LEGO Engineering: Bringing Engineering to all Students

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Introduction

Where science is understanding the world, engineering is changing that world. Imagine a world without the work of engineers: from air conditioning to indoor plumbing, from the clothes you wear to the internet, from transportation to energy generation. One quickly realizes that almost every aspect of our daily lives have been strongly influenced by the results of engineering, yet most people will graduate from college without ever taking an engineering class. As engineering and STEM (Science, Technology, Mathematics, and Engineering) rise in popularity, we are starting to see engineering standards emerging (for instance the design strand in the United Kingdom, robotics in Australia and Asia, and engineering standards in a handful of American states as well as in the Next Generation Science Standards). As these standards emerge, however, we are faced with a problem. The ability to engineer is difficult to test with a standardized test and we can either change our definition of engineering (having students memorize the steps of the design process and regurgitate them on an exam) or change our definition of testing (have students develop portfolios of their engineering inventions).

Over the last 50 years, researchers have developed a better sense of how people learn. Numerous studies have looked at everything from the role that identity and self-efficacy play in academic success, to include the role that pets play in learning. Researchers have tracked individual students in qualitative case-studies, such as… and looked at the distribution of learning outcomes using thousands of students. In all cases, the research clearly shows that, just like we all have our own tastes in food, we all have our own ways of learning. Like taste, there are commonalities in how we learn (Brown & Cocking, 2000), but we would never expect a group of 20 people to all like the same food; however, we do expect classrooms of 20 students to all learn effectively with a single curriculum and a single shared classroom experience.

Some schools, such as the Expeditionary Learning Schools (http://elschools.org), take advantage of all the different learning styles by placing students with different skill sets into teams to solve authentic problems and to do authentic research. Rather than all students striving for the same "right answer," now teams of students are collaborating to find a "viable answer" and the evidence needed to support their answers. Rather than scaffolding for success, these classrooms promote failure in an effort to maximize the students' creativity and innovation. If students are going to be creative (different), they need to take risks. If they take risks, they need to accept and to welcome failure as an integral part of an eventual success. One of the unique aspects of this learning environment is that eventual success is not necessary, as the learning that happens along the way still makes the endeavour worthwhile. Rather than ensuring that every student comes away with the same knowledge or set of facts, these projects push for distributed expertise, taking advantage of the individual student's strengths, interests, and skills.

This is especially important in enhancing STEM learning where we need to find ways to make STEM disciplines personally relevant, such as through projects that encourage students to investigate and to solve problems in their communities (Rosebery et al, 1992), and to draw upon the resources that already exist within the places they live and the people they live with (Moll & Greenberg, 1992). Other practices that can broaden STEM participation include using materials and examples that are inclusive of underrepresented groups, that include …, informal peer-led learning, and tutorials that

focus less on how to use a specific tool and more on how to use tools to achieve motivating ends (Peckham, 2007). Developing role models who invent and create but come from diverse backgrounds can be a powerful way to broaden the appeal of STEM (Gilbert, 2006). Creating opportunities for peer role models and for community engagement in learning may be a way to increase the diversity of role models available for students in STEM, overcoming the limitations imposed by the formal role modelling (professor to student) at most universities.

Figure 1: Three Teaching Modes.

Interestingly, one of the great remaining bastions of what Sir Ken Robinson (Robinson, 2006) calls industrial age education (student comes in, gets imprinted with knowledge, and gets spat out) is the home of much of this research: the university. Lectures to hundreds of students are commonplace in almost every university. Laboratory exercises that require the students to follow a recipe rather than thinking on their own are common in the first few years of college. The rising trend toward including more online courses increases class size from hundreds to thousands. What if we could change that? What if the first few years could be a place where students have the ability to create, to fail, to learn from each other, and to be exposed to different cultures and backgrounds in and out of the classroom?

What is the goal of teaching?

When we teach, our goal is to take a story or understanding we have in our head and move it into the heads of the students. We can do this (Figure 1) by *telling* the students our story (a lecture), by *showing* the students our story (e.g. labs, demonstrations), and by *enabling* students to grapple with the idea and develop their own story that will eventually align with ours through argumentation (open-ended research and problem solving). I believe that excellent teachers are those who can individually balance these three learning methods for their students, knowing when to let the students flounder and fail and when to give them support and structure in order to build that story in their students' heads. At college, we tend to do a lot of "tell and show" before "enable." At the graduate level, the "enable piece" drives the bulk of the student learning. If one examines the literature on science education, one sees an increasing emphasis on teachers as listeners and enablers, eliciting student thinking (Hammer, 2006). I believe that the humanities are ahead of the sciences in this area, with students allowed to have opinions and encouraged to find evidence to support their opinions in writing, debate, or in-class discussions. Often in the sciences, teachers do not allow students to have opinions, but rather promote students memorizing the opinions of other scientists, with the goal of students "knowing the right answer" outweighing the goal of "thinking like a scientist."

What are the characteristics of an engineering class?

There are a number of attributes that demonstrate that students are actively "thinking like an engineer." I have identified a few that seem to be consistent across classes. They include:

- *Problem Framing* - Students interact with clients to decide on needs and constraints, to identify their own problems, and to use science and mathematics to help predict a successful path before building.

- *Failure, Iteration, and Resilience* - Students realize the limitations of their first solution and change their solution accordingly.
- *Solution Diversity* - Instead of the familiar "right answer," a good engineering problem is one where everyone's answer is different, as is their process they used to arrive at that solution.
- *Distributed Expertise* - Rather than every student learning the same thing, students within a team choose different aspects of the problem to gain expertise (e.g. programming, user interface, fabrication).

In all these cases, the students are working in teams, resulting in extensive peer-instruction and peer-critiques. Both of these peer techniques have been successfully used even with large classes (Lasry, 2008), with the students thinking more deeply about the knowledge when they have to argue with their peers. From a design point-of-view, the best engineering teams have a diverse skill set.

Research Efforts at the Tufts Center for Engineering Education and Outreach

We have had a number of research directions at the Center, from looking at teacher self-efficacy in engineering pedagogy to the role of race and culture in learning science. There is a full listing of all the work at www.ceeo.tufts.edu. Rogers (2012) and Danahy et al. (Danahy, 2014) give an overview of all of the LEGO Mindstorms work we have done and some of the findings. The two research projects I want to highlight here are: (1) integrating science and engineering; and (2) integrating literacy and engineering.

Figure 2: Sample musical drums.

We recently completed a five year, National Science Federation (NSF)-funded research effort aimed at looking at science content knowledge and how learning changed when the science content was embedded in an engineering activity. In particular, we looked at 12 teachers's science classes, having them teach one year with their traditional methodology and the other with a LEGO-based design problem. We found that the students in the engineering-based class scored statistically higher on a science content knowledge class, but both classes scored equally on attitudinal surveys. This result was somewhat unexpected because many thought that the engineering component would provide motivation and excitement (attitudinal shifts) but not necessarily improvements in content knowledge. The design problems were broken into four different units: the animal unit, the properties of materials unit, the simple machines unit, and the sound unit. All of these units came as part of a complete curriculum and can be downloaded at ***legoengineering.com*** (Wendell and Rogers, 2013). Figure 2 shows some of the student inventions using balloons as drum skins and LEGO beams as support material.

The second project I wanted to highlight is one that is still ongoing - Novel Engineering <***www.novelengineering.org***>. The idea behind Novel Engineering is that students read novels and identify engineering problems in the books to solve. Books provide complex, rich problems with characters that have needs, attitudes, and abilities. Students think about the characters as clients. Figure 3 is a snippet taken from the video data of two boys designing a periscope as part of a solution

to a problem in "From the Mixed Up Files of Mrs. Basil E. Frankweiler" by E. L. Konigsburg. It is interesting to watch how the book causes various constraints on their invention (Would they have wood? Where will they get the money to pay for it?).

Figure 3: Engineering from a book.

The research on this project has focused on the beginnings of engineering in children's thinking (Portsmore 2013; Watkins et al, 2014; Milto et al, in press), as well as on student resources for learning in science (Hammer, 2000). While there have been some difficulties with teachers pushing for a given solution (rather than the student's solution) and with students using "magic" as an engineering tool ("… this button will make the robot cook for you…"), for the most part we have found Novel Engineering very effective at promoting open-ended engineering in the classroom. Teachers are confident in their ability to teach reading and see this as a constructive way to have the students critically think about what they have read. Students get excited to create and to invent and we incorporate engineering into the classroom curriculum.

Conclusion

In conclusion, every country, it seems, is looking at STEM education (or STEAM education if you add the arts) as a way to improve their future economy. Engineering is naturally a project-based subject that includes a diverse set of skills (from art to analysis to accounting), promotes creativity, and student-led learning. If we can embrace it in that way, promoting failure and iteration, promoting solution diversity, and promoting distributed expertise across the classroom, I believe we will see large strides in improving engineering literacy.

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About the Author

Chris Rogers got all three of his degrees at Stanford University, where he worked with John Eaton on his thesis looking at particle motion in a boundary layer flow. From Stanford, he went to Tufts as a faculty member, where he has been for the last million years, with a few exceptions. His first sabbatical was spent at Harvard and a local kindergarten looking at methods of teaching engineering. He spent half a year in New Zealand on a Fulbright Scholarship looking at 3D reconstruction of flame fronts to estimate heat fluxes. In 2002-3 he was at Princeton as the Kenan Professor of Distinguished Teaching where he played with underwater robots, wind tunnels, and LEGO bricks. In 2006-7, he spent the year at ETH in Zurich playing with very small robots and measuring the lift force on a fruit fly. He received the 2003 NSF Director's Distinguished Teaching Scholar Award for excellence in both teaching and research. Chris is involved in several different research areas: particle-laden flows (a continuation of his thesis), tele-robotics and controls, slurry flows in chemical-mechanical planarization, the engineering of musical instruments, measuring flame shapes of couch fires, measuring fruit-fly locomotion, and in elementary school engineering education. His work has been funded by numerous government organizations and corporations, including the NSF, NASA, Intel, Boeing, Cabot, Steinway, Selmer, National Instruments, Raytheon, Fulbright, and the LEGO Corporation. His work in particle-laden flows led to the opportunity to fly aboard the NASA 0g experimental aircraft. He has flown over 700 parabolas without getting sick. Chris also has a strong commitment to teaching, and at Tufts has started a number of new directions, including learning robotics with LEGO bricks and learning manufacturing by building musical instruments. He was awarded the Carnegie Professor of the Year in Massachusetts in 1998 and is currently the director of the Center for Engineering Education Outreach (www.ceeo.tufts.edu). His teaching work extends to the elementary school, where he talks with over 1000 teachers around the world every year on ways of bringing engineering into the younger grades. He has worked with LEGO to develop ROBOLAB, a robotic approach to learning science and math. ROBOLAB has already gone into over 50,000 schools worldwide and has been translated into 15 languages. He has been invited to speak on engineering education in: Singapore; Hong Kong; Australia; New Zealand; Denmark; Sweden; Norway; Luxembourg; Switzerland; the UK; France; and in the US. He works in various classrooms once a week, although he has been banned from recess for making too much noise.

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