"Powerful Play: Using Toys as Tools in Engineering Education"

Abstract

As engineering education has changed to reflect less of a traditional teacher-centered classroom and more of a learner-centered environment, new instructional methodologies have also evolved. Many of these curricular modifications look startlingly different from traditional engineering education at first glance; however, a closer look reveals that some curricular modifications are able to glean the substance of the traditional lecture, mix it up with some learner-based, collaborative, hands-on activities, and integrate the new mandates for technical communication and presentation skills into existing engineering content. More and more frequently, toys are used as cognitive learning tools and manipulative models to aid students in grasping these new skills.

But what do these toy-based modifications actually mean to students? Do toys in the classroom actually impact student learning? Our research presents examples of specific innovative curricular modifications ranging from elementary school classrooms to higher education classrooms with one shared finding: toys can be used successfully as teaching tools in this new era of engineering education. We offer examples from all levels of instruction with assessment instruments, pedagogical rationales, and templates for integrating "toys as tools" into existing engineering courses.

"Powerful Play: Using Toys as Tools in Engineering Education"

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Introduction:

As engineering educators, how many times do we tell our students that as practicing engineers, they will have to continually adapt themselves and their skills to changes in their profession in order to meet client and industry demands? In most ABET-conscious engineering schools, this is a familiar and well-justified refrain if we expect our students to stay employed. Yet what about the other side of the coin? How often do we tell each other that in addition to keeping up with changes in engineering content, we should also challenge ourselves to adapt our curricular approaches to meet the learning needs of our students?

This paper seeks to persuade engineering educators that adaptation and innovation are integral components of successful engineering programs, and our approach is a fun one: we use toys teamed with teaching techniques to supplement and solidify engineering content for multiple levels of learning. First, we present the pedagogical rationale for integrating toys in the classroom into existing engineering courses because research in educational psychology and learning styles supports innovative and "hands-on" learning environments[1,4,5,6]. Next, we provide evidence that this approach has worked not only in our own institutions, but in other institutions. We conclude with templates of curricular exercises and assessment instruments from our programs that can be customized to other programs

Pedagogical background:

The field of educational research and psychology provides a rich source for learning theory in application. The essential purpose for integrating toys in the classroom into existing engineering courses is to build upon constructivism, a well-founded educational pedagogy that encourages authentic learning. The constructivist approach is a theory of knowledge acquisition that originates from the work of Piaget[1] and Vygotsky[2] who are considered to be two of the most prominent theorists in developmental psychology. Piaget was opposed to teaching methods where learners are treated as passive receptacles. He emphasized that learners who are active and seek solutions for themselves, learn best and they do this by making discoveries, reflecting upon them, and discussing them.

This is in sharp contrast to traditional teaching methods where students "learn" by imitating the teacher or by sheer memory work. Vygotsky's contribution to constructivism is based upon his theory that thought development is determined by language. He believed that language/speech, which later becomes internalized thought, involves the agency of other people and is mediated by community and culture. Consequently, the emphasis in learning is on the use of communication where students construct knowledge based on interactions with others.

But how does constructivism apply to engineering education? Within the constructs of engineering education, constructivism supports learning activities that are relevant and engaging, where learners become active participants in problem-solving and critical thinking. Constructivism in engineering classrooms encourages learners to test ideas and approaches based on prior knowledge and experience, then apply the knowledge to new situations; in doing so, they integrate new knowledge gained with pre-existing, intellectual constructs.

An examination of constructivism from an ABET perspective reveals similarities between ABET's "A-K" guidelines for designing engineering curriculum and the goals and objectives of constructivism[3,11]. Importantly, the similarities lend credence to inclusion of both constructivist-based instructional approaches and the use of toys in the classroom as teaching tools. Constructivism affirms that knowledge acquisition occurs amid four assumptions: learning involves active cognitive processing; learning is adaptive; learning is subjective, not objective; and, learning involves both social/cultural and individual processes.[3] Clearly, three of these assumptions (1,2,4) mirror statements found in ABET'S "A-K" as they encourage a more active and student-centered method of engineering education. Other pedagogical similarities are shared in a review of the following five of eight factors essential in constructivist pedagogy:

1. Learning should take place in authentic and real-world environments.
   - ABET guidelines also promote authentically-based engineering projects
   - Toys allow learners touch, feel, and manipulate models of real world-applications

2. Learning should involve social negotiation and mediation.
   - This supports and extends ABET guidelines by letting students work in groups with toys as the shared manipulative for learning

3. Content and skills should be made relevant to the learner.
   - Example: Use a toy to demonstrate fundamental properties of the content in a way a student can easily remember. See "Airplane Exercise" in Appendix.

4. Content and skills should be understood within the framework of the learner's prior knowledge.
   - Link #3's exercise to the student's other subjects by asking questions that encourage critical thinking: Example from airplane exercise: how does this exercise relate to math/science/engineering?

5. Students should be assessed formatively, serving to inform future learning experiences
   - This is more of a curricular planning issue, but it basically supports the idea of taking grades throughout the semester based on actual "hands-on" content knowledge in order to give students some idea of their own levels of learning before a major grading event (midterm, final exam, etc.)

6. Students should be encouraged to become self-regulatory, self-mediated, and self-aware.

7. Teachers serve primarily as guides and facilitators of learning, not instructors.

8. Teachers should provide for and encourage multiple perspectives and representations of content.

With the constructivist emphasis in mind, using toys as tools in engineering education can impact student learning. It is a natural vehicle for integrating technical communication and presentation skills into a traditional curriculum that builds upon student-centered learning and encourages students to engage in real-world experiences.

Examples from Existing Programs

The research reveals that constructivism is a popular and successful method of instructional pedagogy in theory, but our interests in this research concern how to integrate this type of instruction into existing engineering courses. Our answer is an unusual, but fun, one: Use toys in the classroom. Recent research in engineering education demonstrates that using toys as tools in engineering education is not a new concept, and because it's not new, there are many successful ongoing programs to provide other engineering educators with ideas. The following excerpts summarize several existing programs ranging from elementary introductory-level situations to graduate school modeling situations.

Example 1: Toys as Tools in Elementary Settings to Demonstrate Engineering Concepts

Where should engineering instruction start? Why not K-12? As Iowa State's "Toying with Technology Program" reports, elementary school is an ideal place to introduce concepts of engineering. Why? Because children are "natural engineers": give them some materials and many times, they start to build.(2) This interesting example is the partnership between Iowa State's Engineering Department and Education Department's joint program named "Toying with Technology"[2]. This program links engineering with elementary and secondary education majors with the primary goal of reinforcing positive attitudes in the prospective teachers which may transfer to their elementary and secondary level students. Students construct simple systems from inexpensive LEGOs and then model real world applications including elevators and garage door openers[2].

The National Science Foundation funded a grant to extend Iowa State's "Toying with Technology" to the widest possible audience, resulting in additional opportunities to integrate toys in the classroom. One example is a project involving eggs and LEGOs: students are instructed to design a LEGO structure that will transport a raw egg from a tabletop to a floor surface without breaking the egg[2,3]. The basic principle here is for the engineering participants to teach the theory to the education students, and then they work together as mentors in supervising K-12 field experiments in classrooms throughout the area.

Genalo et al also describe a project using the more expensive LEGO Mindstorm kits and "Not Quite C" programming to introduce concepts of time, distance, and speed to students beginning in grade 3 as an extension of the intradisciplinary success of the "Toying with

Technology" program. (Specific instructions for these activities are available at their website: http://class.ee.iastate.edu/twt.)[2]

Each of the examples described adheres to the constructs of constructivist learning environments where students continue to add new knowledge to previously-known knowledge, and in doing so, they learn through play.

Example 2: Toys as Tool in Middle-School Situations

The Joy of Engineering Program at The University of Memphis began in 1999, and is offered as a one-week optional summer school program for 5-8th grade students. This program is unique because it involves multidisciplinary college faculty as instructors teaching both middle school students and middle school/high school teachers. Students may select from three different courses: structures, energy and motion, or robotics. Classes are limited to 16 students, and each class also includes 2-4 middle-school/high-school teacher participants. Like the Iowa program described above, the objective is to motivate these teachers to use toys in their own classrooms in science/math/engineering applications, and to serve as teacher-mentors for other teachers in their schools and communities. To further facilitate these goals, all teacher participants receive a complete set of "toys" in the form of K'NEX sets and Lego's RoboLab sets to take back to their own schools for use in their own classrooms. In all of the programs offered within the Joy of Engineering framework, the students and teachers are given task/goal-oriented projects which allow experimentation and analysis.

Another interesting approach in the Joy of Engineering Program is the inclusion of "low-tech" toys paired with multidisciplinary approaches to reinforcing concepts. An example of one such activity is the paper airplane exercise. Students are instructed to work in small teams to design and test paper airplanes for a class-wide competition. The utilization of a paper airplane places the students in an environment where they believe that they already have some expertise. They are provided 5 pieces of standard paper per group, a stopwatch, and notebooks for recording data, and all teams are given 20 minutes for design, testing, and analysis before the final competition. A simple set of design constraints are provided and the metric by which a most successful design will be selected is provided. The metric provides a multi-parameter optimization and allows the students to decide on trade-offs in selecting their competition design. This relatively inexpensive exercise taps into active learning theories by giving students hands-on experience scaffolded by visually-based experiments: again, students play with toys, and in doing so, they learn new concepts.

In addition to the inexpensive "low-tech" toys, the Joy of Engineering Program also makes use of other classroom toys in teaching engineering concepts. K'NEX building systems, a commonly available toy, are used as design tools in Structures segment to supplement traditional instruction, and throughout the week, students use the K'NEX systems to design and test different types of bridges. Following the constructivist approach of building on previous knowledge, each concept expands a previous one, and the K'NEX toys work as visual representations to aid the students' learning. For example, students begin by learning basic information about different types of bridges: beam bridges, arch bridges, and truss bridges. Then the concepts of stress and strain are introduced and modeled as the students use their own bridge designs to pinpoint areas of stress, strain, and tension when a load is applied. Finally, the issue of cost is introduced as unit prices are provided for specific K'NEX pieces. The week concludes with the final team competition where the students are instructed to build a bridge integrating the week's content by following specific design criteria that will have the highest strength-to-weight ratio (SWR).

The Energy and Motion course content is supplemented with the K'NEX Speed Racer sets. The week begins with the introduction of the concepts of distance traveled and energy/work input into the system, and students are instructed to use the kits to build a car that will travel the maximum distance with the same amount of energy applied. The variable of stability is integrated next and then the students are introduced to velocity and asked to design a vehicle that will travel a straight course of a fixed distance in the shortest period of time. Students are required to collect data from their design tests and this data is used to introduce design analysis. The week culminates with a team-based competition where cost is also introduced as a design constraint to design and build a car that will complete the design course at the lowest cost.

Example 3: Utilization of Toys in the Civil Engineering Classroom

Doug Schmucker, a Civil Engineering Professor at Valparaiso University, uses toys in undergraduate civil engineering courses. Schmucker developed and implemented a Structural Engineering Toolkit to be utilized for projects both in and out of the classroom[12]. Similar to the Joy of Engineering program, Schmucker uses a toolkit composed of rods and connectors obtained from the children's toy manufacturer K'NEX12. The toolkit is specifically designed for authentic modeling activities in the classroom and supplements classical teaching techniques, yet the toolkit can be customized for targeted activities. Other toys such as sponge beams and Wacky Fun Noodles™ demonstrate structural behavior[12]. Relevant courses range from freshman-level Statics to senior-level Technical elective courses.

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Figure 1: Structural Engineering Toolkit

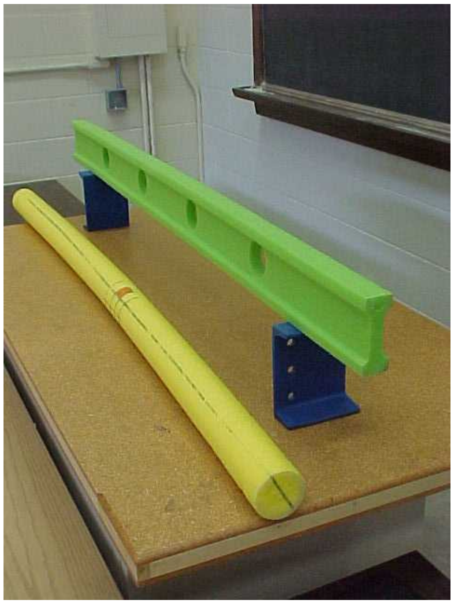

Figure 2: Wacky Fun Noodles™

Another interesting and economical example in a civil engineering classroom involves the use of manila folders[13]. Via this hands-on project, sophomore statistics students use manila file folder material to design and test truss-style bridges. The project requires: experimental testing, data reduction analysis, Monte Carlo simulation, structural analysis and design, construction, and risk and decision analysis. The project is novel not only in its use of an advanced structural reliability application at an undergraduate level, but also in that evaluation reflects real-world engineering constraints and criteria such as site location, budget, building code, and construction processes. In addition to integrating design activities into what is typically an analysis type of course, the project allows students to use basic engineering content knowledge as a foundation for integration of statistics and probability.

Figure 3: Bowstring Deck Truss made of Manila File Folder[13]

Integrating Toys into Traditional Engineering Content: A Template

Using toys as tools in teaching engineering concepts requires three basic components: introduce your topic, use toys as models to illustrate and expand your topic, and then assess for comprehension.

Paper Plane Exercise

Part 1: Introduce the topic: variables such as time and distance related to engineering design.

Part 2: Use the toys as tools
Materials Needed: groups of 3-4 students, lots of plain paper for plane design, a calculator, and a stopwatch.

Instructions:

1. **Explain the criteria for the airplane contest:**
    - **Design a paper air plane that will stay in the air for the longest amount of time**
    - **Use only one sheet of paper for the plane; no additional materials may be used**
    - **All planes must be named and labeled for testing purposes**
    - **Explain the time periods: 20 minutes for design and testing; 5 minutes to construct and label the final design.**
2. **Each group sends one student to the test field with the final design—the designs are tested from a set position, and the time-in-air data is recorded by the rest of the group.**

Part 3: Assess Comprehension

Writing Questions:

- **How does designing a paper airplane have anything to do with math?**
- **How did your group work together in the design process?**
- **What did you learn from the competition that you can use again in the future?**

Figure 4. Template for customization

This exercise represents a simple example relevant for audiences of all levels of experience. We have used it successfully with 5-8th grade students and college freshmen with high levels of satisfaction. What's important is presenting the content in a manner that students will remember;

once the information is remembered, constructivist principles allow it to provide a foundation for subsequent knowledge. Variations on the topic and methodology are encouraged, but it is important that students have hands-on experience with the toys/models before detailed theoretical concepts are discussed.

Assessment Instruments

It is not difficult to believe that students have a good time playing with these toys in our classes, but is there any evidence to support the theory that these toys make a difference in learning? Can a curriculum with toys withstand an ABET inquiry? Assessment data suggest that the inclusion of toys has generally positive effect on learning as it relates to ABET's "A-K" criteria with the following examples.

- Quantitative measurement processes: In general, survey data has revealed that students see a connection between the toys in the classrooms and their comprehension of engineering content. Data from an introductory Structural analysis course at Penn State in the Fall of 1997 revealed a direct link between the toys and content. When students were asked to respond to the statement: "Physical models helped me to understand the material presented in class", the average response was 6.25 on a 1-7 scale with a 7 representing strong agreement.[7] In addition, responses to essay and numerical exam questions clearly indicate that the students are beginning to understand the subject matter at a more advanced level than before the project was used. For example, in response to observations about the differences in construction processes of tubes and bars, students on their own drew a direct connection between the number of steps in the construction process and the resulting relative variability (coefficient of variation) in member strength. They were also able to extend these ideas to explain the difference between system reliability (where more than one member might cause collapse) and a deterministic analysis. In other words, the responses revealed that students were "internalizing" the course content in more profound ways than that achieved by more conventional "black and white" ball examples.[7]

- In-class exercises: The Joy of Engineering program makes use of written exercises designed to assess comprehension and application of course content. For example, at the conclusion of the paper airplane competition, students fill out brief handouts with questions about how the plane exercise relates to distance, speed, and time. In the 2001 session, students were asked to link the airplane exercise to concepts they have learned at school in math and science, and results indicate that this "low-tech" exercise provided large dividends for student learning because most of the participants made direct connections with no explicit instruction from the program faculty.[4]

While many of these assessment instruments are currently in the formative stage, copies of several instruments and example assignments are included in the appendix, and the authors invite adaptation to other applications in engineering education. For additional information about customizing any of these examples to engineering education, please contact Paul Palazolo at ppalazol@memphis.edu.

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Appendix

Joy of Engineering Program, 2001: Week 3: Introductory Survey

Welcome to The Joy of Engineering Summer Program. This survey is designed so you can provide information directly to the instructors and sponsors of the program. Your answers are confidential, and this means that we will collect the surveys in an envelope, seal the envelope, and we won't look at your answers until the program ends. Your opinions are important to us, and we thank you for your help

Name:________________________ Age: ____ School:_________________

Background Questions

What grade did you just complete? _____

Which subjects at school are your favorite? (check as many as you want)
__Math __Art __Science __English __Social Studies __Other

What's the subject you like least at school? __________
Why?

Do you like writing at school? __Yes ___No Are you good at it? ___Yes ___No

Program Questions

How were you chosen for this Joy of Engineering Program?

What are 2 things you hope you'll do or learn in this program?

Engineering Questions

What kinds of things do you think professional engineers do at work?

Group Work/Problem Solving Questions
Have you ever worked in a group for science, math, or writing projects? __Yes __No

If you have worked in a group before, did you like working in a group? __Yes ___No
Explain your answer:

If you were working in a group of three people to build a racecar for the group and all three group members had different ideas, what would you do?

Exit Survey: Joy of Engineering Summer Program June 26-30, 2000

Name:________________________ Age: ____ School:________________

Purpose: This survey is designed so you can give feedback about this program directly to the instructors and sponsors of the program. Your answers are confidential, and this means that we will collect the surveys in an envelope, seal the envelope, and we won't look at your answers until the program ends. Do not worry about making any of us or our sponsors upset by your answers—your opinions are important. Thanks for your help.

Program Questions

How much science information do you believe you have really learned in this program?
__Very little __Some __Something every day ___Lots

How much math information do you believe you have really learned in this program?
__Very little __Some __Something every day ___Lots

Did writing in your journals help you organize or plan your bridge/car designs? __Yes __No

Which of the following statements do you agree with?
__Engineering is more interesting to me than it was before
__Engineering is about what I expected
__Engineering is not for me

Perception Questions

What would you describe as your favorite thing about this program?

What would you describe as something you'd like to change about this program? How would you change it?

Would you be interested in attending other programs similar to this one? __Yes __No

Would you recommend this program to your friends? __Yes __No

Has anything you've learned in this program made you want to study math or science in college?
___Yes __No

How does writing fit with math and science? Why do you think this program had a writing teacher too?

Are there any comments you'd like to make about any of the instructors in this program?

Problem Solving Questions

How much information do you believe you have learned about problem solving in this program?
__Very little __Some __Something every day ___Lots

How can you take what you've learned about problem solving back to your regular classrooms?

Group Work Questions

Before this program, had you ever done group work in science, math, or writing? __Yes __No

Did you like working in a group? __Yes ___No
Explain your answer:

What's the best thing you can say about your group?

What's the biggest problem you've had with your group?

===

Bridge Questions

Draw and label the parts of an arch bridge:

Draw and label the parts of a suspension bridge:

Bridges in our competition were scored on ____________ and _____________________

What is the SWR of a bridge in our competition?

Draw and label something symmetrical and something asymmetrical.

Energy and Motion Questions

Speed is defined as _____________ per _________________.

A variable that you control is called a ___________________ variable

Why would you use a graph in the report about your car?

Name 2 criteria your final cars will be judged by in today's competition

Sample Exam Questions Associated with the Manila File Folder Bridge Project

1. Suppose someone told you that they had designed and constructed a manila file folder bridge that had an estimated design capacity of 100 N. If you could only ask one question, what would it be and why?
2. Observation 1: Prefabricating tubes was much more difficult than prefabricating bars. Observation 2: The c.o.v. for tensile strength was about 25% whereas that for compression strength was about 35%. Discuss what the relationship might be between these two observations.
3. The average system strength predicted by the Monte Carlo (Crystal Ball) simulation is lower than the system strength predicted by a deterministic strength analysis using each member's average strength. Explain why and what the implication is for real-world engineering.
4. Most of the teams not only used the required factor of safety of two for each of their member's but sometimes effectively increased it to three or four. What is the actual purpose of the factor of safety and what is the implication for real-world engineering of using a number larger than that specified?
5. Discuss the ways in which the author has correctly and incorrectly used the term *risk* in her article "Ranking risks according to probabilities."
6. Even conscientious constructors can have a difficult time complying with specifications exactly. Discuss at least three things that you learned in this class via *Rising Tide* and the laboratory components of the course that improve communication with the constructor.
7. You didn't enjoy putting together the full-scale layout drawings at the start of the file-folder project. What real-world construction activity does putting together these drawings represent and how might that influence engineering design?

Biographical Information

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