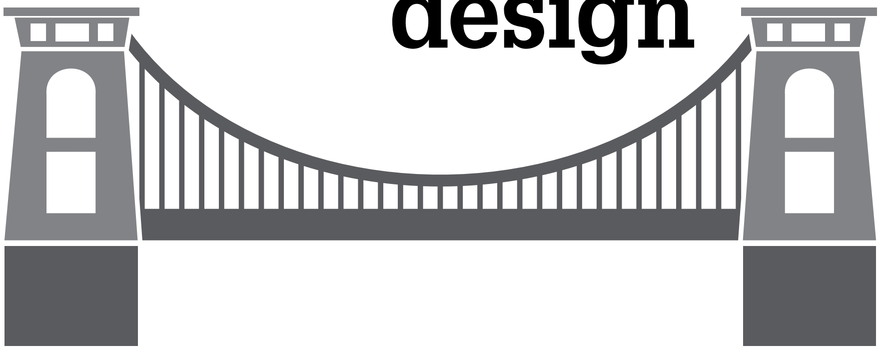
Lukas J. Hefty

Investigating bridge design



Marcus: I think the live load of the bridge is most important, because if you build a bridge and it does not carry enough load, it will fail. We saw that with our first beam bridge.

Patrick: So what you're saying is, you don't know how much weight will be on the bridge until people start driving over it.

Rebecca: I agree that the load is most important. I think location is second, then the span.

Patrick: So what if you know the location and build the bridge, but it stops halfway? If you know the span, and the weather might not be what you expected, it won't be as bad as the bridge not being finished.

The conversation above, regarding a fifth-grade bridge design unit, demonstrates students working in Science and Engineering Practice 7 from the Next Generation Science Standards (NGSS) to engage in argument from evidence (NGSS Lead States 2013). This practice aligns closely with the third of CCSSM's Standards for Mathematical Practice (SMP 3): "Construct viable arguments and critique the reasoning of others" (CCSSI 2010, pp. 6–7). Conversations such as the one above have become commonplace in classrooms that integrate Science, Technology, Engineering, and Mathematics (STEM). Students who study science and mathematics content for the direct purpose of performing science investigations and designing engineering solutions are better prepared to reason and make critical decisions about the data they collect as well as to use specific data to support their reasoning.

In addition to a written report, each team presented its final bridge design to the class, citing evidence that the bridge met or exceeded design criteria.

BRIDGE: ANDJI/THINKSTOCK; PHOTOGRAPH: LUKAS J. HEFTY

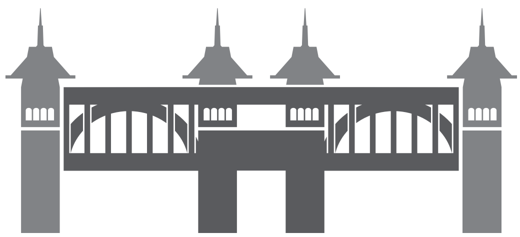
TABLE 1

All the students will have time to develop science and math content knowledge during the four weeks of this investigation, resulting in improved collaboration and bridge quality during the final Bridge Design Challenge.

Lesson	Duration	Lesson focus	Description
1	2 days	Introduction to bridge design	Learn about the job of a civil engineer, bridge types, and how bridge design has changed over time.
2	2 days	Arch bridges—Back to the Romans	Test material strength against tension, compression, and torsion, and study how the Romans developed arch bridges.
3	3 days	Truss supports—Building small design challenge	Investigate how shape affects strength; apply knowledge to a minidesign challenge.
4	3 days	How do beam and suspension bridges compare?	Test and compare the strength of model beam and suspension bridges.
5	3 days	Calculate loads and equilibrium	Identify loads and calculate equilibrium on various bridge diagrams.
6	5 days	Bridge final design challenge	Design a model bridge that meets time, cost, and strength constraints.

The ability to communicate effectively, to analyze data and information, and to think critically about real-world problems has taken on new importance in our rapidly changing society. With the development of practice standards and standards for engineering design, NGSS and CCSSM acknowledge an important shift in the role of the teacher. Teachers making the transition to integrated and student-centered science instruction benefit from sharing resources, and the bridge design unit described below offers one example. The unit was vetted by fifth-grade teachers over a twelve-year span at an engineering and mathematics magnet school in Pinellas County, Florida.

The description provides an overview of the four-week unit, including content knowledge development, investigation and data collection, and use of an engineering design process. It describes the engineering design challenge as an opportunity to develop critical thinking skills while assessing understanding of science and mathematics content.



Building background knowledge

The class is introduced to the Bridge Design Challenge at the start of the unit to pique students' interest and activate prior knowledge. Students are told,

> Your team is a civil engineering company that specializes in building bridges. The Department of Transportation wants your company to submit a proposal for a new bridge in Tampa, Florida. The design must consider such factors as cost, weather, strength, span, and appearance.

FIGURE 1

Students construct simple models to investigate the effect of different supports on bridge strength. They calculate the maximum live load that a beam bridge can hold before failing, then convert the bridge into a suspension bridge and repeat the test.

Group Members: Samantha, Zoey, Malani, Aurorra Date: 11/19/14

What's the Secret of Suspension?

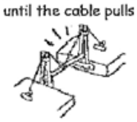
ientists use *models* when they cannot experiment on the real thing (Science Textbook pp.26-27). use model beam and suspension bridges to test the amount of force each can hold.

1. Predict the number of marbles the beam and suspension bridge will hold before failure. Record.

2. Design a simple beam bridge:
Tape one tower to the edge of a desk. Tape the second tower to a second desk of the same height. Position the towers 15 cm apart. Place a straw between the towers so its ends rest on the short pieces. This straw is the bridge deck. Now you have a simple beam bridge.

3. Test the force your beam bridge can hold before failure:
Make a load tester by unfolding a large paper clip into an S-shape. Poke the ends of the paper clip into opposite sides of a Ziploc baggie, near the top. Use a second paper clip to hang the load tester over the bridge deck. Record results in the table below.

Re-design the beam bridge into a suspension bridge:
Tie the center of a 100-cm string around the middle of a new straw. Place the straw between the towers. Pass each end of the cable around the paper clip. Slide the paper clips away from the tower until the cable pulls tight. Tape the paper clips firmly to the desks.



5. Test the force your suspension bridge can hold before failure. Record results in the table below.

	Prediction	Marbles	Force (Spring Scale, N)	Force = Marbles * 0.04 marble + 0.03 bag
Beam	13	13	1 N	.55
Suspension	20	108	5 N	4.35

Why did the suspension bridge hold more force than the beam bridge? The Suspension Bridge can hold more force because of the cables that suspend the bridge, they support more weight than a simple beam deck.

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In nearly every case, students enter the unit with a wide range of background knowledge and understanding of related science concepts. When the challenge is presented in isolation, those with background knowledge engage; others withdraw, detracting from one of the most important elements of engineering design—collaboration. Teaching the unit over a four-week period allows time for the development of science and mathematics content knowledge while providing a platform for contextual application (see **table 1**). The teachers feel that this method improves collaboration and bridge quality during the final Bridge Design Challenge.

Teachers use PBS Building Big: Bridges (http://www.pbs.org/wgbh/buildingbig and the accompanying DVD) to increase student understanding of bridge types, forces that act on bridges, and famous bridges and engineers from around the world. In a series of lessons, students act as human arch bridges, conduct tests on both the strength and shape of various materials, research local weather-related issues that might affect design, and calculate the live and dead loads acting on various bridge diagrams. The class reflects on the findings from each investigation, which leads to deeper understanding of concepts that will improve the final bridge design:

- Why do triangles provide greater stability than squares?
- How will local weather (humidity, thunderstorms, and hurricanes) affect design?
- Which aspects of the bridge structure help it withstand compression, tension, and torsion?

To investigate the effect of different supports on bridge strength, students develop simple model bridges using straws and tape. They calculate the maximum live load held by the beam bridge prior to failure, expressed in Newtons (N), using spring scales and/or a force plate. For example, teams construct a model beam bridge and test it by hanging a zippered plastic bag over the "beam" (a straw) and dropping in one marble (0.04 N) at a time until failure is reached. Students convert the beam bridges into suspension bridges (using string) and repeat the test. Data from each group is combined into a table (see **fig. 1**) that is analyzed and converted into a bar graph.

The design process

The teacher reintroduces the Bridge Design Challenge that students have been eagerly waiting to solve. Three weeks later, every student now has valuable perspectives to share with the team. A simple rubric outlines the Department of Transportation's expectations for the design (see **table 2**), and the classes use the engineering design process below to work methodically toward a solution.

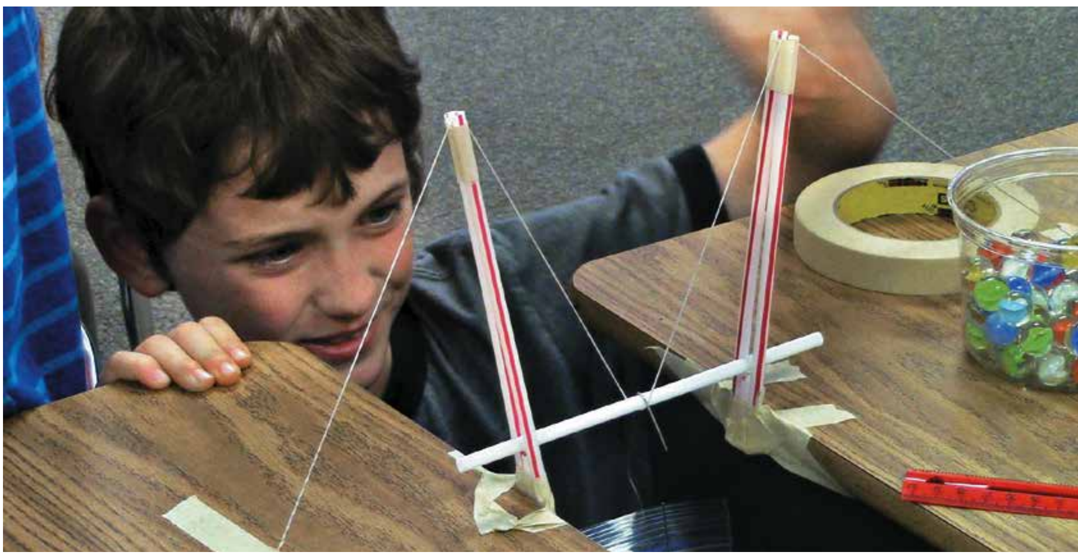
Plan

Students consider the rubric, available materials and costs, and design constraints:

TABLE 2

Three weeks after starting the unit, every student is equipped to meet the Department of Transportation's expectations for the design. Teams will now use the engineering design process to find solutions.

Rubric for final Bridge Design Challenge				
	4	3	2	1
Stability	The shape of the bridge does not change with 5 Newtons of force.	The shape of the bridge does not change with 4 Newtons of force.	The shape of the bridge does not change with 2 Newtons of force.	The shape of the bridge changes with even the slightest force.
Cost	The materials cost less than $5,000.	The materials cost less than $6,000.	The materials cost less than $7,000.	The materials cost less than $8,000.
Appearance	Extremely well-designed, nice looking, clean	Well-designed, nice looking, clean	Somewhat disorganized	Very disorganized
Teamwork	All group members were engaged and had a role that enabled them to complete the task.	All group members were regularly on task.	Group members needed to be refocused. Not all members were engaged.	Group members were often off task. They were not engaged.
Design handout	Detailed descriptions, sketch, budget, calculations, graph	Incorrect or missing details in one section	Incorrect or missing details in multiple sections	Incomplete in multiple sections



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This student is testing his team's model suspension bridge. He hung a zippered plastic bag over the straw beam and dropped one marble at a time into the bag until the bridge failed.

- The model bridge must span 20 cm.
- The bridge must maintain its shape with 5 Newtons of force.
- The total cost should stay below $5000.
- The bridge should be visually appealing.

Each team receives a 6 in. × 24 in. wooden base, with a hole in the center to allow for force testing. This enables the bridges to be elevated and moved. Individually, students write and sketch ideas. This important step allows each team member time to bring ideas to the table and prevents individual members from taking over. Individual ideas are presented and discussed in teams of three to four students. The planning phase often involves argumentation, negotiation, and compromise as students describe specific aspects of their idea and why it should be selected for the final design. For example, one student noted that the “truss (triangle) supports [that are] placed beneath the beam would provide extra stability.”

Another claimed that “a suspension cable would provide stability and look nicer than the truss.”

Most often, the design becomes an amalgam of individual ideas.

Design and check

Each team “purchases” its materials from a “depot” and tracks total cost throughout the design phase. Students are given a sample table that they can use for tracking purposes (see **fig. 2**). Teams check their design against the constraints and make adjustments to their diagram, budget, and model. They test bridge strength using the same method described in the suspension bridge investigation. Each bridge is tested and redesigned multiple times. In general, initial designs fail to withstand 5 Newtons of force, and support structures must be added or changed. Students purchase materials and adjust diagrams and budgets. What is noticeable is the ease and precision with which students perform calculations and measurements. The teachers note that, in general, measurements are taken more carefully, and therefore more accurately, when students work in a real-world context.

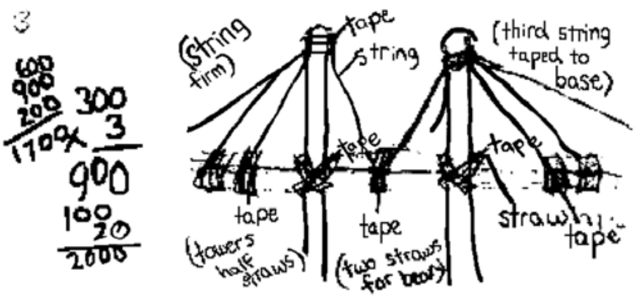
FIGURE 2

After “purchasing” bridge materials, students use a sample table for tracking costs as they design, test, measure, and redesign their bridges.

Material	Cost	Quantity	Item Cost
1 straw	$300	3+1+2+2	2400
10 cm of tape---masking or electric	$100	2+6+2+3	1200
10 cm of string	$200	[illegible]+3	1800
Total cost	x	x	[illegible]

Plan:
Discuss possible types and designs for your bridge with your team. Choose the best design and determine the materials needed. Determine the total cost of the design using the table above.

Include a sketch of your bridge below.



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Share

Each team presents its final bridge design to the class and submits a report to the "Department of Transportation," detailing why it should be selected for the project. The teacher reminds teams to present both orally and in writing the evidence that their bridge meets or exceeds each of the design criteria, along with aspects of the bridge that make it unique. Many of the bridges look very different, using various types of support, but still meet most or all the design criteria. Each team's results and descriptions are analyzed:

- According to the data, which type of bridge support held the most force?
- How would you redesign your bridge?
- Which aspects of bridge design (span, location, strength, appearance) are most important, and why?

The big picture

Teaching the bridge design unit (or a similar STEM unit) for the first time can be overwhelming. Both the amount of material and its content can intimidate many elementary school teachers. Carefully examining the entire unit—especially the culminating design challenge—before beginning to teach is important. Gather all materials in advance, and study the related science and math concepts. The unit is most successful when the teacher and the class understand the big picture from the start. Understanding the direction of the entire unit will enable the teacher to confidently facilitate student learning.

Engineering design is a powerful tool for elementary school teachers that allows for the meaningful application of science and mathematics. Like any tool, it is most effective when it is used properly. Design challenges presented within the framework of a coherent science-mathematics unit will lead to the best results. In this case, the design challenge acts as a performance assessment, enabling teachers to identify whether students can transfer knowledge and skills to a new context. In the bridge design example, teachers assess students' ability to measure length and force with precision, collect and analyze data, and use science content vocabulary appropriately both orally and in a written report.

View a video overview of our school's bridge design unit at http://www.youtube.com/watch?v=ObvcnmdUzoU.

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For the final Bridge Design Challenge, visit **http://www.nctm.org** to access an instructional plan and a student activity sheet. This additional material is a members-only benefit.