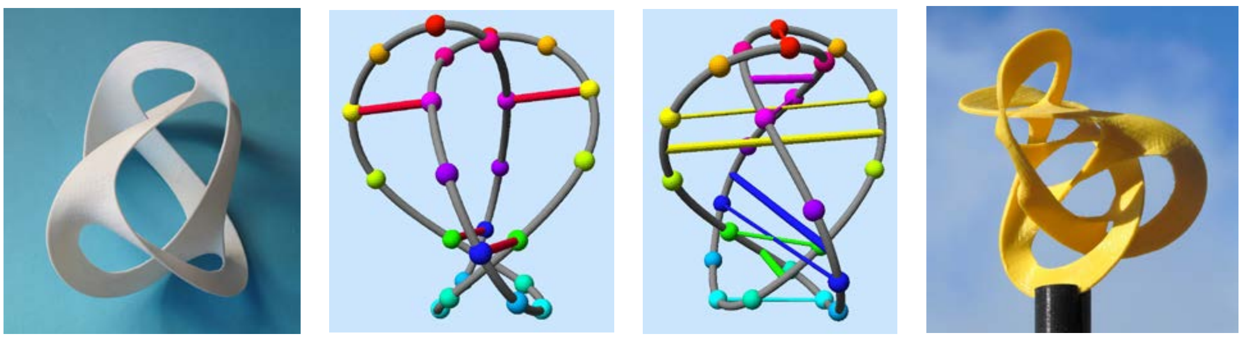


(a) (b) (c) (d)

Figure 10: *(a) Non-planar Wagner graph; (b) Figure8-knot with four cross connectors; (c) corresponding ribbon sculpture; (d) actual (planar) graph of this sculpture.*

It turns out that, when neighboring node pairs are joined into 4-way junctions, this is the same graph as for *Four Orbits*. Indeed, when I colored the edges of the ribbon model (Figure 10c), I realized that this 2-manifold also has four loopy, interlocking borders; but unlike *Four Orbits*, this model is two-sided!

Just like Tetra (Figure 2c) [11], this geometrical arrangement of ribbons lends itself to many appealing variations by changing the twist of some of the ribbon segments. Even without adding overall twist to the Figure8 loop (which would destroy the overall amphichirality of this knot), but by just warping the ribbon orientation back and forth periodically, I obtained another pleasing 2-manifold, also with four interlinked border curves (Figure 11a). But, of course, changing the twist of any ribbon does not affect the underlying skeletal graph.



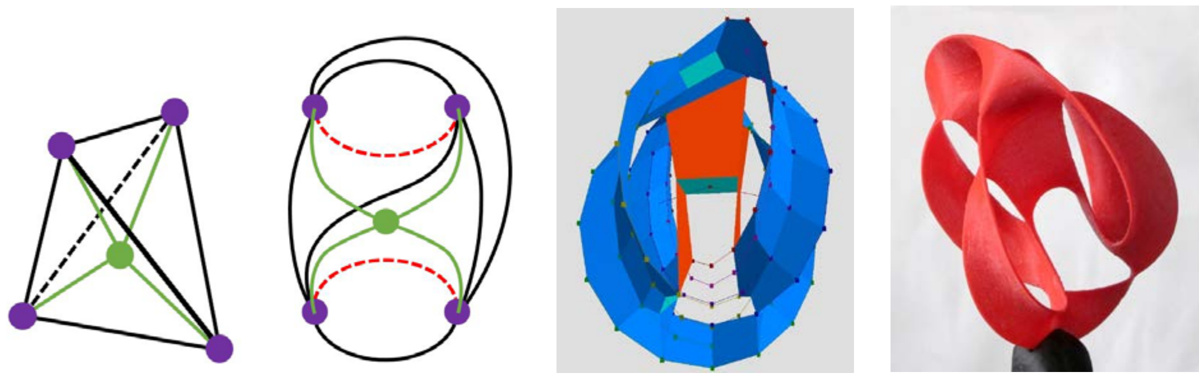
(a) (b) (c) (d)

Figure 11: *(a) Another Figure8-knot with four cross connectors; (b) schematic depiction of the placement of the cross connectors; (c) proper "diagonal" connectors; (d) corresponding3D print.*

To make sure, that I would add true "diagonal" connectors (Figure 10a) into the loop formed by the Figure8-knot, I placed 24 spherical markers around the loop, using 12 different colors and assigning the same colors to "opposite" markers. Figure 11b also shows that the original four cross connectors are not truly diagonal; they connect spheres of different colors. Drawing truly diagonal connectors from the same nodes (Figure 11c), leads to two pairs that cross one another. These intersections can be avoided, by slightly offsetting these connecting ribbons in the vertical direction. This leads to the intriguing ribbon sculpture shown in Figure 11d. However, with its flat, rectangular ribbon profiles, this sculpture does not yet look like one of Perry's *Topological* sculptures. Additional work is needed: introducing the right amount of ribbon-curl, creating more interesting T-junctions, and smoothing out the border curves.

The Complete Graph K_5

The simplest *complete graph* that is not planar is K_5, where every one of the five nodes has a single edge to each of the other four. Perry typically represents valence-4 nodes with simple biped saddles. Thus, to make a highly symmetrical geometrical sculpture based on K_5, one could place four such saddles at the corners of a tetrahedron and place the fifth one in its center (Figure 12a). When I started to design such a sculpture, I suddenly realized that there is already a reasonably symmetrical Perry sculpture with four biped saddles: *Four Orbits* (Figure 7). Moreover, the center of this sculpture is open, and it readily allows the placement of a fifth saddle. The four ribbons emerging from this central saddle need to be connected to the surrounding sculpture. The two saddle pairs near the "poles" share two edges each. One of these edges, each, needs to be removed to realize a skeletal graph corresponding to K_5. Most naturally, the inner edges should be broken, and they then provide the necessary stubs to which the ribbons emerging from the central saddle can be connected (Figure 12b). The corresponding modification of the CAD model was surprisingly simple. I just needed to provide a central (cyan) square for the new saddle, and four (red) rectangles to connect it to the other four saddles near the poles (Figure 12c). Smoothing with Catmull-Clark subdivision [1] then resulted in a pleasing 5-saddle sculpture (Figure 12d).



(a) (b) (c) (d)

Figure 12: *(a) The graph of K_5; (b) the graph of "Four Orbits" and the addition of a 5^{th} saddle; (c) CAD model of K_5; (d) 3D-print of a realization in the style of Charles Perry.*

Twin-Trefoil

As the last design experiment, I have contrived a sculpture based entirely on its border curves, without any concerns of what the underlying skeletal graph might be. I started with two identical trefoil knots separated by a small amount. If the separation between the two curves is smaller than the distance between curve segments at the cross-over points of an individual trefoil, then one could just fit an extruded surface between the two curves and obtain a simple ribbon representation of the trefoil knot.

To make things more interesting, I set the border curve separation to twice the internal crossing distance. Now, some portion of the trefoil curves will intersect the ribbon geometry between them. To prevent this, I placed two small biped saddles at those locations. Moreover, to adopt more of Perry's style, I introduced significant lateral curl into the trefoil ribbon. I did this with an auxiliary center-curve that also had the shape of a trefoil, but is slightly smaller. The model geometry was then created by adding individual quad faces connecting the outer trefoil border curves with the center curve. At the center of the sculpture, there emerged two large, (boring), triangular patches. I perforated them and connected the two perforations with a central, axial tunnel; this did not create any new border edges. Three levels of Catmull-Clark subdivision [1] turned the crude polygonal geometry into a smooth surface. Figure 13a shows the model as it came of the 3D printer. Figure 13b shows the cleaned-up model. The resulting skeletal graph is shown in Figure 13c; – it happens to be planar!

(a) (b) (c)

Figure 13: *Twin-Trefoil: (a) 3D-print as it comes off the machine; (b) sculpture after cleanup; (c) planar skeletal graph with six valence-4 nodes (saddles).*

Summary and Conclusions

I found it rather difficult to make good-looking CAD models of some of the simple and elegant "*Topological*" sculptures of Charles O. Perry. Starting the computer-aided design process with swept ribbons with a gutter-shaped profile, often results in border curves that exhibit ugly kinks or unnecessary wiggles. Perry starts the construction of the master geometry of a sculpture by defining the edges of the future 2-manifolds with steel cables. The inherent elasticity of these cables naturally forms smooth 3D border curves. This contributes a lot to the aesthetics of his ribbon sculptures.


Charles O. Perry

Perry's genius reveals itself, when he turns even very simple skeletal graphs into intriguing and very attractive ribbon sculptures. I don't think he typically concerned himself much with the underlying skeletal structure. Thus, it is somewhat surprising, that all the sculptures that I had a chance to analyze represent planar graphs. It was particularly fascinating to me to see how some of the geometrical primitives – like the curled T-intersection – show up in different places, and how some of the same graph structures lie beneath quite different looking sculptures. I know, Charlie would have liked to discuss those findings.

Acknowledgements

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