Sustainable Development Challenge For BME

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You have been given the challenge to contribute to one of the UN Sustainable Development Goals. After you choose Women’s Health and Ghana as a target country, you call an alum working in rural Ghana in the Peace Corp. She puts you in touch with a nonprofit working with traveling doulas. Through your conversations and research you find that birthing position is the most prevalent cause of mother and infant complications. Over the next two weeks you design, build and test a portable birthing table that can be carried as a backpack. Two years later a more refined version of your prototype is being used in the field in Ghana.

Introduction

Recent themes in engineering have focused on sustainability, entrepreneurship, design thinking, internationalization and social justice (Murphy et al., 2009; Tranquillo 2013; Tranquillo 2017; UNESCO 2010). As improved health care intersects all of these trends, biomedical engineers are well suited to take on leadership roles. In parallel, pedagogical trends have moved toward design challenges, wicked problems, project-based learning and engagement with live case studies (Blumenfeld et al. 1991; Prince 2004; Omenn 2006; Bell, 2010; Bearey 2010; Mote et al, 2016). Biomedical engineering faculty have in fact led the way in developing many of these learning opportunities (Tranquillo and Cavanagh 2009; Gimm 2011; Abby et al., 2013; Dolan 2013).

This paper outlines how these societal and pedagogical themes can come together through work on the 17 United Nations Sustainable Development Goals. The history and content of the Goals are reviewed along with four types of thinking that support engagement with sustainability. Three case studies are presented that highlight the variety of formats and settings in which biomedical engineering students can engage with the Goals. Quantitative and qualitative assessment of student data is mapped to a framework for teaching sustainability. It is hoped that sharing the UN Sustainable Development Design Challenge will inspire other instructors to find ways to adapt the process to other pedagogical environments.

Background

In this section the definitions of sustainability are reviewed along with the history of the UN Sustainable Development Goals. The intersection with biomedical engineering is discussed along with a pedagogical framework for teaching about sustainability.
Sustainability and Engineering
The current definition of sustainability was born out of the environmental movement that acknowledged a significant human impact on the natural world, also sometimes called the anthropocene (Gibson, 2006; Gibson, 2015). The Brundtland Commission of 1987, broadened the definition to include social, economic and environmental dimensions. These dimensions are interwoven and counterbalancing in such a way that business and policy decisions should consider the impact on all three. Although alternative frameworks exist (e.g. Gibson’s seven principle approach, Gibson, 2013), the Triple Bottom Line (TBL) is the most widely cited and used by industry, the UN, and higher education. The TBL goes by other names such as The Three Pillars, The Three Legged Stool, The Three E’s (Environment, Ecosystem, Economy), and The Three P’s (Planet, People, Profit).

Engineering, both in industry and in education, has been an early adopter of sustainable thinking. Product developers design for Life Cycle Assessment (LCA), using terms such as “Cradle to Grave” and “Cradle to Grave to Cradle”, as a way to assess the holistic impact of a product on the world. Likewise, Environmental Impact Assessment (EIA) has expanded to include Life Cycle Sustainability Assessment (LCSA), Life Cycle Costing (LCC) and Societal Life Cycle Assessment (SLCA). Within engineering education, the Accreditation Board for Engineering and Technology (ABET) Criteria 3(2) reads “an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors” (ABET 2017). The ABET definition of design also includes sustainability as a design constraint. In addition, several engineering professional societies, including ASCE, ASME, ASEE, AICHE, and IEEE, have subsections on the importance of sustainable design. Many undergraduate institutions have chapters of these organizations that foster the consideration of sustainability in their programs. Interestingly, the Biomedical Engineering Society (BMES) does not have a specific sustainability subsection. Many different biomedical engineering programs, however, have built sustainability into their curricula (Tranquillo, Unpublished).

The UN Sustainable Development Goals
At the turn of the millennium an international taskforce developed eight challenges for the 192 members of the United Nations (http://www.un.org/millenniumgoals/). The eight goals, with accompanying metrics, were meant to stimulate efforts to meet the needs of the most disadvantaged people on the planet. An ambitious target date of 2015 was set to meet all of the metrics. In 2015 a report was issued outlining the state of the progress. While some metrics were met, many were not. This prompted a reframing and restatement of 17 Sustainable Development Goals, approved by the UN on September 25, 2015, that will be in effect until 2030. The purpose was to provide sub-goals and measurable outcomes that will focus the allocation of resources toward solving the world’s most pressing problems. The website (sustainabledevelopment.un.org) is well organized and contains information on several hundred sub-goals.

In the context of biomedical engineering, the goals of Zero Hunger (Goal 2), Good Health And Well Being (Goal 3) and Clean Water and Sanitation (Goal 6) would all benefit greatly from health care innovation. Other goals, such as Gender Equality (Goal
5), Reduced Inequalities (Goal 10) and Responsible Consumption and Production (Goal 12) have sub-goals that are aligned with health and well-being. Because all of these problems are interwoven, progress toward one often has an impact on the others. Goal 17 (Partnerships for the Goals) is specifically target toward looking for such synergies.

**Sustainability and Education**

Sustainability and the UN Sustainable Development Goals are rich with pedagogical opportunities. The unifying themes, concepts, ideas, capacities, abilities, beliefs, behaviors, and knowledge domains required to work on the Goals can motivate students in any discipline (Wiek et al., 2011). The Sustainability Education Framework for Teachers (SEFT) (Warren et al., 2014) has been proposed as a non-prescriptive way to help students and faculty consider sustainability, while building their capacity to thinking in four interconnected ways (systems, values, strategies, future). The framework is at the intersection of several movements within engineering education and is a way to craft and iterate upon learning environments that are challenge-based, real-world and seeded with hooks for independent inquiry and self-reflection (Stibbe and Luna, 2009; National Research Council 2000; Caine et al. 2009; Bybee, 2002; Byrne, 2010; Huntzinger, 2007). Below each of the ways of thinking are reviewed (modified from the SEFT) and paired with a pedagogical movement within engineering education.

**Systems Thinking and Wicked Problems**

Systems Thinking advocates for a networked, contextual and holistic view of the world. An abbreviate list of elements of systems thinking are:

- Seeing network effects, inertia, positive and negative feedback loops, system delays, path dependencies, bottlenecks, flows, and cascading effects.
- Recognizing patterns and underlying relationships across different bodies of knowledge and processes (from man-made to natural), places (from local to global) and times (from geo-evolutionary history to the future).
- Making sense of a complex system by extracting the dimensions that matter most (Casti and Karlqvist, 1986), so that one can intentionally make incremental interventions that will change the future trajectory of the system.
- Distinguishing between observed symptoms/signals and underlying interconnected system dynamics (Meadows, 2008).
- Dissecting how past decisions led us to the problems of today.
- Viewing a particular problem/solution as one of a constellation of interconnected problems/solutions that could exist (Grunwald, 2004).
- Seeking sustainable solutions by considering a wide range of stakeholders, including policy makers, innovators, and citizens.

There are a variety of educational movements that are closely aligned with Systems Thinking. For example, the Liberal Arts have traditionally endowed students with multiple perspectives through which to view the world. Games, simulations, role playing and toy models are excellent ways to begin teaching systems thinking (Bodnar, 2016; Tranquillo, 2014; Tranquillo, 2008) and have been used in disciplines ranging from physics and management to anthropology and psychology. Likewise, a well-orchestrated
discussion or debate can help students actively explore unexpected connections that lie beyond the information in a primary or secondary source. Among engineering educators there has also been an emphasis on the T-shape (Tranquillo, 2017) and E-STEAM (Entrepreneurship and Arts combined with STEM).

Engineering educators have adopted Project Based Learning (PBL) as a form of Active Collaborative Learning (ACL) that is closely related to Problem Based Learning and Guided Inquiry (Prince, 2004; Prince and Felder 2007). In PBL student teams are presented with a problem that is ambiguous and/or has incomplete information or constraints. Often the problem inherits multiple constraints from different natural and man-made systems and maybe in conflict with one another. Solutions are not prescribed or predetermined ahead of time. Students are often given autonomy over design decisions. Typically, the outcome is a functional artifact, often a physical prototype, but may also be an on-paper solution concept.

An extreme type of PBL is the Wicked Problem. The term “Wicked Problem” was coined in 1967 by C. West Churchman, but more formally defined in 1973 by Rittel and Webber. Wicked problems are those that seem impossible to solve because they are have incomplete, changing, contradictory and trans-disciplinary constraints. These constraints are inherited from such a wide range of disciplines and stakeholders (including but not limited to socio-culture, economic, technological, geo-political and legal) that no one person or discipline can fully define or solve the problem. Because there are no optimal solutions, it is often not clear when the problem has been solved. The UN Sustainable Development Goals are the ultimate Wicked Problems in that they require trans-disciplinary, trans-scale and trans-time thinking. Students are stretched cognitively in their skills, knowledge and attitudes by engaging with these types of problems (Kim and Tranquillo, 2014).

Values Thinking and Live Case Studies
Values Thinking derives from the ethical dimensions of over-consumption and the inequitable distribution of resources, but extends beyond these considerations. An abbreviate list of elements of value thinking are:

- Considering how various views, values and cultures have been constructed from past choices and preconceived value-based beliefs (Rawls, 1985).
- Recognizing major human conflicts as arising from conflicting worldviews, unequal resource allocation and historical biases (Ostrom, 1990).
- Positioning value-based tensions between stakeholders in ethical terms.
- Finding mechanisms to be more inclusive and equitable across stakeholders to reduce bias in the status quo.
- Determining the justice, equity, and social-ecological impact of proposed solutions (Holifield et al., 2010).
- Ensuring broad-based consensus and transparency in decision making (Fisher, 1993; Corburn, 2007; Backstrange, 2003).
Values thinking helps students seek out and understand different points of view, as well as develop (and perhaps question) their own personal point of view. Engagement with values thinking can be emotional and can therefore lead to ‘sticky’ learning environments (Caine, 2009). Active listening/participation, role-playing, debates, structured discussions and case studies have all been shown to be effective techniques in the classroom. Out of the classroom, several High Impact Practices (Kuh, 2008) build value thinking, such as community-based learning, service learning and diversity/global learning. Engagement in these practices has many overlaps with self-determination theory (Gagne and Deci, 2005), most specifically the need to see a wider purpose in one’s actions.

Live case studies are a pedagogical technique that can highlight value-based thinking (Beaury, 2010). Traditional case studies, especially those from engineering and business, are retrospective. A specific story is told of a problem and decision making pathway that resulted in a particular solution, followed by an analysis and take-away message that can be applied in other situations. The learner in these types of case studies is often passive and does not contribute to a solution. A live case study presents a problem and then asks the learner to more actively explore and engage in the decision making and value creation process. Most live cases are presented as a current problem, of varying levels of complexity, faced by an organization that if solved would provide them with some measureable value.

The UN Sustainable Development Goals naturally encourage values thinking. Some other published goals, such as the National Academy of Engineering Grand Challenges (e.g. Enhance Virtual Reality, Secure Cyberspace) do not have a clear connection beyond the developed world and high technology. Generation Z students, defined as those born after the mid-1990’s, are acutely aware of their privileged place in the world and are looking to make a difference. The rise in student outreach clubs, study abroad, service learning and community based learning all demonstrate that students are more attune to social justice issues. In fact, biomedical engineering programs have been early adopters of including value thinking, most especially through Devices for the Disabled (Enderle, 1999), Engineering World Health (www.ewh.org), e-NABLE (enablingthefuture.org), and the proliferation of programs that specifically consider design for the developing world.

**Strategic Thinking and Design Challenges**

Strategic Thinking was born out of the business literature. It also has been a hallmark of engineering design, in the form of project management, and more recently Design Thinking (dschool.stanford.edu). In general it is focused on problem finding, solution generation and execution. Elements of strategic thinking are:

- Seeing inefficiencies, tensions, and stakeholder pains in the status quo as opportunities for a new or improved value proposition.
- Identifying stakeholders and users, uncovering the history of the problem, researching previous attempts to solve the problem, and listing constrains coming from a wide range of disciplines.
- Developing an inspirational vision and strategy that brings people and resources together.
• Exercising creativity in developing potential solutions that take into account needs and constraints (Costanza, 2011; Gibson, 2006; Lawrence, 1999).
• Demonstrating sound decision making in selecting a particular solution that will best balance the competing needs and demands of stakeholders.
• Developing tactics that will make the most of the available resources and skill sets of individuals and groups.
• Finding quick wins that will build further consensus and collaboration so that the solution will propagate outward to meet the problem everywhere that it may be.
• Considering how a solution will scale across time and space for various stakeholders (Loorbach, 2007) so as to ameliorate negative unintended consequences.

Strategic thinking often feels natural to engineers, and is woven into the design process and design thinking. The general idea of strategic thinking, however, can be applied broadly beyond the development of products to include the generation of new policies, institutional frameworks and governance. From a pedagogical perspective, learning is greatly facilitated by real situations and contexts where the strategies employed are truly the decision of the students (e.g. there is no “right” path laid out ahead of time). From self-determination theory this is the ability to have autonomy in the face of ambiguity (Gagne and Deci, 2005). As the UN Sustainable Development Goals are layered, nested and far too large for any particular group to make significant progress on, they require all of the elements of strategic thinking to be engaged in developing and deploying solutions.

A movement that has taken place over the past few decades is Design Challenges both inside and outside of the classroom. They often employ many of the features of PBL but are short, lasting a few days to a few weeks. As such they are immersive, moving from start to finish quickly, putting disparate concepts close to one another in time in such a way that they can potentially form a bond. Immersive experiences can be emotionally intense, another precondition for sticky learning environments (Kim, 2014; Gagne and Deci, 2005). In the literature they are also sometimes referred to as Innovation Challenges (Condoor and Keogh, 2012), Design Sprints, Hack-a-thons, Start-up Challenges and Pitch Competitions. The topics can range from trivial (e.g. design a lunch box for school children, logic puzzles) to very grand, but often focus on early stage entrepreneurship and innovation. Biomedical Engineering was an early adopter of such challenges in required classes (tranquillo and Cavanagh 2009; Gimm 2011; Abby et al., 2013; Dolan 2013). Some advice on running design challenges can be found at http://epicenter.stanford.edu/resource/design-bootcamp-joe-tranquillo-bucknell-university

Future Thinking and Entrepreneurship
Future Thinking, also known as anticipatory thinking, foresight, or trans-generational thinking (Rockstrom et al., 2009) includes the following elements:

• Recognizing how decisions, actions and inactions made by others in the past affect our options, constraints and problems today, and likewise how our decisions, actions and inactions will impact others in the future. (Our Common Future, 1986).
• Viewing current driving forces and emerging trends as guides to possible future trajectories (Robinson et al., 2011; Kuhlman, 2001).
• Envisioning possible futures (e.g. utopian, dystopian, plausible, desirable and likely) (Selin, 2007) and contrast them with the present status quo as a means of building forward-thinking strategies or ‘backcasting’ (Robinson et al., 2011).
• Considering intergenerational perspectives, including interventions, ideas, and/or solutions that might create cascading effects that become tomorrow’s problems (Gibson, 2006).
• Using both causal and effectual thinking (Sarasvathy, 2001) to actively bias history toward a safer, happier and healthier future for all, rather than accepting a less desirable future (Newman & Jennings, 2008).

The nature of grand challenges and goals is to be future thinking. The UN Sustainable Development Goals are perhaps the most ambitious acknowledgement that the world is not as it should (or could) be. The engagement with a future that is larger than oneself can prompt deeper thought into how one might impact the world in the future.

Entrepreneurship and sustainability often seem to be at odds with one another. A simplistic definition would be that entrepreneurship focuses more on short-term value (often localized to particular stakeholders), while sustainability is focused on long-term value (often regional or global) (Tranquillo, 2017). Both, however, are oriented toward the future and there are in fact many marriages between the two. Programs such as social entrepreneurship in engineering schools and sustainable finance programs inside of business schools have grown in popularity. Furthermore, the entrepreneurial mindset, although not well defined (Zappe, 2013), is focused on developing the habits, behaviors and attitudes of an entrepreneur so that they can be applied broadly to any endeavor. The four elements of sustainable thinking closely parallel most definitions of an entrepreneurial mindset. It may be that systems, value, strategic and future thinking could be used as a framework for thinking about entrepreneurial thinking as well.

Offerings and Research Methods
In this section, three versions of a sustainable development challenge are presented that included biomedical engineering undergraduates; One was extra curricular (a January experience), one was co-curricular (a study abroad elective) and another was required (senior capstone introduction). The goal of each was to work in a team to build a prototype for a device to that would aid in meeting one of the UN Sustainable Development sub-goals. Also in this section are the methods used to assess the programs using both structured (e.g. reflection ladder described in Tranquillo, 2016) and unstructured prompts. Specific assignments and a timeline of topics and lectures are given in Appendices A and B.

Senior Capstone Introduction
Over the past 12 years, teams of 2-3 students engaged in a design sprint as a kick-off to the senior capstone (Tranquillo and Cavanagh, 2009). Rather than pass out a syllabus for a two-semester design capstone, the challenge served as an introduction to the course. For the past three years, the challenge has been driven by the UN Sustainable Development
Goals. Each self-selected team was asked to identify one of the Sustainable Development Goals and a country in which that goal is particularly pressing. Through a series of guided exercises they focused on a sub-problem, articulated a value proposition, and developed several on-paper solutions. They then selected a solution, built a working prototype and developed and executed simple validation tests. The challenge concluded with an expo that was evaluated by the faculty. Assessment of the design sprint was formative only, both written and oral, at multiple points during the project. By way of communicating the details, as well as providing instructors with template text to share with students, assignments are shared in Appendix A.

**KEEN Winter Interdisciplinary Design Experience (K-WIDE)**

K-WIDE is a non-credit bearing January design challenge that engages sophomore-level students in developing solutions to Wicked Problems. Over the course of 10 days, and approximately 130 hours, students must move from finding their own problem to building a product to a pitch at an open expo. Students are never shown or taught the design process. Instead they are required to discover and create a process by considering their project from many viewpoints – not just the 5 foot view of how to solve their problem, where most engineers spend their time, but also the 50,000 foot view of impact on the world. Near the end of K-WIDE each student sketched out the process they followed. They were all unique, but there were some themes. None of the diagrams were the simplistic design process found in most textbooks. Instead, they were tangled non-linear webs of activities – exactly what is needed to solve messy tangled problems, mirroring Conway’s Law (Conway, 1967) and theories of organization change (Senge, 2006) Their drawings naturally included economics, ethics, historical context, social and political impact - in essence, they had learned to view engineering design as systems thinkers.

Another feature of the program is the focus on mindset, and in particular six hats that students “wear” throughout the program (Designer, Project Manager, Maker, Professional, Role Model and Value Creator) that roughly align with the four ways of thinking. A great deal of the program also focuses on reflection and intentionality. Details of the program may be found at www.bucknell.edu/kwide and in Kim and Tranquillo (2014). Prior to 2015, the motivation for the program was from the NSF Grand Challenges. The past two years, however, the themes have aligned with the UN Sustainable Development goals. The program has spread to several other schools.

**Chilean Ruka Project**

In May 2016, a course called Engineering in a Global and Societal Context was offered in Chile for 33 engineering students. The three-week trip, involving 8 flights and 17 bus rides, was focused on the impacts of engineering and science on natural, cultural and designed environments. Sustainability was a major theme of the trip (Canziani et al., 2012), much of which is documented online at https://www.bucknell.edu/news-and-media/current-news/2016/august/follow-bucknell-engineers-on-an-educational-adventure-through-chile.
As part of the trip, the students and faculty stayed in a Ruka (a large round, traditional Chilean structure) where they engaged in a Sustainable Development Challenge for four days. The format was similar to the Senior Capstone and K-WIDE described above, with one notable exception; The Ruka was out of cell phone range, did not have internet access and the nearest source of building materials was approximately 50 kilometers away. Appendix B contains the two pre-assignments used to prepare students for the challenge.

**Research Methods**
For each offering an IBR approved survey (Appendix C) was administered after the experience. Included in the data collection for this study were the past three years of the senior capstone experiences (n=46 out of 47, 27/20 female/male), one offering of K-WIDE (n=16 out of 16, 7/9/1 female/male/trans), and one offering of the Chile Ruka Project (n=33 out of 33, 20/13 female/male). All numerical and qualitative feedback (n=95 out of 96) were combined with end-of-experience reflection and anonymized for analysis. Of the 96 students all but two were engineering majors. Qualitative analysis consisted of isolating 854 student quotes and then coding for the four types of thinking (Systems, Values, Strategy or Future). The two coders developed their independent assessment and then reached consensus on the coding of individual quotes. It should be noted that no questions (in the survey or reflection prompt) explicitly asked about the four ways of thinking. Additional terms that emerged during coding were “Design Competency”, “Mindset Growth”, “Professional Development” and “Advice on Format”. In some cases a single quote identified with more than one code variable.

**Results**
In this section the results of surveys (see Appendix C) and reflections are summarized. For the elements of the design challenge, students believed the length of time (4.2±0.4), team size (4.5±0.6), team formation (4.3±0.7), regular assignments (4.5±0.5) and final physical artifact (4.5±0.7), were appropriate. Students were less receptive to the mini-lectures on design (3.8±0.6), the development of objectives and specifications (3.8±0.9) and brainstorming alternative solutions (3.6±0.7), but appreciated choosing their own problem (4.1±0.5), building a real prototype (4.1±0.8), testing (4.1±1.1) as well as the final pitch (4.5±0.6) and exposition (4.7±0.5). In general students felt that the real-world (4.5±0.5), complex (4.0±1.0) and impactful nature (4.9±0.3) of the challenge aided in their experience and learning. Less important were that the problems solved were nested within larger problems (3.8±0.9) or large in scope (3.4±0.7).

**Systems Thinking**
Of the 854 quotes, 94 indicated systems thinking. Many students commented that a “problem is not always the problem [they] think it is”, but that having a “research-backed and holistic view of the user” and “think[ing] about designs through many people’s points of view” were the keys to “seeing the bigger picture in the project”. They recognized that “most of the technical barriers to impact are fairly low” while it is the “socio-political ones that are really tricky”. They commented that “a solution is not a solution except when it is put in a context”, and that it is “hard to solve even the simplest problems […] when put in a context larger than just the technical”. Likewise students in
the on-campus experiences often cited “how important it was to have a backstory”. Students from the Ruka Project shared that the project “helped [them] understand the culture better when design[ing] for that culture”. Many commented on the synthesis that they encountered, such as how “hard and soft skills come together”, “engineering intersects with the liberal arts” and the “gather[ing] together all of the [design] information helped connect to the country”.

**Values Thinking**  
Of the 854 quotes, 214 indicated values thinking. Students commented that the challenge, “did not feel like a class assignment”, that they “got more out of it because it meant something [to them]”, and “evoked a real emotional response”. For example, one student said, “I have given lots of 1 minute pitches, but I really cared about giving this one”. Several students commented that they never “realized how important story would be in inspiring [us] to do our best”, and that they “were creating a story, not just a device”. Likewise, they could more clearly see “how engineering could really make a difference in the world” by “us[ing] their engineering skills and knowledge to have a positive impact on the lives of others”. To one student it was a “reminder of why I majored in engineering”. Many reported how working on an “uncomfortable yet critical topic” helped them “learn about the problems facing another country” and that this was “really enlightening”. For example, one student “found [herself] pouring over anthropometric data from women in South Sudan” and “never thought that [she] would get into the research aspect of the project but found that [she] really enjoyed it and was surprisingly good at it.”

**Strategic Thinking**  
Of the 854 quotes, 105 indicated strategic thinking. Student often discovered common techniques of project management, teamwork and innovation on their own. They reported that “planning ahead is critical”, “things took longer than expected”. Students tried “not to dwell on wrong turns” and that found that “the quest for perfection can sometimes [be] the enemy of forward progress”. They found they could “g[e]t a lot done through many shorter unstructured meetings than long formal meetings”. Several students commented that they found they could be “resourceful, even when [they] didn’t have many resources”, and that they began to notice “how many resources [they] have around”. They were happy they could “take any direction [they] wanted, but needed to be able to justify it”. “Having a hard budget helped […] focus and eliminate[d] some grand ideas that probably wouldn’t have worked”. Likewise several students commented that they “needed to be creative when [their] original design didn’t work”. They saw the “fast pace” as helping them “recognizing different strengths”, “diverse backgrounds” and “embrace[d] a divide and conquered approach”.

**Future Thinking**  
Of the 854 quotes 34 indicated future thinking. Some students said they were “excited about working on hard problems” and that it “gave [them] faith that [they] could make progress on huge problems” in the future. They “learned to frame the faults of current devices as next steps in the design process”. Through the experience they, “started to recognize when [an] idea might be feasibility and when it was something that wasn’t” but
even when it wasn’t they could “find a way to make it more feasible”. Several students indicated that they “really want to keep working on [the] project” and “[would] look for ways in the future to keep addressing big problems like the UN sustainable development goals”, even though “the payoff may not be in [their] lifetime”.

**Design Competency**

Of the 854 quotes, 153 indicated a perceived growth in design competency. Students often found “a passion for engineering design”, growth in their “ability to be an impactful engineer” and “surprise” about “how much a group of aspiring engineers could come up with” in a short time. A sentiment expressed by several students can be summed up in the quote: “Our team realized that just about everything we were coming up with, we could think of a way to build it. This surprised us. And it got us thinking about all the classes we have taken – now we know why we took them all! It helped really drive home why I want to be an engineer […] I feel even more excited now to be starting our capstone project.”

Following a non-linear design process was also a theme, with students often mentioning “making sacrifices in our design”, moving through “so many different designs and prototypes […] we can’t even remember all the twists and turns we took”. They found themselves “improvising often”, “making assumptions and then testing them out” and “doing small trials along the way”. Students also discovered some important design principles, for example, “[sometimes simple is best]” and “not every device needs to be extravagant to have an impact”. Likewise, “the first, second and third idea are often not the winner” and that “doing background research all throughout the process [was] the key to making decisions”. Several students expressed that “when encountering a truly hard design problem in the future, [they] will most certainly approach it differently”.

The real-world nature of the design challenge was also cited by one student as the “first time that I really felt like I was doing the kinds of things that I will be expected to do in a real engineering firm”. Other students expressed that they had “worked on several design projects in the past through other classes, internships and several summer experiences”, but that this challenge was the “first thing I have designed, from start to finish, that I felt someone might actually use.” Likewise, students who had worked for “product design firms over the summer”, said that the challenge “felt similar” and unlike “the usual sterile classroom assignment[s]”.

**Mindset Growth**

Of the 854 quotes, 117 indicated a perceived growth in attitudes, behaviors and abilities. Students were sometimes frustrated that they “couldn’t use the same mindset as in their classes” but that the experience “changed how [they] would think about challenges in the future”. Many students commented that although they “were hesitant to change solutions” they found they needed to “adapt as [they] tried things […]” and the best approach was to “test and quickly move on”. Students also reported becoming more resilient, “finding ways to pick [them]selves back up after something didn’t work”. For example, one student shared, “we learned that sometimes we needed to just move on if we got stuck and then come back later after we knew more”. Although “at times the project felt
overwhelming – it really stretched what [we] thought we could do in two weeks.”
“Remaining open to new ideas, especially if they [were] coming from someone else”,
“improvement in [our] ability to draw sketches and convey design ideas” and “a focus on
good brainstorming techniques” were also themes. Some students found that the “lack of
resources helped stimulate better ideas, by closing off the obvious paths” and helped
them “overcome design hurdles” by encouraging them to “ask for help from experts”.
The lack of resources also help them “trust more what [they] already knew and to “view
[their] own knowledge and skills as the greatest design resource”. Many students were
surprised by “how much [they] could learn outside of a classroom”, and that they found it
easier to “learn something new, like a skill, […] from a peer [rather] than from a
computer”.

Professional Development
Of the 854 quotes, 58 indicated a perceived growth in professional development, most
especially “how I like (and don’t like) to work”. Students cited becoming “better at
communicating ideas to others”, being a “leader at some times and the follower at others”,
and were “surprised to realize at the expo how much [we] had accomplished in such a
short time”. From the experience and the reflections students generated, “great stories to
tell future employers” and “motivational stories that will keep [them] going in the future
when things are frustrating”.

Advice on Format of Design Challenge
Students provided a wide range of comments on the aspects of the challenge that they
thought added or hindered their progress or learning. They found most helpful the
“frequent assignments”, “choosing their own team”, “finding [their] own problems” and
the “photo essay as a way to get started”. Many of these comments were directly tied to
the immersive nature of the challenge. Although some commented that “it would have
been good to have had more clear directions”, others acknowledge that “this would have
ruined our creativity”. “The pitches really brought home how much we learned”, and
“some guidance” and “encouragement from the faculty was really important”. On the
other hand, some commented that they “would have liked to have more time to
brainstorm”, “a mock-expo […] to work out the bugs” and a “requirement that everyone
should […] test something”.

The Chilean Ruka Project added another layer of comments. Several students said, “the
biggest challenge [they] encountered during the whole trip was the design challenge
because of how much [they] didn’t know” and that the “days we spend in the Ruka were
critical” to bonding as a group. One student shared that the “experience was totally
different than if it was in a classroom or even if it was in the US. “It introduced me to a
different way of thinking.” Another student wrote, “I thought this challenge would be
impossible when I heard about it”, but then “realized that I can be an engineer even when
I’m not surrounded by technology.” One month after returning, several students
commented that, “of all the amazing things we did and saw, the thing I will remember the
most [will be] the design challenge”.
Discussion
The UN Sustainable Development Goals are as open-ended as any problems students will encounter and they naturally exercise interdisciplinary thinking and innovation across disciplines. Feedback from students shows that The Goals resonate with Generation Z students and helps to bring out active, creative and collaborative engagement with the problems they will face as a generation. Although students are often aware of global problems, they appreciated a deep dive into a particular problem. From a technical perspective it was striking how quickly a group of students could identify and build a working prototype of a device that could matter. These experiences also build powerful stories, such as the vignette at the beginning of this article.

The Sustainability Education Framework for Teachers (SEFT, Warren et al., 2014) was not only a good framework for coding student comments but also revealed dimensions that could use more attention (Wiek et al., 2011). Future thinking scored relatively low compared to the other coded terms. Perhaps some changes to the mini-lectures or assignments might direct students to consider the future more. Likewise professional development scored low. One intervention that has worked in other settings is to conduct mock interviews midway through and at the end of an experience (Kim and Tranquillo, 2014). The intention is to allow students to practice how they will describe what they did, not in the form of the formal pitch but in a more natural conversation.

The opportunities provided by the UN Sustainable Development Goals are vast and only a small corner of the pedagogical space was explored in this study (Adams, et al., 2003; Byrne et al., 2010; Huntzinger et al., 2007; Omenn, 2006; Tillbury, 2011). Entire courses could be offered, potentially where technical iteration and validation testing could be combined with stakeholder interviews, business model generation, impact statements and grant writing. Likewise the deliverables could range from on-paper design to technologies to the design of social programs or policies. Some students commented verbally that they would have appreciated including non-STEM students into the challenge, seeing that these students could have made meaningful contributions to the designs. Many high schools and middle schools are also including design and entrepreneurship in their curriculum and there has been a rise in maker spaces and socially oriented clubs in K-12 (Omenn, 2006). This author has run similar challenges with Kindergarten classes and at a retirement home. Regardless of the setting, it is important to tune the challenge and deliverables to the students’ zone of proximal development (Wertsche, 1984) and couple work with reflection (Adams, 2003).

Conclusion
Biomedical engineering students and faculty, due to the interdisciplinary nature of our field, are particularly well situated to lead both in sustainability education and making progress toward specific UN Sustainable Development Goals. Student feedback has shown that BME students gain a great deal from engaging with the Goals. It is hoped that sharing the UN Sustainable Development Design Challenge will inspire other instructors to find ways to include sustainability in their own pedagogical environments.
Acknowledgements
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Tranquillo J (Unpublished) BME Program Survey


Appendix A: Capstone Timeline and Assignments

It is important that students receive scaffolding to navigate the open-ended nature of the challenge. Below is a

Project Introduction
You will work in teams of two or three to identify and construct a device that will address one of the specific Sustainable Development targets listed in the bottom section of https://sustainabledevelopment.un.org/focussdgs.html. Regardless of the topic chosen, the impact must have some tie to improving health and wellbeing. You are encouraged to think and build creatively while also letting you show off your technical talents. While you will only build one functional prototype, you should be able to explain how scaling and distribution will make an impact.

Process and Grading
The overall purpose of the design challenge is to familiarize you with the design process, from problem identification through prototype testing. Class and lab time will be utilized for discussion of design topics and for work on projects. While teams will have frequent written assignments to turn in throughout the process, these assignments will be brief and therefore allow teams to focus most of their time on the identification and construction of their design solution. The design challenge will account for 10% of your overall grade for BMEG 401 and will be based upon your process and performance at the expo as evaluated only by the instructor.

Design Constraints
The instructor will verify that the constraints below have been met at the expo
- Cost less than or equal to the total budget allocated to the team (see below)
- Demonstrate the functionality of the prototype in 5 minutes or less
- Directly or indirectly providing a value to health care
- Directly address one of the first 16 Sustainable Development Goals (see above)
- The device should be scalable and relatively easy to construct
- Show evidence of a quantitative performing assessment of your final prototype
- Contain no more than two 3D printed parts

Supplies and Budget
Each team will have a guaranteed budget of $25 and provided access to an additional $25 following the submission and approval of a your memo (8/30). If teams need a cash advance to make purchases, they should contact the instructor. As teams are expected to go through multiple construction phases, you should plan your budget carefully. Teams are allowed to utilize tools and materials in the BME labs as long as they are returned when the challenge is over. Turning in receipts for your parts will allow you to be reimbursed for your expenses. Any grey areas in policy should be passed by the instructor before a team utilizes a questionable supply.
Final Exposition
The final expo will consist of a one-minute pitch from each team followed by a 45 minute open expo. You may use any materials or aids that you feel will help you in communicating your device, but purchased materials will come out of your budget. Each team will be assessed by those present (potential funders) at the expo. Each funder will have $100 (fake money in $20 increments) that they may invest in a project. The overall winner will be the team who has raised the most start-up funds. Funders may request a demonstration, evidence of testing, details on the technical design, or further clarification of the value proposition. In addition to investing, each funder will indicate their top three teams (ranked 1,2,3) in the following four categories:

- **Value Proposition**: How well is the device matched to the end goal as stated by the team? Would scaling and distribution of a refined device have the intended impact?
- **Functionality and Usability**: Does the device do what it is supposed to? Are the tests well designed and executed? Are the results convincing such that the functionality of the device is sound? Is the device designed with the user in mind?
- **Design and Fabrication**: Is the quality of the design and construction such that the team has made good use of their technique skills? Have they followed a design process?
- **Innovation**: Is the device unique? Does it have a chance in a global marketplace?

Timeline
As indicated in the schedule below, teams will be required to achieve specific milestones as the design challenge progresses. The final prototype will be evaluated in the final Design Challenge Exposition.

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Topic/Event</th>
<th>Assignment Due</th>
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<tbody>
<tr>
<td>8/21</td>
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<td>Design Intro, Users and Objectives</td>
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<tr>
<td>8/23</td>
<td>W</td>
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<tr>
<td>8/23</td>
<td>W</td>
<td>Design Doc, Memos, Specifications</td>
<td>Problem, Users, and Objectives</td>
</tr>
<tr>
<td>8/25</td>
<td>F</td>
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<td>Functions and Specifications</td>
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<tr>
<td>8/28</td>
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<td>Sketches, Design Decisions</td>
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<tr>
<td>8/30</td>
<td>W</td>
<td>Prototypes, Validation and Testing</td>
<td>Solution, Memo, and Meeting</td>
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<td>8/30</td>
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<tr>
<td>9/1</td>
<td>F</td>
<td>Build – Test – Refine</td>
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<td>M</td>
<td>Build – Test – Refine, Presentations</td>
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<tr>
<td>9/6</td>
<td>W</td>
<td>Build – Test - Refine</td>
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<tr>
<td>9/6</td>
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<td>Design Competition, Capstone Teams</td>
<td>Design Challenge</td>
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<tr>
<td>9/8</td>
<td>F</td>
<td>First Day of Capstone Project</td>
<td>Design Challenge Reflection</td>
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**Assignment #1: Problem, Users and Objectives**
Based upon your research, you must generate a problem statement for your device. The following guidelines will help you craft your statement:
1. The statement must be one self-contained paragraph
2. No graphics (figures or tables) are allowed
3. The writing style should be understood by a lay audience
4. No particular design solution should be stated or implied
5. The last line of the statement should be in bold and give a one sentence summary of the problem.
6. You must focus on a particular developing country, but may also point to other countries or areas that have a similar problem.

Based upon our discussion of users and needs,
1. Create a list of the people you would contact to discuss the needs for your device
2. Create a list of the multiple types of users of your device
3. Create a list of known and anticipated needs and wants for each of the users identified above (thoughtful work here is key to success in the rest of the assignment).
4. Identify which needs are objectives and create an Objectives Tree of at least four levels

**Assignment #2: Functions and Specifications**
Based upon you problem you must report the functions and specifications that should guide your solution generation and later validation testing.

**Functions**
Using the user needs and objectives you identified in assignment #1, identify up to 10 desired functions of your device. Recall, functions are derived from user’s needs and are intended to describe what the artifact must do. Identify each function as basic or secondary

**Specifications**
For at least 5 of the functions identified:
   a. Determine (or estimate) the appropriate design specifications. Recall that the specifications must be measurable and indicate how well the artifact performs each function.
   b. Indicate the type of specification (as outlined in class) next to each specification.

**Assignment #3: Alternative Solutions**
Generate a list of preliminary solution ideas for the design challenge. Do not constrain yourself as to what seems reasonable or doable. In your team brainstorming generate as many ideas as possible, no matter how far fetched. You must submit a list of all solutions generated. Solution ideas may be presented in graphical form (i.e. a sketch). You will be asked to share your alternative solutions at a meeting on August 31st.

**Assignment #4: Update Memo and Meeting**
As an interim check-in you must submit a one page memo and run a meeting.
1. Write a formal one-page memo outlining the following items:
   a. A solution chosen from the list of alternative solutions along with justification. Your solution should include a sketch of your intended design. Justification should be tied directly to how your device will solve the problem as stated in your problem statement by meeting all of the specifications.
   b. Timeline for building and testing the chosen solution by the design challenge contest.
   c. A list of materials (for building and testing your device) with associated costs. This includes any requested additional funds, with justification.
   d. Tests you may conduct to demonstrate the functionality of your device.

   The memo must be placed in Dr. Tranquillo’s dropbox

2. Conduct a meeting with Dr. Tranquillo on August 30th. The meet should be no longer than 15 minutes and address points in the memo. The team should drive the meeting forward using questions that are prepared ahead of time.

Assignment #5: Reflection
The design process is THE defining characteristic of the engineering profession. You have just spent two and a half weeks confronting the process, and will continue on with a new project for the next year. The purpose of this reflection is for you to take an hour or two to look back over your notes, assignments, and final project.

You must summarize your reflection in a one-page (single spaced, 12 pt font) first-person narrative style. You are ‘graded’ not by what you say you got out of (or did not get out of) the design challenge, but how in-depth have you looked at new skills, knowledge or attitudes that you may have gained, or where have you identified shortcomings that you would like to address. You are encouraged to use the reflection ladder to help you go deeper.

Some question to consider are the following:

1. What do you feel were the strengths / weaknesses of your team’s effort?
2. What do you feel were your own strengths / weaknesses?
3. What would you do differently when you encounter design again?
4. What skills from the design challenge will you carry over to your design project?
5. What technical experiences and skills did you gained?
6. How might you describe these technical and soft skills to a potential employer?
Appendix B: Pre-assignment for Chilean Ruka Project

To be completed in country (Chile)

Spend 10-15 minutes on your own (quietly) exploring the 17 UN Sustainable Development Goals at: https://sustainabledevelopment.un.org/sdgs

On a sheet of paper write down your name and the top three topics you would like to explore while in Chile (not counting Goal 17). You are not committing yourself to any one topic at this point. This is the first step to identifying potential problems to solve.

Once we are in Chile we will assign you to two of your three choices. As we explore Chile during the first week of our trip, you will create two photo essays (of your own photos) that show challenges and opportunities that exist with regard to your two assigned UN goals. You are expected to find stats, cite sources and use text to supplement your photos.

Your photo essay should capture the following dimensions of your problem

- Who are the stakeholders (broadly) (*)
- Economics (micro and macro)
- Socio-political impacts
- Geographic/climate considerations
- Cultural/historical perspectives
- Ethical concerns
- Technical solutions, either existing or possible (*)

You must do the ones that are * and then pick at least two others (or come up with one on your own)
Appendix C: Design Challenge Student Survey

Consent Form
It was wonderful to see what you have accomplished over the past few weeks on the UN Sustainable Development Challenge. This challenge was part of a wider educational trend, started at Bucknell, to use design challenges as a way to illustrate the complex and real-world nature of the design process. This study has the following research questions:

1. What elements of a design challenge (scope, teams, length of time, complexity) contribute to the learning experience?
2. To what extent do students carry lessons learned from the design challenge into their senior capstone?
3. What skills, knowledge and attitudes do students take away from design challenges?

We are asking that you spend 10-15 minutes filling out the survey below to the best of your ability. You will fill out the same survey again once you have completed the year-long senior capstone. You are not required to fill out the survey, and your answers are in no way linked to formal course evaluations or student assessment. Any answers you provide will remain anonymous, and the individual data will be destroyed after the results have been tabulated.

Each question should be score on the following scale

1 = strongly disagree
2 = disagree
3 = neutral
4 = agree
5 = strongly agree

Design Challenge Elements
We would like to collect information regarding the make-up of the design challenge.

1) The length of time was appropriate
   1   2   3   4   5

2) Regular assignments helped navigate the challenge
   1   2   3   4   5

3) The team size was appropriate
4) A physical artifact (e.g. not an App, business plan or policy) was appropriate

5) Short talks on elements of the design process were helpful

6) Self-organization of teams was helpful

**Design Challenge Assignments**

We would like to collect additional information on what you feel you learned throughout the challenge that you will carry with you into your senior capstone project, and perhaps beyond.

1) Your own Identification of the problem

2) Developing your own objectives and specifications

3) Brainstorming alternative solutions

4) Performing background research on your problem and existing solutions

5) Building a real prototype

6) Designing and running a test for your prototype

7) Preparing a pitch and product demonstration

8) Ending the challenge with a expo and competition
**Design Challenge Motivation**
We would like to also understand what elements of a design challenge make for good design challenges.

It is important that the design challenge was

1) Large in Scope (e.g. they apply in space to the entire globe and in time to centuries if not millennia).
   
   1 \hspace{1cm} 2 \hspace{1cm} 3 \hspace{1cm} 4 \hspace{1cm} 5

2) Real-World (e.g. motivated by problems that you hear about in the news)
   
   1 \hspace{1cm} 2 \hspace{1cm} 3 \hspace{1cm} 4 \hspace{1cm} 5

3) Complex (e.g. There are no silver bullets. No one discipline can claim the problem, and no one discipline will be able to solve it).
   
   1 \hspace{1cm} 2 \hspace{1cm} 3 \hspace{1cm} 4 \hspace{1cm} 5

4) Hierarchical but Decomposable (e.g. the problem is actually several problems which, if addressed will help move toward a larger solution)
   
   1 \hspace{1cm} 2 \hspace{1cm} 3 \hspace{1cm} 4 \hspace{1cm} 5

5) Impactful (solutions have the potential to be of great value to society).
   
   1 \hspace{1cm} 2 \hspace{1cm} 3 \hspace{1cm} 4 \hspace{1cm} 5

**Design Challenge Learning**
From the design challenge I will take away:

1) A broader understanding of how engineering design can impact the world
   
   1 \hspace{1cm} 2 \hspace{1cm} 3 \hspace{1cm} 4 \hspace{1cm} 5

2) The following new skills (things you can do, such as take apart a motor)
   (list up to 3 words or phrases)

3) The following new knowledge (information you gained, such as statistics)
   (list up to 3 or phrases)

4) The following attitudes or mindsets (ways of doing, such as creativity, drive or passion)
   (list up to 3 or phrases)
Open Response
Lastly, we would like to give you an opportunity to share additional feedback about the design challenge.

1) I Liked
(List here particular elements of the Design Challenge that you felt were most educational. Feel free to share stories.)

2) I Wish
(If you were to complete the Design Challenge again what would you change about your own navigation of the process. Feel free to share stories.)

3) I Would
(If you were in charge of running one of these design challenges for another group of students, what would you change?)