AC 2011-1555: USE OF SIMPLE HANDS-ON DESIGN CHALLENGES FOR PRACTICING ENGINEERING DESIGN PRINCIPLES

J. Aura Gimm, Duke University

Aura Gimm is an Assistant Professor of the Practice in the Department of Biomedical Engineering at Duke University. Her research experience include cellular molecular mechanics, transdermal drug delivery, and biomimetic microfluidics. She has developed and taught a senior capstone engineering, a new course in bionanotechnology engineering, and an advanced biomaterials course at Duke. She formerly directed NSF-funded Internships in Public Science Education program as a part of the Interdisciplinary Education Group of the University of Wisconsin Materials Research Science and Engineering Center on Nanostructured Materials and Interfaces.

Richard Goldberg, University of North Carolina, Chapel Hill

Richard Goldberg is a Research Associate Professor in the Department of Biomedical Engineering. He is also the Director of Undergraduate Studies for the Curriculum in Applied Sciences and Engineering, which houses the undergraduate BME program. He teaches several instrumentation courses. He also teaches a senior design class in a collaborative effort at UNC and Duke University. His primary interest is in rehabilitation engineering and assistive technology for people with disabilities.

Kevin Caves, Duke University

Kevin Caves is an Instructor in the Pratt School of Engineering at Duke University and a Clinical Associate in the Department of Surgery at Duke University Medical Center. He coordinates Duke's Assistive Technology Clinic that provides assistive technology services to people with disabilities. In addition to teaching and working with people with disabilities, he conducts research in the area of rehabilitation engineering and assistive technology.

Robert Malkin, Duke University

Dr. Robert Malkin is a Professor of the Practice of Biomedical Engineering at Duke University in Durham, North Carolina. Previously, Dr. Malkin was the Herbert Herff Professor of Biomedical Engineering at The Joint Biomedical Program at the University of Memphis in Memphis, Tennessee and The University of Tennessee. Before moving to Tennessee, Dr. Malkin was a professor of Electrical Engineering at The City College of New York and a member of the graduate faculty at The City University of New York and a research associate at Columbia University. Dr. Malkin received his MS and PhD in Electrical Engineering from Duke University in 1991 and 1993, respectively. Prior to attending graduate school, Dr. Malkin taught English in Thailand, worked at EM Microelectronics in Switzerland designing integrated circuits, worked for Cordis Corporation designing pacemakers and worked for Sarns Incorporated designing heart lung machines. Dr Malkin received the BS degree in Electrical Engineering from The University of Michigan in 1984. Dr. Malkin is a Fellow of the American Institute for Medical and Biological Engineering. Dr. Malkin is the director of Duke University-Engineering World Health and The Global Public Service Academies.

Use of simple hands-on design challenges for practicing engineering design principles

The Biomedical Engineering program at Duke University offers five distinct capstone design experiences for our seniors. This approach provides flexibility to serve the needs of our diverse student population, however a one semester experience can be limiting for both student learning and the depth that project teams can achieve. While providing challenging engineering problems, all capstone design courses address basic principles of engineering design, teamwork, technical communications, ethics, and professionalism. In this paper, we will discuss how a few simple design challenges have been used in three capstone design courses to practice and apply engineering design principles and problem solving skills. These challenges are relatively inexpensive to implement and could be done in teams or individually. The competitive aspects of the challenges can further motivate students. The design challenge goals can be tailored to focus on specific aspects of design practice or skills, such as bench marking, experimental designs for assessing design solutions, use of appropriate statistical models, learning from failure, or using machining tools. In one design challenge, for example, students fabricate a simple structure using only squares and equilateral triangle shaped pieces with one demonstrable function that can be measured.

Introduction

Many types of design challenges have been used in various formal and informal educational settings. Design challenges have been implemented modularly in K-12 classrooms that led to gains in student learning of science, mathematics and engineering concepts,[1-2] and to a decrease in achievement gaps between some demographic groups.[3] A number of studies comparing a traditional teaching model to one with elements of design challenges showed improvement among students experiencing the engineering design approach.[4-5] Some of the design challenge uses, such as Texas Space Grant Consortium Design Challenge Program, are more extensive and narrowly tailored to a defined problem space,[6] while other have used a broader range of design challenges as a vehicle to accelerate learning and implementing basic engineering design steps.[7] Typical design challenges found at the university level are team-based and extensive, often stretching over several class periods. Here we focus on simpler and shorter design challenges that supplement our students' learning, and provide additional experience with engineering design processes.

The BME program at Duke University offers a one semester capstone design experience. Students choose one of five design courses in which students design, build, and test a biomedical device or process. Our design instructors meet regularly to ensure consistency in addressing issues related to health and safety, appropriate regulations, and ethics. We work together to maintain a floor level of core design experience for our suite of design courses. However, for most students, this is their first significant exposure to the engineering design process, and they would benefit from exposure to a brief design challenge before addressing a semester-long, open-ended design project. In order to augment and accelerate the learning of design processes, three capstone design courses have implemented small-scale design challenges. These are all relatively simple and short in duration ranging from one class period to two weeks. The following three sections provide an overview of each design course, a description of the design challenges and their goals, and a summary of feedback and assessment.

Design Challenges used in BME 227L

BME 227L is a client-based capstone design course that focuses on practical solutions in the development of biocompatible devices for biotechnology or biomedical applications. The projects apply materials science and biomechanical core engineering concepts in designing prototypes or processes to address the needs of the client (most from the Duke University Medical Center). The course emphasizes formal engineering design principles and includes modules in intellectual properties, engineering ethics, risk analysis, safety in design, human subject testing, and FDA regulations. Recent examples of projects include: 1) the development of a device for blink detection in nonpalsied eye and blink stimulation in palsied eye; 2) syringe "helper" for ophthalmological injections that minimized finger stretching; 3) a novel design for hip resurfacing implant.

Four design challenges were used in this course, including two group challenges and two individual challenges. The two group challenges were based on well-known activities used widely and readily available online[8]—spaghetti-marshmallow load-bearing tower and modified egg drop contest. These two challenges were modified to meet specific goals.

Group Design Challenge 1: Egg Drop

Many students were familiar with the egg drop contest. This activity is typically performed earlier in the course to facilitate team building, and to apply physics and engineering design principles. Students were asked to design and build a device to protect and accurately deliver a dropped egg. For the first test, the devices were dropped from about 10 feet high, while the second test involved dropping the device from top of an atrium (about 100 feet). Teams were not allowed to modify their design between testing. The instructor provided a point scheme weighing the protection of the egg primarily and accuracy secondarily. Students saw that deployment of parachute like structure was not possible for the first test due to short fall distance.

The goals for this design challenge were to

1. apply basic physical principles
2. apply engineering design process to solve a problem
3. learn to work within specific design constraints
4. become familiar working with teammates.

Group Design Challenge 2: Spaghetti Tower

Before starting this activity, student teams were asked to devise and agree on a metric to evaluate the design, including the height of the tower, and the maximum load it carried, the duration the tower should carry a load before collapsing, the increment of load added, the minimum height requirement for the tower, and the points gained for the final height and load. Teams were given a time limit to construct their first tower, and after the first round of testing where many realized the issue of spaghetti twisting and buckling, teams were given a chance to build a second tower. Figure 1 shows one such tower built before it was "destroyed" through load testing.

The goals for this design challenge were to

1. understand the importance of fair rubrics for measuring success of design solutions
2. appreciate the importance of having those goals set prior to testing
3. apply quantitative measures to evaluate design solutions
4. learn from failure of a design.

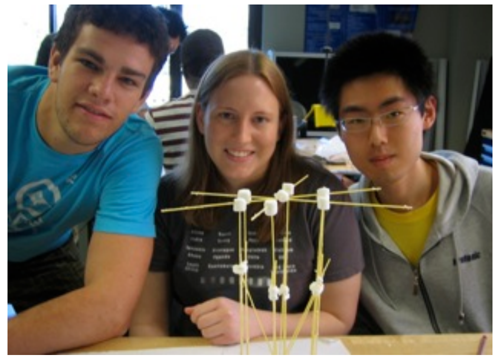

Figure 1. An example of structures built using spaghetti and marshmallows. Students worked with their "normal" teammates.

The two individual design challenges involved using different machining tools. Either before or during these challenges, the students were trained in using the laser cutter, Solidworks™ computer aided design software, and a 3D rapid prototyping machine. Each module took 2-3 weeks including the training.

Individual Design Challenge 1: Build "Something"

(from the handout)

> In this activity you will use the laser cutter to create an artifact. Instead of having functional specifications, you are given physical design specifications and material constraints. The completed artifact will be demonstrated in class. So please come to class prepared.
>
> Create an artifact with at least one function (that you define) that can be measured. The artifact must be made of only squares (2'' by 2") and triangles (2" equilateral). You are provided with one sheet of 11" by 11" acrylic and that will be the maximum amount of material you are allowed for this Challenge.
>
> Evaluation of the artifact:
> 0 pts: Artifact was not completed.
> 2 pts: Artifact did not meet the design specifications.
> 3 pts: Artifact met the design specification.
> 4 pts: Artifact met the design specification with a demonstrable function.
> 5 pts: Artifact met the design specification with demonstrable function (s). The designer presented sensible strategies for measuring the function (s) including uses of appropriate statistical tools.
>
> Extra point: Voted best design by the class (optional).

The goals for this design challenge were to

1. learn to use a laser cutter, a relatively simple machining tool
2. learn to define and demonstrate function of an artifact
3. learn to measure functional performance using statistical tools

4. learn to work within specific constraints (amount of material and shapes of basic building blocks).

The artifacts created ranged from cup holder, pencil case to pasta dispenser with serving size wheel and six-sided die. Figure 2 shows two students showing their artifact.

Figure 2. Students created an artifact with a demonstratable function using specified building material. Two example artifacts—pasta dispenser and a jewelry box—are seen here.

Individual Design Challenge 2: Design a Paring Knife Handle that Customers will Buy

(from the handout)

In this activity you will use Solidworks™ software and 3D rapid prototyping printer to create an artifact. You are asked to design a new handle for a paring knife that is easily manufactured and is ergonomic.

Simplified Design Specifications:

- fits in average adult's right hand
- has a housing slot for blade of 3/32" in thickness, 5/8" in width. The depth of the slot should be 1/2". Acceptable tolerance is 10%.
- allows paring motion (once assembled with a blade)

The evaluation of your design consists two parts: 1) does the artifact meet the basic design specifications? and 2) benchmarking of the artifacts using blind testing where random subjects will evaluate the ergonomics—is the artifact comfortable to hold, well designed for paring?

Evaluation of the artifact against the Specifications:
0 pts: Artifact was not completed.
2 pts: Artifact was not fully formed as a functioning handle; not all specifications are met; manufacturing issues encountered, safety concerns.
3 pts: Artifact met all the design specifications.

Benchmarking on ergonomics (only the artifacts that has met all the Specifications will participate):
1 pt: Artifact considered acceptable for purchase by the majority of the test subjects.
1 pt: Voted most ergonomic by the test subjects.

The goals for this design challenge were to

1. learn to use Solidworks™ to design an artifact using design specifications
2. experience bench marking
3. be exposed to concept of ergonomics.

Once the handles were prototyped, each were labeled with a number and put into a bin. Possible customers (BME graduate students, staff in the office, Profs.) were asked to pick as many knife handles they would consider purchasing while performing their own simulated paring motion. The length and width of their dominant hand were measured and recorded as the numbers indicated on the handles they were likely to purchase.

Assessment and Feedback from Students

At the end of the semester, students were asked the following questions regarding design challenges utilized in the course.

1. For each activity indicate what you learned from the experience.
2. Were the design challenges helpful in practicing engineering design process and team building? Explain.
3. Any ideas for making these challenges more effective?

Many students thought the group design challenges were fun but too simple for them. Most did not see the goals of those activities without direct prompting, but did find them to be enjoyable as change of pace. A few students did see them as useful way to practice the engineering processes. Fewer students (2 out of 14 respondents) thought they were waste of time and one commented that it caused “head butting” between teammates.

All the students who responded indicated they felt that the activities met one or more of goals listed. In particular, the goals of learning to use the rapid prototyping tools were most commonly cited by students. Most students thought these activities did help them to apply engineering design process. Few students thought these challenges were too time consuming.

Design Challenge used in BME 260L

In BME 260L, the students design, fabricate and deliver custom assistive devices. Each device is built for an individual in the local community who has a disability. Student teams work closely with the client, their family, and local health care providers to develop a device that meets the client's needs. At the end of the semester, the students deliver their completed device to the client. Examples of past projects include a custom modified trike for a boy with congenital limb deficiencies and a special rock climbing prosthesis.

During one of the first lab periods, student teams are given a design challenge to: “Create a device/mechanism that will launch a ping pong ball. Best launch in each category will receive a prize.” The faculty provide them with the following criteria:

Fabrication materials:

- Cardboard
- Masking tape and duct tape
- Pencils
- Rubber bands

Initial rules

- Device must launch ball

- You can setup the device (e.g. load the ball, set the rubber band)
- No part of the device can pass the start line

Students are given no other formal instructions except to ask questions. They are given a short time (e.g. 20 minutes) to construct their device. Students are encouraged to test their device before the competition.

The goals of this exercise were to:

1. Teach students the importance of fully understanding the problem
2. Show that working device prototypes can be created with simple materials in a short time period
3. Reinforce the importance of testing your device prior to its use.

With great enthusiasm, student teams dive into fabrication of the device (Figure 3). Invariably, one of the student teams finishes and starts to test their device. It is often at this point that the students begin to ask the questions they need to define the problem.

Figure 3: Students constructing their ping pong ball launcher

As the students ask appropriate questions, we reveal that the competition has two categories: Distance and accuracy. Teams get 3 trials for each category. Scores are recorded on a white board in real time. The additional rules are:

- Distance task: launching a ball down the hallway
    - 1 point is awarded for each foot of travel in the air to the first bounce
    - 1 point is subtracted for each inch the ball lands off a center line
- Accuracy task: launching a ping pong ball into a container
    - 50 points for each ball that stays in the container
    - 30 points for each ball that bounces out of the container
    - 15 points for each ball that hits the container

Figure 4: Students using their ping pong ball launcher in the competition

Assessment and Feedback from Students

While the students clearly enjoy the competition (Figure 4), most of the teams score poorly on the distance task due to the scoring system that deducts points for launches that veer off of the center line. Most student teams assume that the competition is based on distance only without getting the necessary information on the tasks and scoring systems. Therefore, these challenges do help students appreciate the importance of understanding the problem *before* they start thinking about solutions. This is particularly an important task for our class because students need to address a clinical issue with people with disabilities, a subject area that is often not familiar to our students.

After completing the design challenge in January 2011, students filled out an anonymous survey to assess the effectiveness of this experience. The survey listed the following statements:

1. The activity reinforced the importance of fully understanding the problem BEFORE I start on the design.
2. The design challenge showed me that working device prototypes can be created with simple materials in a short time period.
3. This experience reinforced the importance of testing my device prior to its use.
4. The design challenge was fun.

All of the students answered "agree" and "strongly agree" to each question (12 out of 18 students responded). Furthermore, virtually every student commented that the most important thing they learned was to ask lots of questions and fully understand the need before attempting to work on the design for their project.

Deign Challenge used in BME 262L

Design for the developing world is a course where the projects focus on medical devices for resource-poor settings. The lecture portion of the course is dedicated to traditional design concepts such as the engineering design cycle, regulatory considerations, design analysis and synthesis, intellectual property and ethics. All points are taught using the case method and, wherever possible, the cases are selected to come from or bear on the developing world. The lab portion of the class divides the approximately seventeen weeks into four weeks dedicated to a design challenge, one week dedicated to a simulated poverty exercise and the remainder focused on accomplishing their design project.

On the first day of class, students are divided into four teams. Each team then has four weeks to design a medical instrument. At the fourth meeting, the teams take their devices to the engineering quad with the goal of measuring as many people as they can, as accurately as they can, in one hour. Typical medical instruments measure things like reaction time, vertical leap, pupil separation, hand strength and foot length. The devices must be stand-alone, battery operated, hand-held devices that can store up to at least sixty measurements. Students only receive points if they measurement is within 5% of the gold-standard measurement (also designed by the team) of that same parameter, and that measurement appears in their data dump at the end of the hour.

Most students enter the class without knowing quite enough to complete an entire instrument. Therefore, the teams are further divided into construction, electronics and software. The construction teams learn to CAD (InkScape) and CAM using a laser cutter to construct the physical box from 1/8" acrylic. The electronics team learns to design (expressPCB or Eagle) and make double-sided PCB's, including exposing, developing, drilling and populating the boards.

The software team learns to program a PIC micro-controller (PICAxe) with ADC and serial display LCD capabilities to accomplish the measurement task.

Assessment and Feedback from Students

Each student team gets points for every measurement they make accurately. Teams do not get additional time if their device breaks. Therefore, they must take the time to insure that their device is repeatable and reliable.

This is most students' first exposure to design. In particular, this is often their first exposure to the design cycle and the demands for repeatable performance - as opposed to their typical lab, where a single result is expected. Nevertheless, there has never been a team that does not produce an instrument that is able to accomplish the task to some extent. Approximately one out of four teams end up with a device that breaks or does not produce data for the entire hour. Typically, this is because they do not anticipate having to redesign their boards after the first attempt does not provide repeatable data or completely fails.

Students are surveyed on the value of this exercise. Most students report that they enjoy the exercise and the chance to build a complete medical instrument. They feel that this "pulls together" their previous theoretical courses. Many feel that four weeks is too much time to devote to the exercise. They would have rather spent the time on their class projects. However, in the years since the design challenge was incorporated into the class, the overall success rate of the class projects has notably increased, so this has been a useful addition to the course.

Conclusion

Different design challenges, all relatively simple to implement and short in duration, were used in three separate capstone design courses to augment and complement student capstone design experience. Although not all the goals were perceived to have met by the students, these activities were generally effective. Design challenges were more effective when they required learning and utilizing a new tool such as a machining tool. What ever the ultimate goal of design challenges are, it is important that "challenges, however, must be at the proper level of difficulty in order to be and to remain motivating: tasks that are too easy become boring; tasks that are too difficult cause frustration"[9].

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