Preparing Students for Senior Design with a Rapid Design Challenge

Introduction and Motivation
Design is arguably the most important class in an undergraduate engineering curriculum. It can, however, be one of the most challenging classes to teach as it ventures far off the traditional lecture and lab format that students are accustomed to. As engineering educators, we therefore want to optimize the process such that our students get the most out of the experience [2]. In an effort to improve our own two-semester, senior design sequence, we have implemented a three-week, rapid design challenge at the beginning of the biomedical engineering senior design experience. This abbreviated design experience challenges the students to rapidly learn and implement the basic steps of design to produce a functional prototype for entry into a culminating design challenge contest.

In the 2006-2007 academic year our senior design sequence was taught for the first time but without the design challenge. Based upon this initial experience, we made the following observations which motivated the creation of the design challenge.

1. Capstones are a different type of course
   By the time students are seniors, they have become accustomed to the cycle of technical lectures, homework, labs and tests that compose the typical undergraduate engineering course. When they enter senior design, this familiar cycle is replaced by lectures and assignments on topics such as device specifications, ethics, memos, decision matrices, economics, prototype construction, benchmarking and careful documentation. While the students are used to new topics in a new course, design topics are of a type that is very unfamiliar to the students. Furthermore, as design is an iterative process, students can easily get lost in the repetitious nature of the design process. We have found that some students find this switch in course structure difficult and view their design project as a daily exercise in paperwork rather than a year-long experience of learning and implementing a technical design process.

2. The conclusion of the first semester of design can be unsatisfying
   Like many other institutions, our senior design is a two-semester sequence where the first semester concludes with a written design proposal and the second semester culminates in a functional deliverable. As such, teams are typically far from a final deliverable at the conclusion of the first semester. For students who are accustomed to finishing a course project at the end of the semester and experiencing a strong sense of completion, the first semester of the capstone leaves many students feeling unfinished and unfulfilled.

3. No two projects are the same
   Once all design projects have been identified, teams head in many different technical and clinical directions, sometimes at vastly different rates. This variability creates a climate unlike what students have experienced before (e.g. taking the same tests on the same days). For the faculty member coordinating the design course, it is challenging to keep the class unified and lecture topics relevant to all groups.
4. **Build early but do your homework first**
   An important message in any capstone design course is that careful research, brainstorming and iteration up front lead to a better device. This is especially important for teams who want to begin building prematurely. In contrast, some teams use “careful process” as an excuse to keep their design on paper rather than building and testing early prototypes. Balancing these two competing student reactions to design can be challenging.

5. **Senior design projects should not be the first time students design**
   Seven courses in our curriculum prior to senior design required students to complete an open-ended design project. Prior to senior design, however, students have not followed a formal design process from start to finish. Based upon our experiences in the first year of our design sequence, we strongly felt that the students would have benefited from a concentrated introduction to the design processes (from problem analysis to prototype deliverable) before they initiate their primary design projects. Furthermore, we felt that it was critical for the design challenge to occur in the curriculum just prior to the year-long senior design. In this way, the concepts and techniques are fresh in the minds of the students.

In an attempt to address these challenges, we implemented a rapid design challenge in the 2007-2008 academic year which was repeated in the current 2008-2009 year. Serious consideration was given to limiting the time frame of the challenge so as to not drastically interfere with the normal mechanics and content of the senior design capstone.

In the remainder of the paper, we present the major characteristics of our design challenge and also provide descriptions of accompanying student assignments where appropriate. As this concept has potential beyond the specific technical challenge used by our program, we also offer suggestions on how to adapt this idea to a range of educational settings. Finally, we present some preliminary assessment of the design challenge.

**Overview of the Design Challenge**
Our three-week design challenge quickly leads students through the major milestones of the design process. In our specific implementation, students are challenged to design and build a device for a third-world clinic to infuse a cholera treatment solution. We provide them with information about cholera and the technical constraints that the device cannot use an external power source, must be portable and once started must operate without any manual intervention. The performance metrics are to deliver 60cc of fluid over 10 minutes at a constant rate. With the exception of a syringe and tubing, all parts must be purchased at either a discount store or a local hardware store and stay within a budget of $100.

Class lectures and five specific assignments guide the teams through the major steps of the design process including:

1) writing a problem statement
2) translating user needs into engineering specifications
3) brainstorming alternative solutions
4) choosing a solution
5) fabricating and testing a device.

Although our implementation is for the design of an infusion device, the general concept can be easily adapted to other project topics. Prior to the implementation of our design challenge, we identified five key qualities of a problem that we believed would facilitate successful implementation of the design challenge. We felt the problem should:

1) be of interest to the students
2) have a solution that is technically simple enough to be built in a short amount of time
3) allow for many types of viable solution concepts
4) have a high probability of success in the allotted time limit
5) be presented in such a way as to create an environment where healthy competition is rewarded and risks and creativity are encouraged.

After generating the general and specific characteristics of the design challenge, we focused on ensuring that we addressed the five challenges we experienced in our first offering of senior design. With regard to capstones being ‘different’ courses, we hoped that the design challenge would assist the students in becoming more comfortable with design such that when they ventured into their year-long projects their progress would not be impeded by adapting to a new course type. To address the second challenge that the students will not be done at the end of one semester, we hoped the design challenge would give them insight into the entire process and enable them to foresee how their first semester progress is critical to success in the second semester. As stated earlier, each team will move at its own pace and in its own direction depending on many variables such as project topic and input from an external clinical mentor. To address the frustrations that can arise in design, we structured the design challenge to allow student teams to identify unique solutions and go in different directions. The design challenge also provides the class with a single unifying experience that can be referred to throughout the remainder of the course. With regard to encouraging the students to understand the need for an iterative approach, we required design challenge teams to build and test in an iterative fashion. Finally, we hoped that the design challenge would provide a starting foundation for the students and ensure that their year-long senior design experience would not be their first exposure to a formal design process.

Below we detail the events and assignments that drive the design challenge.

Presenting the Design Challenge
We feel that the design challenge should be explained on the first day in such a way that the five qualities of a successful design challenge are conveyed to the students. This may be done explicitly, with the rationale of this paper as motivation, or implicitly through examples. We have found two helpful practices. First, we distribute a syllabus on the first day that covers only the duration of the design challenge rather than details the entire semester. We explain that the design challenge is meant to provide a hands-on, open-ended introduction of the entire two-semester capstone sequence. Second, we show on the first day a 20 minute video featuring the design company IDEO where the process of redesigning a shopping cart in five days is followed by a television crew [5]. After the introductory talk and movie, student teams of three to four students are created and more detailed design challenge documentation is distributed. These
documents include the medical motivation, medical challenge, design requirements, daily plan for the design challenge, milestones of the process, budget constraints, available facilities, device testing procedures, intellectual property matters, and a description of the culminating design challenge contest. We set the stage that each team is a small company charged with designing a liquid infusion device over the next three weeks. To enhance the competitive nature of the process, each team is informed that they are responsible for preventing other teams from gaining an advantage through “industrial espionage”, e.g. spying on systems, reviewing devices or notes left in public, etc. The first day is concluded with groups finding a common time to meet before the next class period. The table below is an example daily outline for the design challenge.

### Design Challenge Schedule

<table>
<thead>
<tr>
<th>Month</th>
<th>Date</th>
<th>Day</th>
<th>Topic/Event</th>
<th>Assignment Due</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>22</td>
<td>W</td>
<td>Problem Statements, User Needs</td>
<td></td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>M</td>
<td>Functions, Specifications</td>
<td>1. Problem State / User Needs / Prelim. Ideas</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>T</td>
<td>Solution Generation, Solution Analysis, Solution Planning</td>
<td>2. Functions &amp; Specifications</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>W</td>
<td>Sign Off Meeting by Friday with Prof. No Formal Class Time</td>
<td>3. Possible Solutions &amp; Plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>September</td>
<td>3</td>
<td>M</td>
<td>Prototypes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>T</td>
<td>Team Project Time</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>W</td>
<td>Review Preliminary Testing Results and Planned Device Improvements</td>
<td>4. Device Testing Results, Planned Improvements</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>M</td>
<td>Team Project Time</td>
<td>5. Team Evaluation of Design Process</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>T</td>
<td>Design Challenge Contest</td>
<td>Design Contest</td>
</tr>
</tbody>
</table>

### Design Challenge Assignments

Below we outline the sequence of assignments in the design challenge. Relevant lectures are delivered either slightly before the assignment or just in time. The lectures focus on the key points of the design process and are therefore revisited later in the semester when students are engaged in their year-long design projects. This ensures that they have seen the design concepts at least twice before working on their primary senior design projects. Readings from a design textbook are assigned to supplement the lectures [1]. The major steps of the design process that are to be emphasized in the design challenge are incorporated into the assignments described below.

**Assignment 1: User Needs and Solution Concepts**

To begin the process, we aim to have the students carefully review the information about the medical challenge, i.e., the treatment of cholera via a controlled infusion process in a third-world, understaffed clinic. We then have them begin the formal design process in the first assignment where they must:

1) Identify the people who would need to be contacted to discuss the needs for the infusion system. These must include both direct and indirect users.
2) List the known and anticipated needs and wants for each of the users identified above.
3) Identify which needs are objectives and create an Objectives Tree of at least four levels.
4) Generate an unedited list of preliminary solution concepts for the design challenge. In creating the list, students are asked to ignore what seems reasonable or doable and simply brainstorm any and all ideas.

To support this assignment, accompanying lectures focus on the definitions of direct and indirect users, methods to determine user needs and wants, the definition of an objective, and construction of an objectives tree. Students in our program have previously had a formal introduction to team dynamics and brainstorming techniques so they are expected to transfer these skills into the design challenge.

**Assignment 2: Functions and Specifications**

After determining the information that would likely come from the users, the teams are tasked with converting that information into specific design functions and specifications. For this assignment, teams must:

1) Identify up to 10 desired functions of their device, based upon the user needs and objective tree.
2) Categorize each function as either basic or secondary.
3) Explain how both convergent and divergent thinking were used to brainstorm and refine device functions.
4) Determine the appropriate design specification(s) for at least five of the identified functions.
5) Categorize each specification as procedural, prescriptive or performance.

To support this assignment, accompanying lectures define a function as an operation a device can perform and a specification as a measurable attribute of a device. Emphasis is placed on translating imprecise user needs into testable engineering specifications. The three broad types of specifications are covered and we explain how specifications will serve as a roadmap to building, testing and evaluating a device. This assignment is also a second opportunity for teams to practice brainstorming as a way to generate, modify, combine or eliminate ideas.

**Assignment 3: Design Solution and Planning**

With the design specifications determined, teams then move onto generating potential design solutions and a plan for evaluating potential solutions. For this assignment, teams must:

1) Submit an updated list of all brainstormed solutions.
2) Document how the list was narrowed to a “best” solution using one of the methods discussed in lecture.
3) Create a Gantt chart showing a projected timeline for the remainder of the design challenge.
4) Conduct a “sign-off” meeting with the course coordinator. Teams are not allowed to begin fabrication until after this meeting.
To prepare the students for this assignment, accompanying lectures are focused on the importance of good documentation of all ideas and the process followed to arrive at a final solution. Examples are given of how good documentation can help in the iterative process when testing does not go as planned. Additional lectures are delivered on how to conduct efficient meetings. Skills to create the Gantt chart were acquired in previous a biomedical engineering course.

**Assignment 4: Preliminary Results and Planned Changes**

After fabricating the first prototype, teams are required to test the system and plan modifications based upon the results. To test the systems, teams are provided with the instructor-designed statistical tools that will be used to evaluate the deliverable of the design challenge. For example, a straightforward sum of squares tool is used to evaluate how close a team’s device stays to 6 ml/min over the duration of the infusion. For this assignment, teams write a formal update memo in which they must:

1) Present an overview of tests performed to evaluate their infusion system prototype. The summary is limited to one sketch/photo and 300 words.
2) Present an analysis of results from the testing of the design prototype with regard to the design specifications.
3) Present a list of planned changes with justification to show how the current system will be modified to remedy any identified problems or limitations.

To support this assignment, accompanying lectures are focused on writing efficient and effective memos as a means of communicating incremental progress. We also emphasize that memos are an effective method of documenting progress. Additional lectures focus on the importance of the iterative plan, build, test, analyze, and reevaluate cycle in the design process.

**Assignment 5: In-class Evaluation of Design Process**

Just before the final design challenge contest, teams have in-class time to write a memo in which they must:

1) Compare how their solution compares to the:
   a. Objectives identified in Assignment 1
   b. Functions identified in Assignment 2
   c. Specifications identified in Assignment 3
2) Summarize project progress and team performance. Items to address are:
   a. Is the team on schedule? Why or why not?
   b. What are the main challenges in completing the project?

In addition, a third point must be addressed by each individual on each team.

3) Reflect on your own individual role in the project.

Assignment five is not accompanied by formal lectures, but rather is meant to induce individual and group meta-analysis of the design process. The aim is that by identifying strengths and weakness, students will transfer their experiences to the year-long design project. In a discussion
with the class, the idea of feedback between steps in the design process and the need to iterate is reinforced. We also emphasize in the discussion that feedback and meta-analysis can occur during or after the design process and may be an individual exercise or team exercise, with or without input from clients and users.

The Design Challenge Contest and Wrap-up

The Design Challenge Contest
The design challenge concludes with a class-wide contest where all teams must compete and all of the department faculty are invited to attend and serve as judges. Each team shares with the class their design strategies and how their infusion device works. Three criteria are used to judge teams with the first two covering the ability of each device to achieve two specifications, i.e., infuse 60 cc in 10 minutes and infuse as close to 6 cc/min as possible. These specifications are tested in a parallel competition so that no team knows how the others are performing. To keep teams honest, a faculty member is assigned to each team to monitor the testing. The third criterion focuses on creativity and ingenuity as judged by the faculty after the device testing. The results are tallied and presented in the final wrap-up session.

The Wrap-up
We believe it is important that the design challenge conclude in a way that rewards the students for their intense work over a short period of time. An official awards ceremony is held where prizes are given for the teams that score the highest on each individual criteria as well as a grand prize to the team with the overall highest score. For the past two years, the prizes were gift certificates to a local restaurant. Students are encouraged to share their prizes with other members of the class. Following the design challenge, students fill out team and individual assessments of the design challenge process. We will comment on the results of these evaluations below.

The final component of the wrap-up is a congratulatory and motivating discussion with the students involving all of the faculty in the department. We aim to take advantage of their positive feelings of accomplishment in that they just completed an intense project where they learned the design process and fabricated an operational medical device. Phrases such as “hard work pays off” are used through the discussion. As they can see the concrete results of their intense efforts, we use this as an excellent opportunity to inform them that there will be weeks during the year-long design process when they will be required to work at least as intensely.

After these final discussions, the students are matched into new teams for their year-long projects and the full course syllabus is distributed. They can now accelerate rapidly into their year-long projects know that they have the skills and knowledge on how to formally design a new medical device.

Suggestions for Implementation
As mentioned earlier, our three-week design challenge has been implemented twice thus far. Below we review our experiences with regard to the critical elements, added benefits and alternative implementations.
Critical Elements
We believe there are four aspects of the rapid design challenge that are critical for success:

1) The rules must be clear enough that it is obvious when rules have been violated. At the same time the rules must be flexible enough to accommodate creative solutions. Likewise, constraints and specifications must be clear and easily evaluated.
2) Time must be allocated for students to review and analyze their experience in the design challenge.
3) The experience should be fun and have little impact on the final grade. Students are rewarded with prizes and not grades for good performance in the design competition. The only grades assigned are for the assignments which focus on the design process and not the product.
4) Deadlines and policies that will be enforced during the year-long project must be enforced during the design challenge.

Added Benefits
In addition to hands-on learning of the design process, our design challenge allows for some additional topics to be addressed early in the capstone. First, as each team is a company that must protect their design ideas, the topic of intellectual property and ethics is at a surface level. As some teams take advantage of opportunities to learn about the design and performance of other teams’ devices, a number of ethical situations arise. When a team feels as though their idea has been stolen, it is a perfect learning opportunity to ask them to prove it using their documentation. Second, to assist in developing design concepts, students are encouraged to walk around a local store as a way to generate ideas. Many students find that there is an enormous difference between brainstorming in an engineering building and brainstorming in a different environment. We have found that many teams continue this practice in their year-long design project. Third, it is clear to the class that the teams who have iterated on their device, all the while testing their current device against the specifications, perform well in the competition. This naturally emphasizes the importance of writing testable specifications and using these specifications to guide iteration. Finally, teams gain additional exposure to writing technical and design focused memos as they will be expected to do in the year-long design process. Overall, the design challenge not only introduces a formal design process but also touches upon many of the most difficult to teach peripheral design concepts.

Alternative Implementations
We have presented our implementation of a rapid design challenge with regard to the design of a third-world fluid infusion device. This design challenge concept, however, could be implemented in a variety of situations with minor modifications. Some possible situations where we believe a rapid design challenge may also be useful include:

1) introductory engineering or biomedical engineering courses [3]
2) high school outreach programs
3) service learning in partnerships with an external client
4) elective courses for non-engineers to introduce the concept of design.

In addition, many variations on the design challenge format exist including:

1) varying the problem motivating the challenge each year
2) varying the constraints (e.g. allotted time or money)
3) altering the evaluated criteria for the competition
4) and many more.

Each of these modifications would require some aspect of the design challenge to be modified, but the core concept could remain the same.

**Assessment**

In the first offering of our program’s capstone design sequence, we did not include a design challenge while in the past two offerings we have included the challenge. Based on our limited experience with the design challenge, we can offer the following observations.

**Faculty Observations**

In comparing student performance and attitude toward their year-long design project, with and without the design challenge, faculty observations are that the design challenge effectively:

1) engaged students in design on the first day of class
2) allowed students to experience the design process at least twice during the capstone
3) provided the class with a common design experience that could be referenced later in the course.

Two concerns were identified through written evaluations (see below) and conversations with students. First, the design challenge delays work on the year-long design project. Second, not all students realize that they have in fact transferred concepts from the design challenge to their year-long projects.

**Student Feedback**

Following the design competition and awards ceremony, students were asked to comment on the following questions:

**Team-Based Questions**

1) What do you feel were the strengths of your team’s effort?
2) What do you feel were the weaknesses of your team’s effort?
3) If you were to do it again, what do you do differently with regards to your team’s process?

**Design Challenge Questions**

1) What were the strengths of the design challenge as it was presented and defined?
2) How could the design challenge be improved in the future?
3) What skills from the design challenge do you think will aid you in your upcoming senior design project?

From the responses to these questions we have come to the following conclusions:

1) Most students identified weaknesses in their individual and team efforts and made suggestions on how they could improve in their year-long design project.
2) Students found a simple project with clear goals a good way to provide an overview of the design process.
3) Students were anxious to begin their year-long project and felt the design challenge was either not necessary or too long.
At the conclusion of the first semester students were asked to evaluate the design challenge as a means of introducing the steps in the design process on a 1-5 Likert scale. The average score from 31 students over the two offerings of the design challenge was 3.9.

At the end of the second semester of the capstone, after the year-long project was nearly complete, a discussion with the class revealed that students found the design challenge to be fun and motivational. They did understand the rationale behind the design challenge, but reiterated the point above that they would rather have used the time to begin their year-long project. We have argued in this paper that the design challenge is worthwhile, but it does come with the cost of time not spent on the year-long project. The only true method of assessing the effectiveness of the design challenge is, therefore, to perform direct assessment on the objectives of the senior capstone with and without the design challenge. As our program has only implemented our senior capstone without the design challenge for one year, we do not have sufficient data to claim in any rigorous way that the design challenge improves performance in the year-long project.

Conclusion
The senior design capstone affords engineering students experience with the design process. The traditional implementation, however, unveils the design process slowly over the course of many months and students can sometimes have a hard time seeing the endpoints and the big picture. We have presented a rapid design challenge that occurs at the beginning of the senior capstone and aims to address some challenges with the slow roll out of the design process. The goals of the design challenge are to provide an effective overview of the key steps in the design process and to give students some experience before their year-long project. Our approach fits into a broader range of educational techniques that emphasis the need for multiple exposures to important concepts [4]. Furthermore, the concept of a rapid design challenge can be easily modified to fit within other courses in a biomedical engineering curriculum. Although time spent in the design challenge is then not available for the year-long project, we feel that students are better able to navigate their year-long design project when the key steps in the design process are fresh in their minds.

References
2. K. Holzblatt, S. Wood and J. Wendell, Rapid Contextual Design: A how-to guide to key techniques for user-centered design. Morgan Kaufmann Publishers 2004