Enhanced learning through a “virtual laboratory”

Michael Karweit
Dept. Chemical Engineering, Johns Hopkins University

Abstract:

This work reports on the effectiveness of a “virtual laboratory” for helping students transfer engineering theory to the design and building of a model truss. When students had only a series of lectures in strength of materials, statics, and structures, students were only marginally able to incorporate that knowledge into reasonable designs. But, , by additionally providing students with a graphic-based design tool that allowed them to think in terms of the geometry of the application (www.jhu.edu\virtlab\bridge\truss.htm), the designs improved dramatically. Two educational objectives were achieved with this virtual laboratory: integrating ideas from multiple disciplines; and providing physical insight into a problem that is typically treated through the abstraction of mathematics.

Introduction:

Throughout high school and college, instruction typically consists of classroom lectures and textbook reading assignments with material organized into homogeneous modules—topics, chapters, or units. Questions or problems at ends of chapters are surely to be addressed within the chapter, and almost never from the chapters before. As a result, students are rarely required to develop problem-solving skills that span several topics or disciplines. In fact, they are not even required to completely understand the problems they are assigned. To solve an end-of-chapter problem, many students—without reading the chapter—will thumb through the chapter until they find an equation or formula that seems to fit the problem. Then, they “plug and chug”, i.e., they fill in the known values and algebraically solve for the unknown ones.

Unfortunately, such problems are not at all representative of those found in science and engineering. And, the somewhat-automatic problem-solving technique does not enhance the student’s ability to solve real problems. Yet, success in solving textbook problems can give the student the false sense that he has mastered the material. It is inert knowledge: students know something, but they are unable to use it[1] .

In contrast to classroom instruction, Collins, Brown, and Newman[2] suggest that a much better model for learning is the apprenticeship—years of training under the guidance of a practicing professional. In this environment, students develop skills in the context of applications. students learn not just the “what”, but also the “how” and the “when”, and “under what circumstances.” But such training is not practical in a university setting. The question is: can these elements be integrated into university curricula in a different way.

Engineering educators agree that laboratory and project work can provide some of these elements. Experiments provide hands-on experienced for validating or discovering physical principles; projects provide contexts in which to exercise these principles. These projects should require students to synthesize and apply their theoretical knowledge. Performing experiments and carrying projects are examples of "contextual learning".

But, simply assigning a contextual problem does not ensure that the learning gap will be spanned. How the project is presented and taught can greatly influence the chances for understanding.[3]

This paper examines how one assignment—the designing and building of a spaghetti bridge—essentially failed until a virtual teaching device was introduced. Students simply were not able to transfer the theoretical knowledge contained in mathematical symbolism to a physical application. After the introduction of the "virtual lab", students bridged the gap between theory and practice much more readily. The situation has arisen in a freshman college course *What is Engineering?* In its sixth year, this course covers topics which apply to every branch of engineering: problem-solving, team projects, design, error analysis, and collection and interpretation of data. The course consists of lectures, laboratories, virtual laboratories, and projects[4].

The bridge project: to build a bridge made from spaghetti that weighs no more than 0.75kg, spans a meter, and holds the heaviest load. Although, building a bridge out of spaghetti is clearly a tongue-in-cheek engineering project, the problems incurred in its design and construction are very real, and student competition is keen.

Project Preparation:

Preliminary lectures and laboratory experiments prepare students for this bridge project. This material consists of the following:

1) Lectures on properties and strengths of materials.

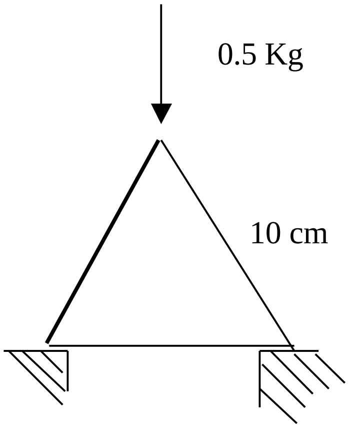
2) A laboratory experiment in which students measure the tensile strength and Euler buckling strength of different diameters of spaghetti.

3) Lectures on statics. Sample problems are presented in two dimensions.
4) Lectures on structures—principally the calculation of forces in trusses.

With respect to the bridge project, two concepts are most important: tensile strength is proportional to cross-sectional area; and the Euler buckling strength is proportional to r^4/L^2, where r is the radius of a solid cylindrical rod (in this case, spaghetti) and L is its unsupported length. When a structural member is in compression, its first mode of bending failure is the Euler mode, so the Euler buckling strength is essentially the strength of a member in compression. Both these concepts were addressed in lecture, and confirmed in lab. In experiments the students measured the tensile strengths of various diameters of spaghetti. They then normalized the data to confirm that cross-sectional is indeed the relevant parameter. Similarly, the students measured the Euler buckling strength, normalized the data with respect to radius and length, and confirmed the r^4/L^2 relationship. These elements constitute the theory.

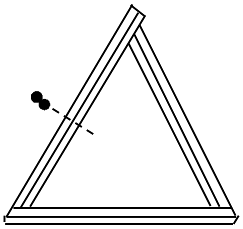
Preliminary Project:

To test their understanding of this material, we asked that the students carry out a simple project: build an equilateral triangular truss out of spaghetti. The truss was to be 10cm on a side and should support a 0.5 kg weight pushing down on its vertex. The goal was to build this truss using the least amount of spaghetti. (5 minute epoxy was to be used to hold things together.) The diagram illustrates the problem.

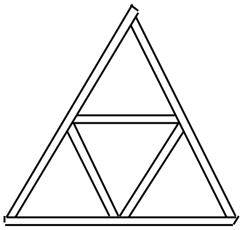


There are two steps to the problem: first to determine the forces in the members. Most students correctly deduced those forces from theory--with a tension force in the horizontal member, and compression forces in the other members. Then, the idea was that students would use the data from their materials experiment to decide how each member should be reinforced. In fact, most students did consult their data, but in a naive way.

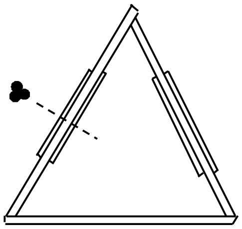
Here are three designs. The first two a) and b) are typical of students' solutions; the third c) is an optimal solution, but one which, in the six years the course has been taught, has never been produced by students.



a)



b)



c)

Solution c) is optimal because it reflects that a single strand of spaghetti has adequate tensile strength to support the tensile load on the horizontal member. And it reflects that additional radius is required to increase the buckling strength in the two compression members. But, the added strength is only necessary where the bending moment is largest, i.e., at the center of the member.

Virtually all the students' trusses were constructed like a) and b). And all failed to hold the design load (except for a few trusses which were significantly overbuilt.) Students recognized that one strand was not sufficient to carry the load in compression. So, they added mid-point supports to reduce the unsupported length; or they attempted to increase the radius—different ways of increasing buckling strength, given that strength is proportional to r^4/L^2.

But they failed to take into consideration buckling in the third dimension. In the first design, the doubling of strands in the compression members improves buckling strength primarily in the plane of the double members; in the second design, the mid-point supports improve buckling strength only in the plane of the truss. But, since example problems given in lecture were restricted to two-dimensions, the students never considered the third dimension in applying the concept. Only by building and testing real trusses did the students begin to appreciate the physical consequences of the theory.

So, the building and testing of the trusses was both a testing and a learning tool. And, it was an efficient learning tool. Calculating the load distributions, developing a design, and constructing the model truss required approximately a two-hour effort. For that effort, the students indelibly learned that blackboard examples are only simplifications of what must be considered in real world applications.

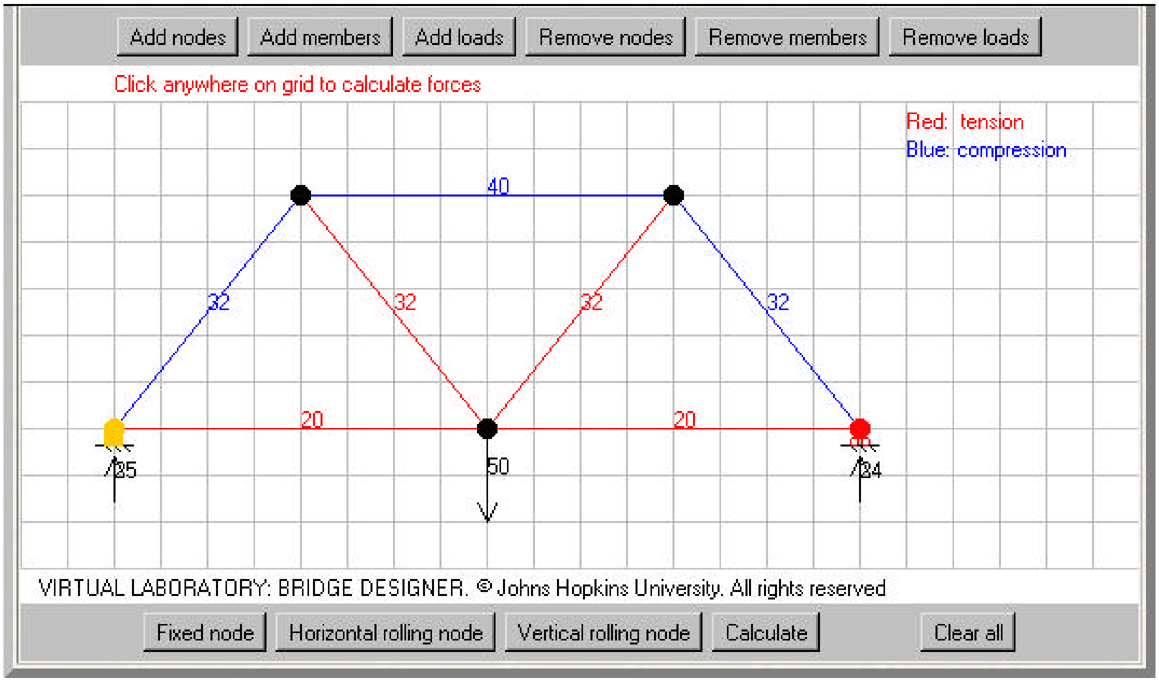
The bridge project:

Having now some experience with these model trusses, the students were then confronted with the bridge project. For the first two years of the course, the student bridges were poorly and inappropriately designed. Rather, than tailor their design to the assigned problem--a truss supporting a load from a fixed point--they produced designs emulating bridges they had seen in real life: suspension bridges, railroad bridges, pre-stressed concrete bridges. That is, the students chose to draw on their life experiences rather than infer a proper design from theory. And, where students developed an almost-correct truss design, they incorrectly deduced which truss elements were in tension and which were in compression. As a result, some of the bridges did not hold their own weight; others held a few kilograms. It was clear that, although the students had been exposed to all the necessary theoretical considerations, their ability to apply this material to a real design problem was very limited. We needed to provide an educational stepping-stone.

One problem was evident: the students were not using the mathematical theory to design their bridges. Carrying out load calculations for complex trusses requires solving systems of algebraic equations—a very time-consuming procedure. And, with each design, an entirely different set of equations is required. Further, since the algebra of the mathematical theory masks the role of geometry in determining stress in the truss members, students could not even produce a reasonable beginning design. What the students needed was an instructional tool that eliminated the need to carry out the calculations, but allowed them to gain insight through visualization.

A virtual laboratory:

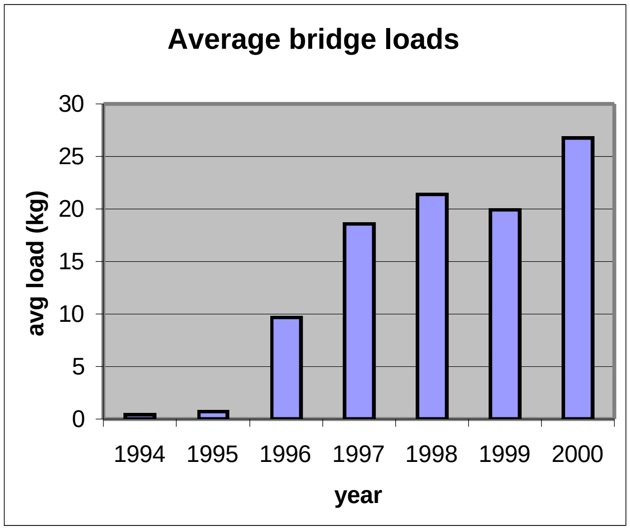
To serve this need, we developed "Bridge designer", a virtual laboratory for exploring the loads on trusses. Written in the programming language JAVA, this truss simulator has a graphic user interface and is accessible on the Web at (www.jhu.edu\virtlab\bridge\truss.htm). It allows a user to generate two-dimensional trusses visually. The user establishes locations for nodes and members, defines supporting points, and prescribes positions for loads--all graphically. The Bridge Designer then carries out all the load calculations for that design and indicates magnitudes and directions of loads in the members. Here is a sample display:


Click anywhere on grid to calculate forces

VIRTUAL LABORATORY: BRIDGE DESIGNER. © Johns Hopkins University. All rights reserved

How are the loads distributed if the bridge is taller? Are there other designs that would have shorter compression members? Would a more complex design lessen loads on each member? Theoretical answers to these questions could be calculated. But with each design, an entirely different set of equations is required. This tool eliminated the mathematical drudgery. Students could now experiment with new different designs to gain insight.

Assessment:



Was this virtual laboratory effective? To address this issue we compare the average load-carrying capacities before and after the introduction of the virtual lab. Presented is a graph of the average number of kilograms that student bridges held for each of the seven years the course *What is Engineering?* has been taught.

The Bridge Designer was first available to students in 1996. Clearly, the simulator had a significant impact on the success of their spaghetti bridge projects. The projects again noticeably improved in the following year. Because, then, not only did students have access to the Bridge Designer, but also they could obtain ideas from the previous year's successful bridges. Since 1997, average bridge loads have been fairly constant. (Note: The record student bridge in this class held 64 kg. Not bad for a spaghetti structure weighing less than 0.75 kg.)

Assessing the effectiveness of instructional methods or tools is often difficult. In many cases, effects cannot easily be identified. But, here, the impact of the efficacy of a virtual laboratory was directly quantifiable in terms of the success of a project.

Why was this virtual lab so effective? First, the computer screen is a natural medium for displaying the problem (at least in two dimensions). It's natural because the distribution of stresses in a truss is geometrically determined. Second, because Bridge Designer has a graphic interface, students could input their design ideas geometrically, not as abstract lists of numbers. Finally, once the geometry of the truss was defined, the program could carry out the necessary load calculations and display them, again, geometrically. Although, lengthy calculations produce the ultimate results, the essence of the problem is spatial. And that is how Bridge Designer was able to present the problem.

Conclusion:

In science and engineering, the language for expressing concepts and theories is usually mathematics. However, mathematics is just an abstraction which represents the actual physical process or principle. And not all students are equally adept at obtaining physical insight from such an abstraction. In this paper, we have shown that when the essence of a problem is spatial or geometric, an interactive graphic simulation is an effective instructional tool for bridging the knowledge gap between mathematical expertise and physical understanding.

Acknowledgements:

This work has been generously supported by the GE Fund through its *Learning Excellence* program.

References:

1. Karweit, N. (1993), *Contextual learning: A review and synthesis.* Baltimore, MD: Center for the Social Organization of Schools, Johns Hopkins University.

2. Collins, A., J. S. Brown, and S. E. Newman (1989), “Cognitive apprenticeship: Teaching the craft of reading, writing, and mathematics. In L. B. Resnick (Ed.*) Knowing, learning, and instruction: Essays in honor of Robert Glaser*. Hillsdale, NJ, Erlbaum.

3. Pierce, Jean W., and Beau Fly Jones (1998), “Problem-Based Learning: Learning and Teaching in the Context of Problems”, *Contextual Teaching and Learning: Preparing Teachers to Enhance Student Success in the WorkPlace and Beyond*, Information Series 376, ERIC clearinghouse on Teaching and Teacher Education, pp 67-98.

4. Karweit, Michael (1997), “A virtual laboratory for beginning scientists/engineers”, proceedings Ed-Media & Ed-Telecom 97, Calgary, Canada.

Biography:

Michael Karweit is Research Professor in Chemical Engineering with primary research interests in fluid mechanics and acoustics. He is also Director of the University’s Instructional Television Facility. His educational interests have focused on technology-enhanced instruction in engineering--in particular,Web-based interactive JAVA applets.