Engineering in Kindergarten: How Schools Are Changing

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A number of speakers on education reform start a talk with a slide of a classroom in the late 1800's and point out that the classroom has changed little and then go on to describe how our education system "is broken," how our teachers are unmotivated, and that our students are failing. However, in my 20 years of working with schools, I have been impressed at the change that is happening in schools; students are excited to learn and teachers are innovating in their classrooms. I do not think today's classrooms look like (or imitate) those of a century ago. I have seen students build plastic worlds with LEGO bricks, measure temperature changes with digital probes, predict and then plot data sets on a computer, research online through a tablet, use social networks like Edmodo.com to share ideas and discuss mental models, program robots to solve challenges or measure data, make stop action movies to argue an idea, and use video and audio recording to learn, validate, and reflect on their knowledge. None of these were in my elementary school classrooms and were not even a dream in the classroom in those old photographs.

My personal quest has been in promoting engineering literacy for all students at all grade levels. When a friend (Ioannis Miaoulis) and I started the quest 20 years ago, we were met with skepticism when we told teachers we wanted kindergartners to engineer. Engineering was not even offered in high schools, let alone middle and elementary schools. No child, it was thought, had sufficient science and math knowledge to "do engineering." Luckily, Ioannis and I were young, naive, and enthusiastic - and soon we found that providing students with open-ended design problems and reverse-engineering problems not only motivated them to ask insightful questions about the science, but also had them actively pursuing knowledge in almost every discipline. Some of those same teachers came back a year or two later with excellent examples of student engineering.

I believe that the work done in engineering classrooms should be characterized by a large diversity of student solutions to the problem, often leading to distributed expertise across the classroom (Jonassen, 1997). Unlike the traditional worksheet where there is an answer key and everyone is pushing to get the same "right answer," in an engineering classroom, everyone's solution is different and therefore peer learning (which is often labeled "cheating" in the worksheet case) becomes a powerful pedagogical tool, as students look to each other for advice and expertise. As a result, engineering classrooms see increased argumentation as students validate and defend their ideas to each other (similar to the peer tutoring and peer assessment research) (Topping, 1988). Students learn to be skeptical and to question. In this way, the classroom is more like an English classroom, where students have differing opinions about the literature that they need to support with evidence from the text, than a typical science classroom, where opinions are not always welcome (which is a whole different problem that needs to be addressed) (Hammer & VanZee, 2006).

Engineering classrooms are also characterized by repeated failure, resilience, and eventual success. If one wants to promote creativity and innovation, one must promote risk-taking and, as a result, one must expect failure. If there is no failure, then there are no risks. Students learn how to fail, how to gain expertise as a result of that failure, and how to become more adept at identifying potential failure early on in the project. The power of math and science knowledge often shows up as the ability of the students to predict an outcome of a given design choice, and therefore predict success or failure long before any fabrication has happened. One recent study documented an approach called "productive failure" that shows impressive mathematics gains for middle school students who engage in challenging problems that foster failing (Kapur & Bielaczyc, 2012).

The engineering classroom is substantially different from the traditional classroom (and the one in those pictures of the past), where students are rewarded only for successes and for getting the answer the teacher has already worked out. Instead, we are asking the teacher to promote failure and solution diversity, to teach students how to balance constraints, and to support their decisions. In the last 20 years, I have met teachers around the world that have done this very effectively with a number of different tools and technologies. Because of my long collaboration with LEGO Education, most of the ones I will talk about here were using the LEGO Mindstorms robotics product, but there are also great examples with digital probes, multi- media, stop-action animation, and social media that I won't cover.

Since the introduction of the first LEGO Mindstorms Robotics set in the late 90's, a number of us at the Center for Engineering Education and Outreach (CEEO) at Tufts University have been working with LEGO Education to develop software, activities, and teacher professional development to promote engineering in the classroom (Lego Mindstorms). The Center's mission is to promote engineering literacy for all students and employs graduate students in education (examining student learning), graduate students in engineering (developing new hardware and software products based on the education research), and outreach to classrooms to complete the feedback loop between practitioner, researcher, and inventor (Tufts University). My personal involvement started with the development of ROBOLAB (a software package using the LabVIEW engine from National Instruments). Our goal was to work with LEGO Education and National Instruments to produce a software environment that was easy to use (low barriers to entry) and very capable (high ceiling), with many different points of entry (wide walls) (Resnick & Silverman). As ROBOLAB entered classrooms around the world (eventually in 15 different languages), I had the opportunity to meet many different, and innovative teachers. I thought I would tell a few of my favorite stories as a demonstration of how the classroom has changed. For those interested in similar research studies, references are available from the author upon request.

Rachel taught third grade math with LEGO robots. In an effort to teach graphing, she posed the following question to her students: build a robot that drives, measure how far it goes in 1 second, 2 seconds, etc., and build up a plot of time versus distance (calibrate your car). Making the graph was interesting in that many students needed to learn how to measure, and if asked to take the measurement multiple times, would often measure from a different starting point. After much teamwork and discussion, all groups had a calibration plot. Rachel then asked the kids to program their cars to go exactly 12 centimeters - but they were not allowed to test them. All cars were lined up, a LEGO minifigure was placed 12 centimeters in front of the car, and everyone hit "run". The team whose car came closest to just "kissing" their mini-figure without knocking it down won. Because every car was different, there was typically a fair amount of discussion between the students on the relative merits of the design. A group of New Zealand students doing the same exercise figured that if their car stopped the other cars, then they would win. Another group decided to build a hood in the front of their car that was just higher than the mini-figure - so that even if their calibration had some inaccuracies, the hood would be just above the mini-figure, and therefore they would win. This problem can be made more complex by giving students a photograph of two lines outside with a LEGO car on the lines instead of telling them 12 centimeters. They will have to use their measuring skills and scaling arguments to deduce the distance between the two lines and again visit their calibration plots to determine the appropriate time. All students then go outside and put their LEGO vehicles on one of the lines and see who comes closest to the second line.

Terry taught first grade and had students build LEGO vehicles that drove across a carpet with the map of the solar system. She then asked them to make their "spaceship" fly from Earth to Mars by driving across the carpet, thereby introducing her students to fractions. Because cars were built differently, the appropriate number of seconds varied from car to car. The exercise brought up some interesting discussions, when students argued about the difference of 1.5 and 1.50 and wondered (since 5 < 50) why the two cars went the same distance. Terry capitalized on these opportunities for the students to think about the role of the zero after the decimal point.

In a fourth grade classroom, Linda was teaching her students about ancient Egypt and wanted to promote the notion of robotic exploration while still teaching math. So she used tape to draw a large letter on the floor and then covered the letter with her desk (and a sheet draped over the desk). The students could not see the letter, but their robots could drive over the letter with a light sensor pointing downward and return with a graph of light sensor reading with time. From that graph, the students could guess the letter after 3 - 4 passes (in different directions), and learning how to form a conclusion from multiple data sets along the way. One innovative team drove their car across the diagonals of the letter and were still able to identify the letter.

David's fifth grade class decided to design and construct a LEGO town completely off the grid. After deciding what they needed in a city (including public transit and water reclamation as well as electrical power), the class split into groups, with one group becoming the solar experts, another the wind experts and so on. In the end, they had a town with a shopping mall (with LED lighting as suggested by the lighting experts), a public transportation system and a sewer system. Further, the town was completely powered by LEGO solar collectors, LEGO wind turbines, and rechargeable batteries. Each of these power systems were designed, built, and analyzed by the respective student teams.

Deniro's middle school class in Japan had the students develop the activities for the next year's class, complete with educational videos, instructions, and challenges. As a result, students mastered the concepts through deciding how best to teach it. Monika's middle school class in Switzerland decided that they should be able to cook hamburgers with LEGO robotics and built an automated system that took the burger off the grill, added pickles, lettuce, and a bun (Hamburger). In this case, the construction was completely student-led, as the students were the ones that originally approached the teacher about building the device. Rob's high school class in Tasmania, Australia built the arcade part of a fairground and Ethan's college class in Boston built LEGO controlled puppets and marionettes. In all cases, the goals of the class were to teach student teams how to invent, design, test, assess, and present their work.

Barbara incorporates engineering into her eighth grade physics class by having students build and construct their own science experiments, as outlined in her books (Bratzel, 2009). She also led a group of fourth graders in an investigation that sent marshmallow Peeps to 90,000 feet with a weather balloon, with a LEGO robot measuring Peep size, air temperature and air pressure along way. Bill's high school physics class in New Hampshire also uses robotics to investigate physics (Church, Ford, & Perova, 2009). He engages the entire class in large authentic projects like one where students designed and built an automated system to heat the sidewalks in the winter. He has also started a student volunteer program where high school students volunteer in the local middle school to help younger kids learn about robotics.

Claude has spent many years working with high school students in Luxembourg and together they have designed everything from robots that follow your voice to a system that takes your picture, reduces it to a number of lines, and then controls a LEGO-based pen plotter that draws it out. They have built up an impressive website that includes driving a Mars rover remotely and a number of hints for those wanting to push the limits of the Mindstorms kits (Robotics Workshop). What has impressed me the most with this group is the total belief that nothing is too difficult to accomplish and, as a result, the amount of math, science, and engineering they learn along the way. Sound localization, for instance, had these high school students learning about cross-correlations and building a system that used two microphones and a PIC processor to perform the correlations.

There are many more great examples, from LEGO-driven science investigations in Norway to robotic zoo animals at the Rhode Island School of the Future to musical instruments made from LEGO bricks here at Tufts (Rhode Island, 2012). A high school teacher in Switzerland had his students build robots that paint; another had his students automatically mix drinks (non-alcoholic of course). What stands out across all of these classrooms is the student enthusiasm to learn, the quality of student questions, the diversity in the solutions, and the high failure rate. What also stands out is that these teachers had the freedom to innovate in their classrooms and that they were allowed to be creative and take a risk by bringing in a new form of education. Finally, whether the teacher is from a special education school, a gifted school, or a small one-room schoolhouse, the one remark I hear over and over again is the story about the student who went from being the class problem to the class star. Engineering got these students excited to learn, to help their peers, and to change their learning and social habits.

In conclusion, we have come far from when Ioannis and I had 40 elementary school students throwing paper airplanes in the gym. Engineering in the K-12 classroom is now a national topic of conversation on the state standards in many US states and on national standards in other countries (National Academy, 2009; Carr, Bennett, & Strobel, 2012). Research is emerging in curriculum design, students' engineering skills, and teachers teaching engineering (Sadler, Coyle, & Schwartz, 2000; Puntambekar & Kolodner, 2005; Portsmore & Brizuela, 2011; McCormick & Hynes, 2012; Capobianco, Diefes-Dux, Mena, & Weller, 2011; McRobbie, Ginns, & Stein, 2000; Hynes, 2010). Schools like the Rulang Primary School in Singapore have included creativity and innovation as one of their six strategic thrusts, with engineering and robotics being their vehicle for teaching innovation (Strategic Trust). Kindergarten engineering is no longer something that is met with disbelief, and there are graduate students around the world looking at student learning as a result of solving open-ended, authentic problems. It will be exciting to see what the next two decades bring in changing the classroom from that photograph in the late 1800's, to a dynamic, student-driven, authentic, team-based learning experience.

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