Freshman Design Course: Device Design for Low-Resource Settings

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Barbara S. Smith is currently an Assistant Professor in the School of Biological and Health Systems Engineering at Arizona State University. Dr. Smith has 14 years of educational and professional experiences as an engineer, having worked in various engineering fields with diverse populations for over a decade. Her research expertise includes: point-of-care diagnostics, tissue engineering, and nanotechnology.Dr. Smith gained expertise during her postdoctoral research training under the mentorship of Dr. George M. Whitesides at Harvard University, whereshe worked on concept to product translation – collaborating with industry affiliatesand working on product translation with partnersin India.Dr. Smith's lab develops non-invasive methods of diagnostics, in real-time, including specialized imaging modalities and olfactory biomarker identification.As an independent researcher, she implements experimental approaches to real world problems, in collaboration with clinicians and industry affiliates, to develop and effectively translate useful technology. Dr. Smith's innovative approach is aimed towards driving (inter)national exposure and product translation; connecting ASU students to relevant problems that exist throughout the far-reaching areas of the world.

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Introduction

The biomedical engineering (BME) program at Arizona State University (ASU) includes a 14-week freshman hands-on design experience addressing global health needs. Core objectives of this 1-credit course include (i) introducing students to key concepts and processes in biomedical device design and development (specifically: needs assessment, concept generation, and CAD-based device design), (ii) providing an early experience of team-based learning, and (iii) encouraging the development of communication and presentation skills. Additional teaching goals include priming students for subsequent 'design spine' courses and their final-year BME capstone experience, and developing interactive project-based teaching at scale. The two faculty who teach this course (Frow, Smith) have co-developed the content over the past two years; we also meet biweekly during the academic year with faculty members teaching the other BME 'design spine' courses, to coordinate program content and learning outcomes across courses.

Our semester-long course focuses on global healthcare markets and device design for low-resource settings. The course revolves around an open-ended, team-based design project (Smith et al. 2005). A core aim is to foster curiosity and creativity[1] in students' first formal experience of engineering design (Dym et al. 2005). At the start of the semester, students self-assemble into teams of 4-5, and each team chooses a lower-income country to explore. Over 14 weeks, teams use their chosen country as a starting point to work through a cycle of biomedical device design, including broad scoping and needs assessment, problem definition, concept generation and iteration, CAD prototyping, and design iteration based on peer, student instructor, and faculty feedback (see Table 1). They also examine case studies of (successful and unsuccessful) biomedical device design, learn about healthcare innovation systems, and reflect on key challenges and best practices for biomedical engineering design.

Over 3 consecutive semesters, our students have developed a variety of innovative device prototypes, including antiseptic patches to place over the cut umbilical cords of newborns, dust masks for miners, portable first-aid kits to treat minor motorcycle injuries, devices providing anti-HIV therapeutics for sex workers, monthly STD tests, and food sanitation and preservation units. Providing clean water has been one of the most common problems tackled in this course to date, with about 25% of all teams working on possible solutions to this basic healthcare need.

With class sizes of 50-100 students, scale has been a key factor in our course design and implementation (Allen & Tanner 2005). During 2.5-hour lab sessions, our instructor approach is to engage with each student team for at least 5-10 min per class, providing real-time feedback on their research and design practices (Chickering & Gamson 1987). After a short lecture (sometimes accompanied by an in-class activity, see Table 1), student teams use the lab session to work on their weekly design task. These assignments, as shown in Table 1, provide a step-wise path for the students to develop skills in problem discovery, concept generation, design iteration, Solidworks

[1] Curiosity is identified by the KEEN Network as central to the development of an 'entrepreneurial mindset' among engineering students (http://engineeringunleashed.com/keen/).

modeling, and final product presentation. The course instructor, together with trained graduate and undergraduate teaching assistants are on hand during the lab sessions to work with teams and encourage critical engagement with the design process.

Assessing student mastery of course objectives

This is our second year of piloting this large-scale, project-based course. Overall, we believe that this course is helping students to develop basic skills in biomedical product design and development. Thus far, assessment of learning outcomes has relied on both formal and informal methods (Powell 2004). Weekly engagement by faculty and student instructors with individual teams provides informal, real-time indications of how well students are mastering project management and core design tasks. During the semester, students also complete 'muddiest points' exercises, and perform self-evaluations of their ability to work as a team. End-of-semester written reflections in response to a set of open-ended questions have helped us to capture the key points students are taking away from the course, as well as their self-identification of how well they are mastering different aspects of the design process.[2] We have obtained IRB approval to use homework submissions and end-of-semester reflections from consenting students as part of our assessment data for the class (Spring 2016: 104 students; Fall 2016: 78 students).

Overall, the course has thus far been well-received by students, with very strong final course evaluations. We analyzed the end-of-semester student reflections to determine, among other things, which aspects of the course they most liked and disliked (Table 2a, b), as well as the topics they self-identified as being strongest and weakest at (Table 2c, d).

(a) Course topics most enjoyed	**Spring 2016 (# of students)**	**Fall 2016 (# of students)**	**Total (# of students)**
CAD / Solidworks	59	39	**98**
Needs assessment	12	14	**26**
In-class games / activities	19	1	**20**
Design process	9	7	**16**
Getting feedback from colleagues & experts	10	4	**14**
Final presentation	5	8	**13**
Brainstorming	7	3	**10**

[2] We are aware that student self-identification might not correlate directly with more 'objective' measures of mastery, but in practice our student responses to end-of-year reflection prompts come across as honest, and match our observations as instructors relatively well. This may be in part because (i) the students were offered open-ended prompts that allow them to write their own thoughts, and (ii) the reflections were not graded, but rather students were given full credit for submitting a completed reflection (reducing pressure to come up with 'the correct' answer). Irrespective of 'accuracy' in their self-evaluations, encouraging students to reflect actively on their design experience makes them attend explicitly to what they feel they have learned, and what they have struggled with. We believe raising this personal awareness is an important part of preparing students for subsequent design experiences and 'design spine' courses (Turns et al. 2014).

(b) Course topics least enjoyed	Spring 2016 (# of students)	Fall 2016 (# of students)	Total (# of students)
Needs assessment / research	44	25	**69**
CAD / Solidworks	21	17	**38**
Brainstorming designs	5	6	**11**
Problem identification & refinement	0	11	**11**

(c) Most challenging parts of course	Spring 2016 (# of students)	Fall 2016 (# of students)	Total (# of students)
CAD / Solidworks	34	19	**53**
Figuring out and refining what problem to solve	10	25	**35**
Teamwork / making group decisions	26	8	**34**
Coming up with an original problem / solution	8	9	**17**
Figuring out a design that suits identified needs	12	4	**16**

(d) Student mastery of course topics: self-evaluation	Spring 2016 (# of students)		Fall 2016 (# of students)		Total (# of students)	
	Strongest	Weakest	Strongest	Weakest	**Strongest**	**Weakest**
CAD / Solidworks	19	11	11	11	**30**	**22**
Creativity / Coming up with ideas	26	18	11	9	**37**	**27**
Technical skills / scientific knowledge	5	6	8	2	**13**	**8**
Problem definition	19	6	10	9	**29**	**15**
Problem solving	4	1	11	18	**15**	**19**

Table 2. Student identification of (a) most enjoyed, (b) least enjoyed, (c) most challenging parts of the course, and (d) student self-evaluation of their mastery of course topics. Students were asked open-ended questions, and were not limited to providing a single response. Responses were tabulated according to an iterative coding process, in which the responses were mined for key themes, words and phrases (examples in tables). Each student response was attached to one or more theme codes. If the response did not match any existing theme, a new code was created to capture the response. Some students provided multiple responses to a single question, and others did not provide any responses. The tables above note all themes receiving a total of at least 10 responses across the two student cohorts. The trends are largely consistent across semesters; striking differences are typically attributable to differences in course content across instructors: for example, the Fall 2016 classes contained fewer in-class activities than Spring 2016 (a), and did not invite faculty experts in half-way through the course to give the students feedback on their designs (a). They did, however, spend more time grappling explicitly with problem identification and specification (b, c). The Spring 2016 section also required students to complete an explicit reflection exercise on teamwork, which may help to account for teamwork being singled out more frequently as a challenging component of the course. Upon completion of the course, students were able to identify a number of the key learning objectives from the course (see topics identified in (d)), and perform a self-evaluation of their strengths and weaknesses across these domains.

The CAD/Solidworks unit was identified by almost every student as either their favorite, least enjoyed, and/or most challenging parts of the course: 98 students identified it as the class topic they most enjoyed, while 38 singled it out as the least enjoyable; it was also the unit identified by students as being the most challenging of the course (58 students). Many of the students who enjoyed the CAD unit said it was challenging but very rewarding to see their ideas come to life in 3-D. Regarding least favorite parts of the course, several students expressed frustration with the needs assessment process and the amount of research required before they could start 'building' their devices using CAD, with some describing it as 'busywork' that felt pointless, and others as tedious but necessary. The needs assessment was identified as by far the least enjoyable part of the course (69 students), although 26 students identified the process of learning about and scoping key needs in their chosen country as their favorite topic. The degree of impatience we observed with the research process in favor of designing/building devices may point to a mismatch between our freshmen students' expectations of what engineering is, and what most biomedical engineers actually end up doing when they enter the job market (Caplan & Frow 2016).

When asked to reflect on the most challenging parts of the course, in addition to CAD drawing, 34 students identified teamwork and making collective decisions as particularly challenging. Several also identified different aspects of the design process, including problem definition (35 students), figuring out how to design within constraints to suit users' needs (16 students), and identifying an original solution (17 students). This list is broadly consistent with our instructor observations of which course topics proved most challenging for students. However, we identify the development of clear and precise problem statements as a more significant issue than many of our students do (Box 1); our observations in class suggest that students are often too quick to jump into articulating solutions rather than carefully constructing solution-independent problem statements.

Team A: The problem we are going to address is postpartum hemorrhaging during at home births with mothers who have no medical assistants.

Team B: Our goal is to reduce the prevalence and burden of diabetes in [country] through preventative care, early detection, or proper treatments.

Team C: The problem we are going to address is rehabilitation and recovery from war trauma relating to bombing/shooting wounds, targeting the affected population.

Team D: The problem we are going to address is the availability of clean and purified water in the rural areas of [country].

Team E: The problem we are going to address is reducing the presence of waterborne diseases, due to unsanitary water with contaminants that result in diseases such as cholera, diarrhea, and typhoid.

Box 1. Example problem statements developed by teams. Student teams are tasked with developing solution-independent problem statements. The above examples reflect the second iteration of the teams' problem statements, and demonstrate variety in the degree of detail and specificity in the problems that teams are proposing to address.

Interestingly, 5 of our students noted creative brainstorming as the most challenging part of the course for them (Table 2c). While this might not have been singled out as overly challenging, we noticed that many of our students struggled to think broadly and creatively when challenged to come up with as many ideas as possible for tackling their identified problem. (We note here that a poorly identified problem can in turn make brainstorming difficult.) When asked in the end-of-semester reflection what skills engineers need to successfully tackle global health problems, creative thinking / thinking outside-the-box emerged as the most frequent response (50 students, Table 3) – notably, this skill did not seem to be one the students identified as particularly challenging (Table 2c), but 27 did identify it as one of their key weaknesses (Table 2d). We wonder whether our students do not see creativity as a 'skill' that can be practiced and honed, but that it is a more innate characteristic that someone simply has or does not have. Similarly, 29 students identified 'research' as a critical skill (Table 3); it is a skill they did not identify as among the most challenging, but rather as one of their least enjoyed parts of the course. We speculate that one of the reasons students were resistant to the research component of the course is that we imposed high standards for the construction of consistent, logical arguments based directly on the needs assessment data being collected. We noticed that many students struggled to construct logical accounts of the problems they identified based on data they had collected; again, it was not unusual for students to want to rush into fixing problems that they had not carefully and thoroughly defined.

Engineering skills	**Spring 2016 (# of students)**	**Fall 2016 (# of students)**	**Total (# of students)**
Creative thinking / thinking outside the box	31	19	**50**
Teamwork	30	15	**45**
Communication skills	22	15	**37**
Human-centered design / needs of others	17	19	**36**
Research	19	10	**29**
Patience / flexibility / open-mindedness	20	15	**28**
Cultural awareness and empathy	10	18	**28**
Problem solving	11	11	**22**
Being resourceful / practical	16	4	**20**

Table. 3. Student responses to the open-ended question 'What skills do you need as an engineer to successfully work through the challenges of improving healthcare in low-resource countries?' Students were not limited to providing a single response to this question. Responses were tabulated according to an iterative coding process, in which the responses were mined for key themes, words and phrases (examples in tables). Each student response was attached to one or more theme codes. If a given response did not match any existing theme, a new code was created to capture the response. Some students provided multiple responses to a single question, and others did not provide any responses. The tables above note all themes receiving a total of at least 20 responses across the two student cohorts. The trends are largely consistent across semesters.

Of note, many of the engineering skills volunteered by students as being most important (Table 3) are not 'technical' skills, but instead highlight specific virtues (e.g. creativity, open-mindedness), teamwork and communication skills, and an ability to develop cultural awareness and an understanding of the needs of others (Rugarcia et al. 2000). We believe that these are critical skills for engineers (as do many employers), but they are not always ones that students are encouraged to prioritize in their engineering programs. We are encouraged that students leaving our freshman design course are proposing (rather than being told) that these are key skills to master.

Lessons learned and good practice tips

In our course, students have a very limited time in which to run through several core elements of the biomedical engineering design cycle; owing to curriculum constraints, they spend on average no more than 3 hours per week engaged in work for this course (total both in and out of class). There is little time for them to repeat steps and still meet the required project and presentation deadlines. As freshmen, for the most part they also bring limited technical knowledge and design experience into the classroom.

We thus face a challenge of trying to provide a clear, structured first design experience for students, but one that is also open-ended enough to allow for students to grapple with the challenge of design, and to develop creative and critical thinking skills. Whether global healthcare development is too challenging a topic is a question we continue to debate. Simply learning about the resources and healthcare systems in other parts of the world has proven to be an eye-opening experience for several of our students, and one that leaves many of them inspired to consider a career in biomedical engineering for low-resource settings (at the end of the course 55% of students say this is a career they would actively consider, with 13% not sure, and 32% looking for a different career trajectory). But we recognize that this course design allows for only very superficial engagement with potential users – a topic critical to successful engineering. Our students do not have the opportunity to meet or engage directly with the communities they are proposing to design for; nor (in almost all cases) had they visited the country their team was researching. But many of them leave the course with an awareness that this kind of engagement is critical to engineering design success.

A key challenge to developing a course where students engage more directly with clients or possible users is scale: with over 300 freshmen BME students, finding enough local partners and possible projects on an annual basis becomes resource-intensive. The very limited time available for coursework also means that local partners are unlikely to see truly viable designs emerge. In their end-of-year reflections, our students report great satisfaction with being able to develop their own projects – because no two teams work on the same country, they are not 'competing' with anyone else and have freedom to choose problems that they find interesting to work on. They have an early opportunity in their engineering program to grapple with the challenge of identifying a clear problem to work on, and to identify what kind of problem is amenable to solutions that include biomedical engineering approaches. During the course, they are also being challenged to develop teamwork and professional communication skills. Each of these skills is arguably foundational to successful engineering projects later in their undergraduate curriculum. We thus propose that this course does offer a viable approach to introducing freshman BME students to principles of product design and development, and translational healthcare in a global context.

Key lessons we have learned from running this course to date is that student instructors are critical to the success of this course; with upwards of 30 student teams working in parallel, experienced student instructors are critical to providing real-time feedback and ensuring the success of this course. Our experience from Spring 2016 suggests that students also value in-class activities and games to introduce them to different aspects of the design process. With a broad course structure now in place, we will focus our attention in upcoming semesters to devising effective methods for promoting and measuring the following key learning objectives for the course: (i) problem definition, (ii) fostering creativity, and (iii) building tolerance for ‘failure’ / revisiting ideas.

References

Allen, D. & Tanner, K. (2005) Infusing active learning into the large-enrollment biology class: Seven strategies, from the simple to complex. *Cell Biology Education* 4(4): 262-268.

Caplan, M. & Frow, E.K. ‘Work in Progress: Promoting career reflection among freshman biomedical engineering students,’ *American Society for Engineering Education*, Biomedical Engineering Division, New Orleans, 26-29 June, doi:10.18260/p.27026.

Chickering, A.W. & Gamson, Z.F. (1987) Seven principles for good practice in undergraduate education. *AAHE bulletin* 3: 7.

Dym, C.L., Agogino, A.M., Eris, O., Frey, D.D. & Leifer, L.J. (2005) Engineering design thinking, teaching, and learning. *Journal of Engineering Education* 94(1): 103.

Powell, P.C. (2004) Assessment of team-based projects in project-led education. *European Journal of Engineering Education* 29(2): 221-230.

Rugarcia, A., Felder, R.M., Woods, D.R. & Stice, J.E. (2000) The future of engineering education I. A vision for a new century. *Chemical Engineering Education*. 34(1): 16-25.

Smith, K.A., Sheppard, S.D., Johnson, D.W. & Johnson, R.T. (2005) Pedagogies of engagement: Classroom-based practices. *Journal of Engineering Education* 94(1): 87-101.

Turns, J.A., Sattler, B., Yasuhara, K. & Borgford-Parnell, J.L. (2014) Integrating reflection into engineering education. *American Society for Engineering Education*, Indianapolis, 15-18 June; available at: https://peer.asee.org/20668.

Table 1. Course structure and weekly objectives

Week	Topic	In-class Activity	In-class Assignment	Learning Objectives
1	Introduction	Role-playing game[3]	Individual	• Learning to identify user needs
2	Global health needs assessment I	Light switch activity[4]	Group	• Mapping and understanding contexts in which healthcare devices are used • Learning about national contexts and healthcare systems outside the US
3	Global health needs assessment II		Group	• Brainstorming and prioritizing among key healthcare challenges • Identifying the kinds of challenges amenable to BME interventions
4	Problem definition & concept generation	Design case study: writing problem statements	Group	• Identifying needs & users • Formulating problem statements
5	Design concept brainstorming	Lego® ducks[5]	Individual & Group	• Practicing creativity • Formulating design specifications
6	Design presentations & feedback	Design case study: Asking important questions[6]	Individual	• Learning to ask valuable questions • Practicing listening skills
7	Product assessment for selected ideas		Group	• Using feedback to inform design • Detailing design specifications

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[3] See http://www.nisenet.org/catalog/nano-around-world-card-game. This game is used to get students thinking about technology from a global perspective, and to pay close attention to the needs of different users of potential technologies.
[4] See http://cspo.org/nano-society-video-clips-part-5/. This activity is done with the class to encourage them to reflect on how biomedical devices are inevitably part of larger socio-technical systems, to justify the necessity of careful needs assessment.
[5] See e.g. http://coffeeforthebrain.com/the-powerful-learning-in-making-a-lego-duck/. This exercise is used to set a creative tone for the day.
[6] A guest faculty member comes in to share a real-life experience of designing a device for a developing-world context, where the design team didn't think to ask critical questions that led to a device that didn't suit user needs. We use this as an exercise to practice asking critical questions to inform device design, and also to think carefully about who should be asked these questions.

8	Solidworks I – introduction		Individual	• Creating simple parts with CAD
9	Solidworks II – drawing & assembly		Individual	• Creating assemblies of simple parts with CAD
10	Solidworks III – product prototyping		Individual & Group	• Creating assemblies of simple parts with CAD
11	Case study & presentation preparation	What makes for a strong presentation?	Group	• Developing presentation skills
12	Group presentations		Group & Individual	• Developing presentation skills • Asking relevant questions and providing constructive feedback
13	Group presentations		Group & Individual	• Developing presentation skills • Asking relevant questions and providing constructive feedback
14	Design iteration	Marshmallow challenge[7]	Group	• Listening to and incorporating feedback • Identifying core project assumptions • Designing experiments to test device
15	Wrap up	Decisions in innovation systems[8]	Individual	• Developing reflection skills

[7] See http://www.tomwujec.com/design-projects/marshmallow-challenge/. Students embark on this challenge at the start of class, in order to (i) set a creative atmosphere for critical review of project designs, (ii) encourage identification of core assumptions ('marshmallows') in their existing designs, and (iii) prompt individual student reflection on their approach to team work when faced with a challenge.

[8] See http://cspo.org/nano-society-video-clips-part-6/. This activity is done as part of the course wrap-up, for students to engage with 'what next?' questions regarding their specific projects/designs, as well as topics they will cover in the remainder of their BME curriculum.