Improvisation, Ingenuity and Design of Experiments to Reinforce the Civil Engineering Curriculum

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Abstract

One very effective outreach activity and a staple of Engineer's week events is the Popsicle® stick bridge building contest targeted at K-12 students. Since first being offered in the 1960s, the contests have succinctly demonstrated basic engineering mechanics and efficiency concepts, such as the strength to weight ratio. Although the format varies, the bridges are typically loaded until failure and then judged by a combination of their performance, efficiency, and aesthetic design. Students are challenged to design and carefully construct their scale model bridges, exercise ingenuity, and enjoy the fun and thrill of competing with other students.

What is often overlooked in these contests is the improvisation and ingenuity that go into designing the contests themselves. A survey of past contests showed wide variation in the rules and means of testing the bridges, suggesting that the contests have been designed "organically". Despite this variation, the educational outcomes appear consistent A group of civil engineering undergraduate students at George Mason University was tasked with designing the rules, judging criteria, and testing apparatus for a bridge building contest in February 2007. Using only basic materials and a general notion of how other contests were run, they successfully designed and carried out the contest with 14 participants from local high schools. This paper will profile their experience specifically in the context of civil engineering curriculum design, ABET outcome achievement related to design of experiments, and the effect of organized student activities providing synthesis to the curriculum where it was never planned to occur. We discuss the role of students as mentors and as exemplars and the utility of improvisation for directed learning. Finally, we discuss how design of instruction theory can apply to engineering students at the peer level with approaches for measurement.

Keywords: design of experiments, Popsicle® stick bridge contest, improvisation, curriculum design

INTRODUCTION

Whether it is called a craft stick or the propriety Popsicle® stick, these small-scale structural members have been used for engineering education outreach for K-12 programs for many years. The Popsicle® Stick Bridge Contest has been run during Engineer's week [1], in high school sciences classes, and at other venues where a non-intimidating and fun introduction to engineering design is desired. The contests have succinctly demonstrated basic engineering mechanics and efficiency concepts, such as the strength to weight ratio and estimated versus actual capacity. Students learn how simple wood members, approximately 4.5 in (114 mm) long, 0.375 in (9.5 mm) wide, and 0.09375 in (2.3 mm) thick, can be combined using glue into trusses, girders, or decks that span long distances and carry impressive loads. Although the format varies, the bridges are typically loaded until ultimate failure and then judged based on a combination of their performance, efficiency, and aesthetic design traits. Students are

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challenged to design and carefully construct their scale model bridges and enjoy the fun and thrill of competing with other students.

A recent advance that has increased awareness about design contests is the annual virtual bridge design contest hosted by the US Military Academy at West Point [2]. Beginning in 2002, student teams have been invited each fall to design and submit for competition virtual truss bridges according to specific rules, load conditions, and site configurations. Free access to The West Point Bridge Designer, an innovative software application for design and simulation of truss bridges, is provided. A rolling score card is kept on the contest website that shows rankings at the national, regional, and local levels. Each summer, prizes and recognition awards are given to teams with the best performing bridges. The virtual contest has been widely acclaimed for its approach. Since 2001, over 250,000 bridges from 75,000 teams have competed.

Whether virtual or physical, what is often overlooked is the design of the contests themselves. A great deal of planning and foresight is needed to successfully conduct the design competitions, to develop and enforce fair rules, to apply consistent judging, and to achieve the educational objectives associated with engineering outreach. Practicing engineers and engineering faculty have frequently helped organize and administer design competitions such as the Popsicle® stick bridge contests. At George Mason University, a group of undergraduate civil engineering students were charged with designing their own bridge building contest for high school students in February 2007. Although inspired by other contests, they designed their own rules, judging criteria, and most notably the testing apparatus whereby the bridges were loaded until failure. The exercise produced some interesting outcomes related to how synthesis, design of experiments, and peer instruction can reinforce the civil engineering curriculum.

SYNTHESIS THROUGH IMPROVISATION AND INGENUITY

Plato is often credited with coining the phrase; *necessity is the mother of invention*. In modern history, this truism has been a mainstay of 19th and 20th century innovation from the industrial revolution until today. While some technological advances occur as the result of a push, for example e-commerce made possible by the Internet and WWW, others occur as the result of a pull, a true need leading to innovation.

The pull approach to innovation is well suited to civil engineering education and practice. Civil or environmental works rise from specific needs subject to resource and economic constraints. Successful and efficient designs often test the limits of traditional approaches leading to new technologies and techniques. These designs bring together established practice with new innovations to achieve a holistic solution. The process of delivering an integrated solution, referred to as synthesis, is at the core of civil engineering practice and is the overarching goal of most engineering education programs.

One vehicle for delivering synthesis in engineering education is through the use of open-ended or semi-structured problems that require students to effectively apply their knowledge and skills. These are usually comprehensive design problems assigned in either upper-level or capstone design courses, or both. While design is certainly effective at achieving synthesis in the curriculum, there are other sources closely related to the design process, namely improvisation and ingenuity. Improvisation has an unfortunate connotation of being negative. To say that a solution is *improvised* suggests that it is cobbled together or shoddy, temporary, or not planned. We contend that a more useful interpretation of improvisation is the best use of available resources under limiting constraints. Ingenuity is the quality of being clever or inventive – to exhibit "out-of the-box" thinking. Ingenuity occurs when physical, mathematical, or computational principles are applied to achieve a totally new or never before tried solution or approach. Improvisation and ingenuity are sources of synthesis in that both apply known principles for a problem domain, but with the opportunity for a hands-on solution. The solution may be less efficient than one reached through formal design, and may in fact be temporary, but it is no less valuable, especially for educational purposes.

A focus on ingenuity and improvisation has grown recently due in part to popular television shows such as "MythBusters" [3]. MythBusters is a science television program on the Discovery Channel starring film special effects experts Adam Savage and Jamie Hyneman. Each episode uses a somewhat loose application of the scientific method to debunk or validate various myths or urban legends. In one episode, the team attempted to dispel the myth that one could survive a multi-story elevator fall by jumping in the air right before the elevator hits the bottom of the shaft. Of course, this myth could be proven wrong using simple physics to compare the relative velocities of a person and the elevator car. But, the show's approach is based on improvised experimentation rather than strict theory. Not only does it make for good television, it is instructional in that ingenious testing apparatuses, usually made from common materials are designed and constructed for each episode. The show illustrates how, given a hypothesis and scientific facts about the problem domain, experiments can be designed and conducted. Put simply, their approach allows one to apply what you know to the problem at hand, and build (synthesize) a solution to what is unknown, or unproven.

Designing vs. Improvising

In some ways, improvising can be seen as counter to designing. As previously mentioned, the negative connotation of improvisation is that of not planning, whereas design is carefully planned. Engineering design is usually concerned with applying engineering principles for designs with adequate performance, that are safe, and that are cost effective and efficient. Is improvisation the antithesis of design? We do not believe so. There is a role for design in determining the necessary parameters for a solution and a role for improvisation in making use of what is available. Through this combination, a specific vehicle for synthesis is possible. In designing a bridge contest, this synthesis was particularly evident.

Designing the Bridge Contest

The 1st Annual Popsicle® Stick Bridge Contest at George Mason University was planned as an outreach and recruiting activity for the Volgenau School of IT and Engineering. Held during Engineer's Week in February 2007, student teams from local high schools were invited to submit bridges and compete for prizes. Bridges were evaluated on the basis of efficiency (i.e., ultimate strength to weight ratio) and aesthetics. A team of civil engineering students designed the contest based on web research of similar bridge building contests. The annual contest held by the Younger Member Forum (YMF) of the Seattle Section of ASCE [4] was the primary inspiration.

A set of official rules was created [5] to outline the requirements, judging, and testing procedure to be used during the contest. The goal of the rules was to have fair, coherent, and consistent guidelines for the high school students to follow in designing and constructing their bridges. The rules were separated into design, material, dimensions, construction, and loading requirements for the hypothetical scenario of a roadway bridge with sufficient clearance for a truck.. A sample list of rules and requirements is given in Table 1.

Table 1: Sample contest rules and requirements for GMU bridge contest.

Rule or requirement category	Rule or requirement
Design	The total weight of the bridge must be less than 12.3 ounces (350 grams).
Dimensions	The bridge length must be between 30 inches (76.2 cm) minimum and 32 inches (81.3 cm) maximum, with a clear span of 28.5 inches (72.4 cm).
Material	Only Popsicle® or craft sticks and white (e.g., Elmer's© glue can be used to build the bridge.
Construction	The bridge must have a roadway that can accommodate a 4-inch high, 4-inch wide vehicle. The roadway is the portion of the bridge to be loaded. A 3-inch square opening must be maintained above the loaded area.
Loading	The bridge will be loaded on the roadway at the mid-span in a 3 inch x 3 inch (7.6 cm by 7.6 cm) area.

The rules also specified limitations on specific construction techniques. For example, sticks could not be combined into laminated “stacks” to form large beams. Figure 1 depicts a schematic loading and support plan as well as the scale model truck clearance and roadway loading area.

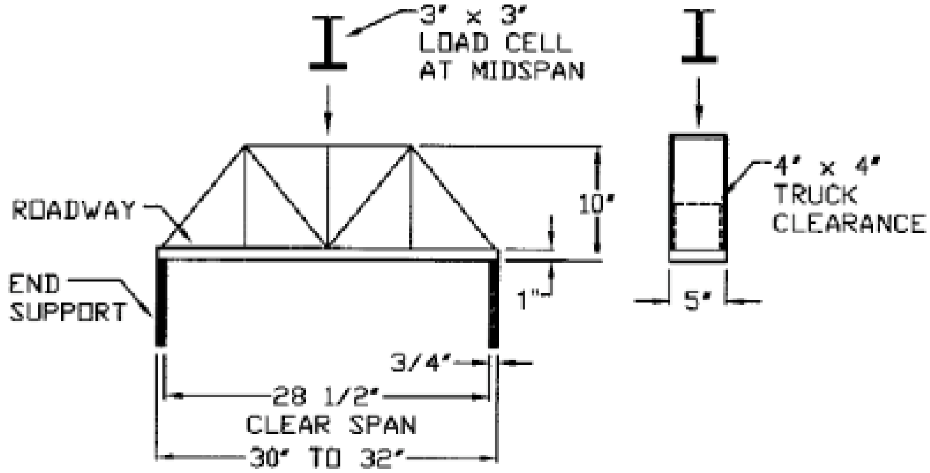

Figure 1: Schematic plan for bridge supports and loading.

The event was announced and promoted to local high schools based on the rule booklet. Fourteen high school teams (i.e., fourteen bridges) entered the contest. The real challenge for the student contest design team was to devise a means of testing the competing bridges to ultimate failure based on configuration of bridges shown in Figure 1.

Bridge Testing Apparatus

The bridge testing apparatus was a critical problem for the contest design team. While many schools have laboratories with mechanical testing equipment and even data acquisition systems, the GMU team had none of these resources available. Attempts at borrowing testing equipment failed, so the team decided to design and construct its own testing apparatus for the contest. A budget of $250 was allocated for materials that were to be acquired from a local home center.

The challenge of loading the bridges was one of handling extreme values. Research into past bridge competitions showed that Popsicle® stick bridges weighing under 14 ounces (400 grams) could reach ultimate load capacities between 0 and 1 ton (907 kg). The apparatus needed to be capable of generating and also measuring this wide range of loads. In terms of deflections, the team wanted to be able to test bridges that could literally fold in half, or approximately 15 inches (38 cm) of allowable deflection. Several loading mechanisms were considered including sandbags, water tanks, and a sliding mass over a lever and fulcrum. Ultimately, the application of “off the shelf” ingenuity solved the loading problem.

A 4-ton hydraulic, hand pumped bottle jack was chosen as the load cell for the apparatus. Next, a suitable load frame was needed to contain the bridge to be tested, the abutment supports, the bottle jack, and the point load application area on the roadway of the bridge. A 48 inch (122 cm) wide, by 36 inch (91 cm) tall, by 12 inch (30 cm) deep frame was constructed out of laminated plywood plates and 1inch (2.5 cm) diameter threaded steel pipes with flanges. The frame was connected together with steel lag bolts and construction adhesive. The roadway loading area was created by using a 12 inch long (30 cm) steel pipe with a flange on its free end as a fixed support. In this way, the Popsicle® stick bridge to be load tested was lifted from the bottom to meet the fixed support. A 2x4-laminated beam with 4x4 wood blocks serving as the supports sits between the bridge and the vertically advancing bottle jack at the lower part of the frame. Figure 2 shows the completed testing apparatus that was built for a total material cost of $238 and took approximately 20 person-hours to construct.

Figure 2: Custom-built bridge testing apparatus.

The final element to the bridge testing apparatus was the load measuring method. With no mechanical testing gauges, sensors, or other equipment available, the students improvised by using two bathroom scales capable of recording 300 lb of mass each. Each scale was placed under an end of the 2x4 beam and zeroed relative to the weight of the jack and support beams. The students were confident that the capability to measure approximately 575 pounds (the scale capacity minus tare) would be sufficient for this contest, with the testing frame capable of accommodating up to four scales if the applied load exceeded the two scales. Finally, the performance of the testing apparatus was verified by loading a single 2x4 until it reached ultimate bending failure without damage to the frame. Breaking the 2x4 gave confidence to the design team that their apparatus could handle the range of load capacities expected.

Bridge Contest Execution and Results

In sequential fashion, the 14 bridges were assessed for conformity to the official rules and regulations, judged on aesthetics, and load tested to determine their ultimate strength. The contest team developed a standard procedure for carefully loading each bridge into the testing frame, gradually lifting the bridge and applying load to the roadway using the bottle jack, then recording the applied load from the bathroom scales. Figure 3 shows the load testing for a particular bridge.

Figure 3: Load test of a bridge. ASCE student members Kalen Bauman (left) and Alejandro Prieto (right) pictured.

The results of the competition were a relief for the students as no bridge approached the load generation or load measurement limit of the testing apparatus. Four of the bridges could support no load and eight supported less than 50 pounds. One arch truss bridge supported 137 pounds with that team ultimately winning first prize based on both efficiency and aesthetics. Table 2 summarizes the results of the contest.

Table 2: Summary of 2007 GMU Popsicle® stick bridge contest results.

Team Number	Bridge Weight (g)	Actual Load (lbs)	Efficiency*
1	333	55	0.17
2	237	23.5	0.10
3	302	137	0.45
4	434	5	0.01
5	239	0	0
6	236	0	0
7	224	37	0.17
8	221	41.5	0.19
9	291	42	0.14
10	201	0	0
11	160	10	0.06
12	253	30.5	0.12
13	241	20	0.08
14	198	0	0

Efficiency is the ratio of bridge weight [g] to load [lbs]

Synthesis through Improvisation

Ideally speaking, the civil engineering curriculum should by itself address the educational objectives and produce the educational outcomes typically desired in an ABET accredited program. The reality is that the needed synthesis can come from other sources or programs that may act as catalysts. The bridge contest was an external activity that brought synthesis to the civil engineering program (for the students involved at least) in engineering design, construction techniques, and design of experiments. Students applied knowledge of engineering mechanics as well as data collection and reduction in an activity outside of the classroom and did so by improvising a solution to a pressing need. They designed a contest and testing apparatus that delivered a holistic solution given the knowledge, skills, time, and resources they had available.

The George Mason University Volgenau Schoool of IT and Engineering, and the Civil, Environmental, and Infrastructure Engineering (CEIE) Department in particular are interested in increasing the number and student involvement in these external opportunities for synthesis in the future. The planned 2008 Popsicle® stick contest will introduce a collegiate class to the competition where undergraduate civil engineering students will be invited to compete in the contest. They will be required to rigorously design their bridge, however, using the concepts of truss design. We look forward to comparing and contrasting bridges in the high school class, which we expect to be more improvised with the collegiate class, which will be designed.

DESIGN OF EXPERIMENTS

Besides the reinforcement of synthesis in the civil engineering curriculum, the bridge contest also contributed to ABET Engineering Accreditation Commission Outcome achievement. Released as part of EAC2000 [7], outcome 3b puts an emphasis on experimentation. The outcome calls specifically for "*an ability to design and conduct experiments, as well as to analyze and interpret data.*"

Several papers have been written that describe approaches for achieving this outcome. Du et al. [5] developed a general approach for design of experiments in engineering curricula. Komives et al. [9] raise several points about design of experiments. They suggest that a continuum of inquiry level exists that spans from formulaic experiments that quickly and easily reproduce expected results to open ended and semi-structured problems where students have to use a combination of the course material and improvisation to reach non-obvious conclusions. Komives et al. also developed an instructional rubric to be used for designing and assessing experimental design for engineering education. The rubric can be very valuable in designing experiments that address the upper range of the inquiry continuum which appear to be the most successful at promoting student learning.

Citing lectures, demonstrations, assignments, or projects in the engineering curriculum is typically used to claim achievement of Outcome 3b. At George Mason, the CEIE Department based its achievement during its recent re-accreditation on lectures and assignments beginning in its freshman ENGR107 Introduction to Engineering course all the way through its CEIE490 Capstone Design Class. [8]. The civil engineering program was found to have met outcome 3b, but we are constantly looking for improvement. While evidence at the lower range of the inquiry continuum suggested in [9] is fairly easy to identify in the curriculum, evidence at the opposite range is much more difficult.

Reinforcing the Civil Engineering Curriculum

The Popsicle® stick bridge contest at GMU is an activity that provides direct evidence of Outcome 3b achievement, albeit for a select group of students. The exercise of designing the contest and especially the testing apparatus offers a rich example of upper level inquiry based learning. While the bridge contest was intended to be an outreach event, the end result had a more far-reaching impact. The activity demonstrated synthesis and outcome achievement that will be expanded upon in the future.

Now that the contest and apparatus have been for the most part designed, except for the addition of the collegiate class mentioned planned for 2008 (mentioned above), the shift for evidence of design of experiments needs to move back towards the curriculum or other outside activities. In CEIE463 – Construction Systems and Management, taught by Michael Casey (co-author), students will prepare schedules, cost estimates, and bid documents based on designs used for the bridge contest beginning in spring 2008. Other activities are planned as well now that the value of experimental design in promoting inquiry-based learning has been experienced first hand.

DESIGN OF INSTRUCTION AT THE PEER LEVEL

One tacit component of the bridge contest not yet mentioned was the role of peer mentoring. The contest was conceived and organized by Jesse Coleman, co-author of this paper. A team of students, however, was responsible for building the testing apparatus and conducting the contest. There is much evidence to support the effectiveness of student led instruction in the classroom. There is less specific research in the effectiveness of peer level instruction on group projects and activities in engineering education.

The team peer group is meant to include both the civil engineering and high school students in this case. We found that during the bridge building process and during the contest, the civil engineering students were involved with answering questions and giving impromptu and basic lessons about engineering mechanics. This occurrence was reported anecdotally, but the authors see the potential to measure it directly in future activities.

One possible measurement approach would be to assign one civil engineering student to a select group of high school bridge design teams. Other teams would be composed only of high-school students. Although still under development, this approach is being considered for the 2008 Popsicle® stick bridge contest. A design methodology survey will be prepared to capture which choices, design rules, and physical principles were used and if the assigned peer mentor influenced them. More research needs to be done to control for the influence of other individuals such as high school science teachers. Their involvement is of course welcome, but could potentially cloud the influence of the peer mentor.

CONCLUSIONS

This paper profiled the experience at George Mason University of designing and conducting the 1st Annual Popsicle® Stick Bridge Building contest. The experience produced some direct evidence of synthesis in the civil engineering curriculum through the exercising of improvisation and ingenuity at the peer level. The relative benefits of improvisation over strict design were discussed. Evidence to support achievement of ABET outcome 3b related to design of experiments was presented. The task of designing and constructing the bridge testing apparatus in particular demonstrated how student design of experimentation, data collection, and reduction could reinforce the civil engineering curriculum. The CEIE Department at George Mason has future plans to increase the number of and student involvement in these activities. Finally, the role of peer instruction and mentoring was discussed with future plans for measuring its effect.

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