Laser-Cut Plywood and Cable-Tie Sculptures

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Abstract

I have been making a series of geometric sculptures from laser-cut plywood parts that are held together with cable ties. This method has many advantages for use in group "sculpture barn raisings": (1) Laser cutters are extremely accurate, so allow for very precise fabrication. (2) Laser cutters are becoming widely accessible through maker spaces, universities, and online service bureaus. (3) The template files can be distributed via internet, allowing others to replicate the process widely. (4) Readily available plywood is inexpensive and cuts cleanly. (5) Cable-ties are inexpensive and easy to use by participants with no special training. (6) Unlike glued wood joints, cable-ties can be easily undone with wire snips if a mistake is made. (7) Cable-ties adapt to any desired dihedral angle between the plywood parts, so no special brackets are required. (8) As illustrated below, the resulting sculptures look very crisp, creating a 3D volume from 2D panels and highlighted 1D edges, and can incorporate laser-cut designs etched on the surface. I have been exploring variations of this technique, leading teams of students and the public in making intricate geometric sculptures and taking the opportunity to informally present mathematical ideas. I encourage others to replicate these designs and this paper provides enough details to make this possible.

Process

I travel widely around the world to create geometric sculpture from various materials. [1] I often design these works to be assembled at group construction workshops, where participants, typically students or the public, help me assemble the parts. These activities are both artistic and educational as I have the opportunity to informally teach the participants about geometric ideas and to demonstrate how mathematics can apply to art and design. In the past two years I have been making many such sculptures using laser-cut wood and cable ties (a.k.a. "zip ties"), e.g., Figure 1. Related techniques have been used in hobbyist furniture [2] but I know of no previous sculpture made similarly.

Figure 1: *"Elephants" Two 1.1 m mirror-image orbs made by Philips Academy students, and template.*

The process of arranging for such a sculpture varies from event to event, but typically it begins with a school or university contacting me because someone there is familiar with my work. They may specifically ask about the possibility of creating a permanent sculpture or they might initially ask me only to give a lecture but I respond by proposing a sculpture assembly as an additional activity during my visit. Sometimes people are familiar with my larger metal sculptures and inquire about commissioning one for their campus, then discover the cost of metal-working is beyond the available budget, so I propose wood as an affordable alternative.

I design most of my sculptures to be lightweight and suspended. It is usually not difficult to arrange for an attachment point in the ceiling. There are economic advantages to having no fixed, solid base, but my main reason for suspending sculptures is aesthetic. A sculpture floating in the air is lifted above the earthly realm and perceived to have a more elevated existence. In addition, air currents may cause a suspended sculpture to gently rotate, adding an additional richness to the viewing experience.

Once the visit date and the site are set, I ask for images or plans of the space so I can design a work appropriate for the environment. My personal aesthetic leans towards intricate self-contained orbs and most of my works might be described as generally spherical. However, I see the spherical form merely as a canvas to design upon. The patterns in and on the sphere are the actual artwork. It is best to choose an appropriate size which is neither so small that it is lost in the room nor so large that it feels cramped. For some sites, multiple orbs are appropriate. Given my interest in symmetry, I sometimes create two mirror-image orbs for a room and install them symmetrically, as in Figures 1 or 2.

The design process is difficult for me to explain as it partly involves visualizing complex forms and ensuring the parts connect in a sufficiently rigid manner, while maintaining an aesthetic balance between an exact crystalline geometry and an overall organic feeling. I tend towards modular designs in which only a single component shape or a small number of component shapes are required. I usually adjust the designs extensively, to maximize a feeling of internal coherence and inevitability of the structure. The fundamental geometric constraint is that laser-cutters work on planar stock, so I am designing in a set of planes. Pairs of planes intersect at lines in space, so I am constrained to have the parts reach these lines in order to have them attach to neighbors and form a connected whole. Between those lines, I have a great deal of artistic freedom to adjust the part shapes. For example, to make Figure 3, I created the part in Figure 4, but I could have chosen a different curve or even straight segments to join the connection points shown. I write custom 3D design software [3] for keeping track of the geometric details.

Figure 2: *Aalto, two orbs, each 2m diameter.*   **Figure 3:** *Celebration of Mind, 76 cm*

Figure 4: *Part for Fig. 3 (37cm)*

Figure 5: *STEAM, 76 cm, (Science, Technology, Engineering, Art, and Mathematics) after completion at Brown University, before installation.*

When I am happy with a design, I may be confident enough to begin fabricating the components or I may first make a model. For paper models, I find that a robotic paper-cutter is excellent for making parts, [4] simply scaling down the full-size design. In some cases, I make small-scale plywood models, laser-cutting thinner stock. The laser-cutter in my studio is capable of cutting up to 6 mm plywood, so that is the thickest stock I have been using. But many of these designs could be scaled up and cut from thicker wood if I sent my design files out to an industrial laser-cutting or water-jet shop (as I also do when I need to cut components for a metal sculpture).

Figure 4 is a single part of Figure 3, to illustrate how cable ties are incorporated. For these sculptures, in which the parts connect with cable ties, I need to design openings for the ties to loop through. These are generally placed at the midpoints of two matching edge segments, set in slightly from the edge, taking into account the edge bevel (discussed below) which might be required. (For longer edge segments, two ties positioned around the ¼ and ¾ points may be preferable for strength and to eliminate relative twisting.) When the end of one part meets another part in its interior, then a pair of interior holes (see Figure 4) allows the cable-tie to make a complete loop. Whatever the arrangement, I need to select a size of cable tie with appropriate strength and design the holes with suitable clearance.

Eventually, I am ready to cut the plywood. Plywood is a rigid, lightweight, durable, dimensionally stable, structural material that is attractive, widely available, and cost effective. It can be ordered in a variety of wood surfaces and finishes and if desired, the laser-cutter can also be used at lower power to etch designs onto its surface. I have largely been using 3 mm or 6 mm thick Baltic Birch plywood specifically designed for laser-cutting. It contains a different type of glue than most commercial plywood and (in the US at least) standardly comes in five-foot by five-foot sheets. I especially like the way the cut edge becomes scorched to produce a dark line in contrast with the light wood surface. The final sculpture benefits visually from this contrast, which highlights 1D edges bounding 2D surfaces making a 3D volume. In some cases, the venue (typically a university or private high school) has a laser cutter and the parts can be cut on-site. But in most cases I cut the parts ahead of time using the laser cutter at my studio in New York and bring the parts with me.

Figure 6: *One More Thing to Climb, 70 cm.*   **Figure 7:** *Dragons, 70 cm*

For the neatest butt joints, it is worth beveling the part edges where they meet, to take into account the dihedral angles between the planes. Half the angle between the normal vectors can be removed from each edge. This is usually straightforward to do using a disk sander with adjustable table. Very little wood actually needs to be removed. On most disk sanders, the table only tilts from 0 to 45 degrees, so I make custom wedges that replace the table if larger angles are needed. I then sand the wood faces with an orbital sander to remove the smoke marks which were produced by laser cutting. (It is best to bevel first then sand the faces after, as this removes any stray wood fibers which may have been created when beveling. Depending on the grain direction, they may remain attached to the edge after beveling.)

Finally, a finish may be applied and allowed to dry. I typically use tung oil, as I like its natural look. But I also leave the wood unfinished in many cases. If the wood is unfinished, the participants must be alerted to have clean hands during the assembly, as unfinished wood shows stains and grease marks.

For the actual "sculpture barn raising" assembly event, I bring the parts, the cable ties, and some pairs of small wire clippers. Depending on the age of the participants, I might give basic instructions on how cable ties work, the direction of insertion, and how not to twist it into a Mobius strip. With students, I always tell them not to put ties around their fingers, their wrists, or their necks. (Or *their friend's* fingers, wrists, or necks...) Cable ties generally can not be undone without tools, so I always have a pair of wire clippers in my pocket just in case. Cable ties are available in a variety of colors. White blends in somewhat with the wood. Black ties have a crisper appearance, and make the construction technique more evident in the final sculpture. If the sculpture will be displayed permanently in direct sunlight, UV-resistant black ties should be used for their greater longevity.

The assembly could be run by giving step-by-step instructions, e.g., to hold the parts a certain way and connect A to B. Or it could be very open-ended by just treating it as a puzzle and letting the participants explore how they might go together. The best balance between these two approaches will depend on the age of the participants and the time available. Whenever possible, it is best to let people enjoy the puzzle for a while, possibly giving a few clues by pointing out subtle aspects of the holes or bevels that might guide them to discover how the parts mate.

In my designs, there usually is a natural way to assemble the parts in two phases: first making simple modules and then connecting these modules together. Only after the participants show me that they know

how the parts join do I give them cable ties. In this way, I can check for errors such as mirror-image modules before any parts are mis-connected, which would otherwise require clipping the ties of the incorrectly mated components. The actual steps are very different in each case, even when I repeat a design, so I can't give detailed general guidance. It is best to let one's instinct as a teacher set the tone, letting students enjoy the challenge but providing clues and encouragement as necessary to prevent over-frustration. The assembly event is full of opportunities for informal education and enrichment. I can answer questions to explain aspects of geometry, symmetry, the design process, and emphasize the importance of mathematical foundations for all subjects and careers, including art and design.

In my experience, everyone enjoys these assembly events and they create strong positive emotional connections to mathematics, e.g., Figure 5. As in any group situation, some people are very eager to be at the center of the activity and others might sit on the outskirts if you don't encourage everyone to rotate roles occasionally. There is always a point partway through when I can step back and let the group finish without me, knowing that they will check each other's work and point out any errors that need correcting. When they begin to answer each other's questions, I feel like I have done my work as a teacher.

When complete, I prefer that the sculpture be suspended as soon as practical, so it is safe from any damage. As wood may eventually dry out and crack, plywood structures should never be attached at just a single point. I typically connect three or five small flexible cables to a set of symmetrically distributed points of the sculpture. This distributes the load (reducing any stress on the wood), ensures there is no single point of possible failure in the wood, and allows me to orient it with a 3-fold or 5-fold symmetry axis vertical. Multi-strand beading cable and small crimps provide a strong and attractive means. These small cables all connect to a single welded steel ring which in turn can be suspended from a single steel cable connected to the ceiling. If it can be scheduled with the buildings people several weeks ahead of the assembly event, it is often possible to hang the sculpture immediately after completion. If kept dry and well treated, these works should last 100 years or more, but the cable ties might need to be replaced every few decades.

Figure 8: *Seals, 65 cm*

Figure 9: *Mosaic Orb, 60 cm*

The educational value of these activities is clear to me (though I have done no formal quantified assessment), but I can only lead a finite number of events each year. So I would like to get more people leading similar activities. I would be very happy if others emulate this process and replicate these designs in some manner. While some artists do not wish to have their work copied, I consider it a compliment when people find my sculpture worthy of replication. I am very willing to make templates freely available

for noncommercial, educational purposes assuming proper design credit is given. (But if someone wants to make money from my designs, they should first discuss their idea with me and come to an agreement in which I receive a share.) The key ingredient for the designs in this paper is access to a laser-cutter. They are becoming increasingly available at maker spaces, universities, schools, and online service bureaus. I hope this sketch of my process, along with the templates, provides enough information and inspiration for others to succeed in their own analogous sculpture barnraising events. And I would be happy to learn if others adapt these designs to make their own personalized versions, with changes in scale, materials, color patterns, or other variations.

I've been making sculpture with laser-cut wood for fifteen years, [1] but before two years ago did not incorporate cable ties. My previous wood sculpture had explored other ways of connecting the components, specifically controlling the dihedral angle between planes. For example, *Frabjous* and many others use glued butt joints to connect the beveled edges of the components. *Whimsy* uses a custom biscuit joint in the beveled edges. When I was artist in residence at MIT in 2003, I led a group assembly of *Salamanders*, in which the components are screwed to wooden trihedral wedges, cut to the proper angles. Those works were each designed to be assembled just once. For a re-assemblable sculpture that I could re-use at many workshops, I created *People*, for which I fabricated custom metal connectors and used small plastic thumb screws to connect the wooden parts into tapped holes. [5]

In the designs of the previous paragraph, the connection mechanism was specifically intended to maintain the dihedral angle between components, which provides local rigidity. So it was something of an experiment to make a large structure connected with cable-ties, which are hinging connectors. My first sculpture to use cable ties this way was *Aalto,* made at Aalto University in Helsinki in April 2013, shown in Figure 2. It's components were cut with a band saw rather than a laser-cutter, as that was the shop equipment available on site, but the design is certainly suitable for laser-cutting. I made up for the lack of angle control at the joints by designing it so that each part touches seven others. Having many connection points reduces degrees of rotational freedom, resulting in a very rigid structure. After assembling it, I could see the result is rock solid, which encouraged me to explore further with cable-tie connections.

Results

The works below all use laser-cut plywood components and cable ties, and all involve icosahedral symmetry while illustrating a variety of design ideas I have explored in the past two years.

Celebration of Mind, Figure 3. This sixty-component sculpture was assembled at Princeton University as part of the October 2013 "Celebration of Mind" event in honor of Martin Gardner and is installed in the Princeton Mathematics Department reading room. The design incorporates triangulation on both its inner and outer layer, so is quite rigid despite the fact that each part is long and thin and contacts only four others. An etched design of circular arcs adds to its geometric feeling.

One More Thing to Climb, Figure 6. This thirty-component design incorporates snails climbing on each part, so illustrates the laser-cutter's ability to draw arbitrary forms. The etched design is partly on each side of the surface, which required turning the parts over and positioning them in a jig on the laser-cutter bed for etching the back face. The design is based on the uniform compound of five tetrahedra, but with the parts meeting at 90-degree dihedral angles, like the faces of a cube. The part design includes a special spur that connects the tetrahedra to each other.

Elephants, Figure 1. The name for this piece derives from the part shape, which can be seen as an abstract elephant with a long trunk. The tips of the trunks come together in groups of five. Although the parts are long and thin, each connects with six others and it is sufficiently rigid when made from 3mm thick plywood. I built this as a mirror image pair at Phillips Academy, in Andover, MA.

STEAM, Figure 5. An acronym for "Science, Technology, Engineering, Art, and Mathematics," this was assembled by students in the STEAM club at Brown University and is hanging in the Engineering building there. For additional visual interest, I designed ten different pseudo-random Voronoi patterns for

the surface. Because the long thin parts each touch only four others, for rigidity this design uses wood glue that was brushed on to the beveled surfaces before tightening the ties.

Dragons, Figure 7. First test-fit at a Math for America teacher's workshop in NY, this was then reassembled at the Gwacheon National Science Museum during the Bridges 2014 Conference in Seoul, Korea. It is now is at the MathLove Museum in Seoul. The design was a prototype for STEAM and is similar structurally, but has an etched pattern of scales.

Seals, Figure 8. This is an experiment in designing a part shape that is highly representational yet connects well with itself. I first test-fit this at a workshop at the Simons Center for Geometry and Physics at Stony Brook University then reassembled it as a workshop at the 2014 FooCamp in Mountain View, CA. It is now on display at Google Headquarters there.

Mosaic Orb, Figure 9. This is a 60 cm diameter orb that I designed to be assembled as a one-hour workshop activity at MoSAIC Math and Art festivals [6] around the country. The parts are small enough for it to conveniently fit in carry-on luggage with me. It has been assembled and disassembled at MoSAIC festivals at Berkeley Community College in CA, Columbia University in NY, Portland State University in OR, and North Carolina State University in Raleigh.

Sydney, Figure 10. The curved triangular openings of this design remind me of the Sydney Opera House. I built this as two mirror-image orbs with students at the Presbyterian Ladies College in Sydney, Australia, where it is hanging in the school library. There is also a smaller one-orb prototype at Alfred University in Alfred, NY, constructed at the Fall 2014 regional MAA meeting there.

Volcanos, Figure 11. Circular openings on concentric cones give this the feeling of volcanic craters. I built one instance of it at the Iolani School in Honolulu, Hawaii, another at St. Andrew's School in Middletown, Delaware, and another at the International School of Ho Chi Min City in Vietnam.

D Flat, Figure 12. This work (in the Bridges 2015 Art Exhibition) differs from ones above in lacking full icosahedral symmetry. It is compressed along a five-fold axis to have five-fold dihedral symmetry, filling an ellipsoidal volume with axes in the ratios 1:2:2. The thirty components have four different shapes.

Sword Dance, Figure 13. This sculpture consists of two oblate mirror-image orbs, each 2 m in diameter. I built it with students and faculty at Middlesex University in London, England. Like "D Flat," it starts conceptually with full icosahedral symmetry, but is compressed along a five-fold axis to retain only five-fold dihedral symmetry. Each orb is made from sixty parts in six different shapes. I first built a smaller prototype of one orb at Packer Collegiate Institute in NYC, where it is hanging in their campus atrium.

Figure 10: *Sydney, prototype after construction at Alfred University.*
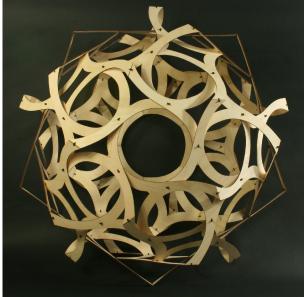
Figure 11: *Volcanoes, 90 cm*

Figure 12: *D Flat, 38 cm*

Figure 13: *Sword Dance (a) under construction, (b) complete (two orbs, each 2 m) before installation*

Conclusions

After years of design evolution, I have discovered that laser-cut wood and cable ties can be combined as an ideal medium for creating large mathematical sculptures which can be assembled by groups of students or the public at sculpture barn raising events. The efficiency of this process has allowed me to work with large groups of people to create dozens of original works that are currently displayed all around the world. At each site, there are now many participants who feel a certain ownership in the sculpture for having helped bring it into being. New viewers who come upon these mathematical sculptures have the opportunity to think about the geometric design issues and realize how mathematics and art are akin as fun creative subjects with many possible interconnections. I hope that others can find beauty and excitement in this process and follow up on this work by replicating my designs and going further.

References

[1] http://georgehart.com
[2] Search online, e.g., "zip tie chair" or "cable tie furniture" for a variety of examples.
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[4] G. Hart, "Modular Kirigami," *Proceedings of Bridges Donostia*, San Sebastian Spain, 2007, pp. 1-8.
[5] G. Hart, "Sculptural Presentation of the Icosahedral Rotation Group," in special issue of *CRM-AMS Proceedings & Lecture Notes series, for the Groups and Symmetries Conference,* AMS publications, p. 211-214.
[6] http://mosaicmathart.org