Structures, for elementary sites [Fall 2011]

<u>The Challenge</u>

Build a bridge that has the largest span while still meeting the other requirements listed below.

Rules

- The bridge must be able to withstand the weight of a “car” (i.e. a soup can rolling on its side) travelling across it from one side to the other.
- The bridge’s deck must be at least wide enough to hold a soup can on its side without any of the can hanging over the side of the bridge.
- The bridge can have only one support between the two bases.
- The bridge has to be freestanding and movable (it can’t require anchoring to a desk or floor).
- There are no restrictions on its base’s footprint (where the “entrance” and “exit” of the bridge are) or height.
- The only restriction with regards to materials is that each team is allowed only 2 sheets of cardboard**.**
- Teams are allowed use of the soup can to do **one** test of their structure so they can make sure it works.

<u>Teaching Goals</u>

- Students will work through the 5 step Engineering Design Process (**Ask, Imagine, Plan, Create, Build, Improve**). The steps will not be explicitly discussed during the session, but each step is listed by the corresponding part of the lesson plan.
- Students will work together in teams to achieve a common engineering goal.
- Students will understand how geometry and structural elements (trusses, struts, cables) affect structural performance and apply these concepts in their design.

<u>Materials</u>

Consumables:

- Popsicle sticks
- Masking Tape
- Twine
- Carboard (food/cereal box type, preferrably no corrugated)
- Pencils and paper (for designing)

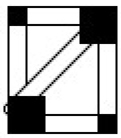
Nonconsumables:

- Soup can (for improving and final test)
- Scissors
- Ruler (for final test)

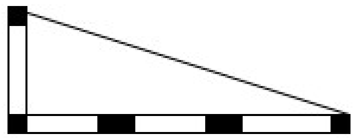
<u>Agenda/Lesson Plan</u>

Setup (5 min, before session begins)

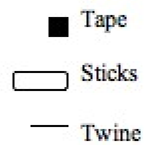
- One person should estimate the number of teams (3-4 students per team) and gather a set of materials for each team. This would include paper, pencils, 2 sheets of cardboard, scissors, a roll of masking tape, some twine, and a generous helping of popsicle sticks.
- Another person can make props to be used during the introduction. Use tape, sticks and twine to make the shapes shown below.



strut example



cable example



Introduction (10 min)
- Introduce the challenge and explain the rules.
- **(Ask)** Ask them what makes a bridge "good"? **(Imagine)** Discuss, and write down ideas on a board if you have one.
- **(Imagine)** Give examples (pictures, at very end of lesson plan) of real-life bridges to "prime" the mentee's minds for bridge design.
- Showcase the strut prop you made and point out 2 things:
    1. The strut (the diagonal) makes the square strong. You can even remove the strut and show how flimsy the square is otherwise.
    2. The strut turns the square into 2 triangles. Triangles help make structures more stable.
- Showcase the cable prop and demonstrate how the twine (like cables on a real bridge) help support the structure from above. Remove the twine from the top point and show how it sags otherwise.

Divide Class into Teams (5 min)
Allow mentees to choose their own teams when possible, but if there is a large age distribution try and make teams with equal ability levels. 4 people *max*, 3 preferred per team. Smaller is better to improve communication and minimize problems while designing the bridge.

(Plan) Design (10 min)
- After the teams are chosen, do not let them touch the materials yet. Have them plan out their design using paper and pencil. Explain that they will be given the materials once they have agreed on a design on paper.
- While groups are designing their structures, mentors should give hints for design, some of which are listed under **Design Concepts** below.
- Once a team produces a design on paper that *all* members agree on, allow them to begin building their bridge.

(Create) Build (45 min)
- While groups are building, mentors should walk around and explain some of the concepts listed below, under **Building Concepts**. This is the best time to get these concepts across because this is when the students can really see and do it for themselves.

- **(Improve)** During the building time, groups can use the soup can to perform a single test of their structure (simply weighting the bridge, rolling the can, etc.). Encourage groups to do this towards the end of the build time unless it seems they are really off track.
- One possible way to spur competition (if you have enough mentors) is to have some of the mentors build their own design.

Test (last 20 min)
- Take pictures!
- Have the students stop building and gather them somewhere with a good view of all the designs. Test each team's bridge by rolling the can slowly from one side to the other. If

it holds up under the rolling test, measure the span of the bridge and tell each team to remember their span.
- (Optional) Reward the 1st place group with some sort of prize. If you have time and don't mind the cleanup, they could be allowed to "godzilla" their bridge....just a thought.

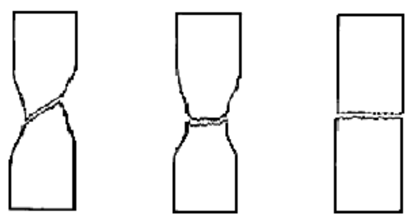
Background for Mentors

In order to build sturdy structures, mechanical and structural engineers have to understand the strength of materials. Materials generally fail in two ways: either the material reaches the *plastic stress limit*, or the part (beam, column, etc) *buckles*. We will discuss these separately.

Plastic Limit

Every material has some inherent strength due to intermolecular bonds, microstructure, or interactions between different phases in a composite material. Simply stated, a material fails (deforms) when the *stress* in the material exceeds a some *critical stress value***.** The stress a material is under is expressed as a *Force per Area*, the same units as that of pressure. Thus a part with a larger *cross section* can withstand a larger force. For a simple, one-dimensional loading:

$$\sigma = \frac{F}{A} < \sigma_{crit}$$



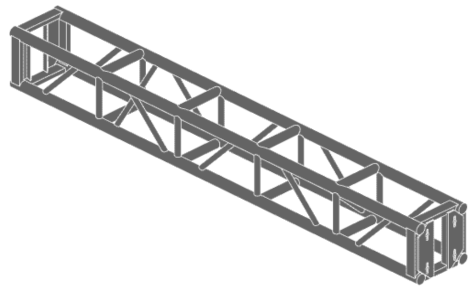
Ductile shear fracture in Aluminum — Ductile fracture in steel — Brittle fracture in steel

Buckling

Many parts used in structural applications have a large *aspect ratio* (ratio of length to width). If a long slender part is put under compression, it is likely to *buckle***.** Buckling occurs when a part deforms long before the *plastic limit* is reached. This is easy to demonstrate with a flexible ruler, a straw, or a toothpick. If you try to compress it along the long axis it will "bow" out and fail to support the load. Analysis of buckling reveals that the critical load for buckling is given by:

$$F_{crit} = \frac{\pi^2 EI}{(KL)^2}$$

where *E* is the modulus of Elasticity, *I* is the area moment of inertia, *L* is the length of the column, and *K* is a factor that depends on how the part is supported. This equation reveals that buckling can be avoided by choosing a stiffer material, decreasing the length, or by increasing the area moment of inertia. Thus if you are making a cardboard or paper tube, try increasing the radius a little to increase the area moment. Buckling can also be avoided by using thinner parts to "stiffen" a long, flexible frame, as shown below:



Design Concepts

Load bearing: Have the mentees think about where the weight is spread within the structure. Optimally, it should be transmitted from the center of the bridge out towards the bases where the bridge contacts the table. You want to minimize forces down the center of the span and out the sides where the bridge is unsupported. The path along the bridge that the stresses take should be as short and reinforced as possible.

Trusses: Trusses are structures comprised of triangular units. Triangles allow for weight, when applied from above, to be spread evenly to either bottom corner of the triangle. This can be used to spread the weight from the center of the bridge, where it is applied, outwards to bases.

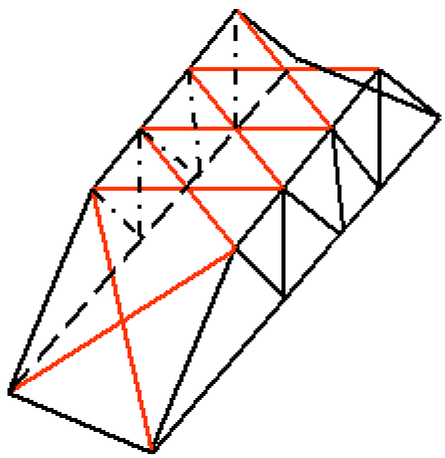
Arches: Arches are another structural technique to spread the load outwards, from the top of the arch to the bases.

Suspension/Cable-Stayed: Suspension structures depend on the cables, which must be under tension, bearing the load. In cable-stayed bridges, the towers bear the majority of the load; in addition, the forces on either side of the tower must be balanced.

Straight beams are bad: Long, straight beams are bad for load bearing because they tend to bow then snap and have bad buckling resistance.

Structural strength: The structure’s strength comes from the popsicle sticks and their arrangement, not from their glue joints. However, it is important that the glue joints do not fail.

Lateral bracing: Lateral bracing prevents the bridge from twisting.



Building Concepts

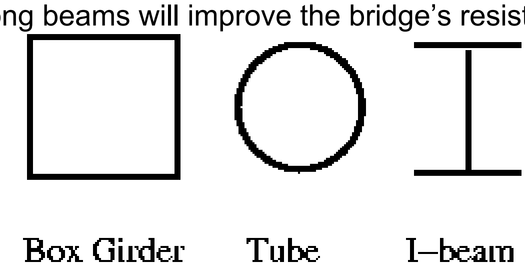
Be picky: Not all popsicle sticks are equal. Mentees should swap out any malformed or weak ones.

Glue under compression: Glue bonds best under compression, so either clamp pieces together or apply weight to them while the glue sets. Another way to do this would be to wind the twine around the pieces and tie them together.

Correct gluing: For best adhesion, spread a thin film of glue (use a popsicle stick as a spreader) across the surfaces, then press together. Too little glue prevents an adequate bond from forming. Too much glue prevents the glue from drying completely and can actually give the popsicle sticks a way to slide by each other.

Stick lamination: Sticks are individually weak because of the inherent weakness in the wood grain. By gluing two together, the weakness of the grain can be nullified, and the cross-sectional area can be increased to improve the material's plastic limit. Demonstrating it with a bundle of popsicle sticks would make the concept stick better.

Complex cross-sections: For any longer sections, using complex cross-sections instead of just long beams will improve the bridge's resistance to lateral stresses and prevent buckling.



Symmetry: Building a symmetrical structure allows for even load distribution, which maximizes material strength. For example, if only one side of the bridge fails, the material on the other side is essentially wasted. Optimally, both sides would fail at the same time. You want all sticks to bear as equal a share of the load as possible.

Attention to Detail: In most cases, structures fail at their weakest point (the "weakest link"), which means that every joint is important. This holds true not only for how each part is constructed, but how the parts are angled and aligned against each other and. Try to keep as consistent an angle as possible; for example, use tabletops as a guide for straight sections.

Compartmentalize: Break down the bridge construction into several simpler steps. For example, start by making all the laminated beams, then build one side at a time, then join together.

Lateral forces: If the bridge is constructed with two sides, make sure they are exactly the same and held together well otherwise the difference in forces and weight will push them apart and the bridge will twist itself apart.

References:

Popsicle stick building guide: http://andrew.triumf.ca/andrew/popsicle-bridge/
Bridge engineering: http://www.apeg.bc.ca/services/branches/documents/pr/Bridge_Engineering_Principles.pdf
Guide to bridge types: http://pghbridges.com/basics.htm
Building tips: http://www.eod.gvsu.edu/~oostdykj/techniques.html
Building tips: http://www.garrettsbridges.com/building/25-bridge-building-tips/

Bridge Examples

A bridge using cables

A bridge using arches

A bridge using both lateral bracing and cables

A bridge using arches and lateral bracing