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Teaching Engineering Design in an Academic Makerspace: Blending Theory and Practice to Solve Client-based Problems

Dr. Vincent Wilczynski, Yale University

Vincent Wilczynski is the Deputy Dean of the Yale School of Engineering and Applied Science and the James S. Tyler Director of the Yale Center for Engineering Innovation & Design. As the Deputy Dean, he helps plan and implement all academic initiatives at the School. In addition, he manages the School's teaching and research resources and facilities. As the James S. Tyler Director of the Center for Engineering Innovation & Design he leads the School's efforts to promote collaboration, creativity, design and manufacturing activities at Yale's academic makerspace. His professional interests in Mechanical Engineering are in the areas of data acquisition/analysis and mechanical design. He is the Co-Chair of the Executive Advisory Board of the FIRST Foundation and is a Fellow of the American Society of Mechanical Engineering. Previously, he was the Dean of Engineering at the U.S. Coast Guard Academy and has had fellowships at the MIT Charles Stark Draper Laboratory, the Harvard School of Public Health and with the American Council on Education. He has also served as the Vice President of Public Awareness for the American Society of Mechanical Engineers and was the 2001 Baccalaureate College Professor of the Year by the Carnegie Foundation, the only national award that recognizes outstanding college teaching.

Dr. Joseph Zinter III, Yale University
Dr. Larry Wilen, Yale University

Larry Wilen is a senior research scientist and lecturer in Mechanical Engineering at Yale University, working in the Yale Center for Engineering, Innovation, and Design.

Teaching Engineering Design in a Higher Education Makerspace

Abstract

The proliferation of higher education makerspaces – sites where students, faculty, and staff design and build solutions to engineering challenges and other problems – suggests that such spaces have a special value on university campuses in a number of contexts. This paper reports on the unique impact of a higher education makerspace (the Yale Center for Engineering Innovation and Design) in the arena of design education. We review the history of design education, identifying the values of this form of pedagogy and highlighting many of the challenges involved with teaching design. These values include facilitating design instruction in lab settings, establishing a continuum of design experiences, and incorporating meaningful problem-based learning activities. Similarly, we review higher education makerspaces to provide insights into how they can play a role in mitigating challenges associated with teaching design. Using examples from eight courses taught in the profiled higher education makerspace, three design-focused instructional methods are presented that integrate course instruction, skill development, knowledge acquisition, and client-based problem solving by student teams. These methods have been applied across all four undergraduate years in courses closely aligned with biomedical engineering, environmental engineering, mechanical engineering, and engineering as a whole (for an introductory course). The courses span design education across the typical gap between cornerstone and capstone design courses. In all cases, the specific role of the higher education makerspace in enhancing the value of these courses is demonstrated.

Introduction

The establishment of higher education makerspaces (also referred to as academic makerspaces) on university campuses provides new opportunities for programs that have built these facilities. One such opportunity is to enhance design education by creating design courses that utilize the unique attributes of higher education makerspaces. Makerspaces generally have a wide mission, with few programs using the spaces to directly support the curriculum with classes and labs. As a relatively new component of engineering education, it is not surprising that while a number of academic articles have been written on higher education makerspaces, few have detailed the impact of the spaces on student learning.

This paper attempts to bridge the design education and higher education makerspace communities by illustrating how courses taught in a higher education makerspace meet long-standing design education goals (such as design across the curriculum). This paper presents the benefits of makerspace-hosted design courses, highlighting three models that illustrate the ability of a higher education makerspace to improve design education.

Design Education: History and Challenges

The importance of design as a component of engineering education is stressed in Fiesel's (et al.) description of engineering as "a hands-on profession where doing is key."[1] According to Fiesel, a key aspect of the profession is to design, analyze, and build creations that harness and modify energy, materials, and information to solve problems and improve humanity's standard of living. The history of engineering education summarized by Fiesel begins with its 1803 military origin that emphasized laboratory learning in curricula that taught engineering students how to design and build physical devices. This emphasis on design was reduced in the 1940's when the role of basic science was amplified, thereby elevating the role of research and decreasing the relative importance of hands-on skills. A renewed focus on laboratory and design skills surfaced in the mid-1980's as the engineering accreditation standards emphasized the need for engineers to be skilled designers.

Included in Fiesel's review of the role of laboratory instruction is the characterization of three types of engineering laboratories for development, research, and education. Education laboratories enable students to learn those practical skills that practicing engineers already know. His review concludes with a list of objectives for engineering students who completed the laboratories in the engineering undergraduate curriculum. Included in this list is the ability to "Design, build, or assemble a part, product or system, including specific methodologies, equipment or materials' meeting client requirements; developing system specifications from requirements; and testing and debugging a prototype, system, or process using appropriate tools to satisfy requirements."[2]

The role of cornerstone and capstone design experiences to mitigate the dominant influence of "engineering science" in engineering curricula was described by Dym and others.[3] These authors explain that capstone design courses are commonly used to demonstrate the achievement of prescribed engineering competencies. The development of cornerstone (or introductory) design courses was prompted by desires to connect new students to the engineering profession in an engaging and meaningful fashion. The value of introducing design thinking and applying project-based learning is emphasized as means to acquire design skills. The Conceive-Design-Implement-Operate (CDIO) process is suggested as a means to infuse design throughout the curriculum.

Design thinking is characterized as the designer's ability to tolerate ambiguity, address uncertainty, iterate, maintain a systems perspective, work in a team, make decisions, and communicate the results. The cornerstone and capstone design processes are presented as experiential learning models that address these skills. The ability to motivate students and integrate learning is accelerated though the incorporation of project-based learning methods in cornerstone and capstone courses when students work for clients. In the course of doing so, real-world problems require students to integrate learning skills from across a spectrum of disciplines and combine that learning with design skills to produce a solution. As claimed by Dym, the use of real projects has developed into a major innovation in design pedagogy as the experiences provide students with the know how to solve practical problems.

Efforts to improve engineering design certainly originated before the above calls for action by Dym and his colleagues. For example, a 1991 National Academy of Engineering (NAE) report on this topic summarized that "design education is clearly weak" and outlined a number of possible improvements.[4] Included in that list was a call to distribute design "throughout the engineering curriculum, beginning with introductory design courses, which serve the dual purpose of introducing the design process and demonstrating the relevance of the engineering courses to design, and continuity as a part of more advanced engineering courses."[4]

This point was amplified in the report's statement "adequate design education requires a coordinated approach among several courses in the curriculum."[4] The report went on to specify that undergraduate engineering design education must, among other things, "show how fundamental engineering science is relevant to effective design" and teach students the design process as well as the tools of that process.[4] Also included in the list of suggested initiatives was the creation of "change agents to plan and implement improvements." [4] We demonstrate here that teaching design in higher education makerspaces over a series of courses answers this challenge.

A second NAE report titled "Approaches to Improve Engineering Design" (written in 2002) addressed some of the issues raised a decade earlier and focused on the methods, theories, and tools of design.[5] This report echoed the need for interdisciplinary design courses that included intellectual property, social, and economic issues. Exposure to decision-making tools and decision theory was suggested to be included in undergraduate design courses, along with methods to build and work in teams. Increasing opportunities for team-based design experiences and learning how to use emerging tools was also emphasized in the 2015 NAE report on the future of manufacturing, technology, and employment.[6]

In review of "studio methods" for introductory design courses, Little and Cardenas propose using a series of exercises to expose students to design concepts.[7] These exercises train the students in formal skills and prepare them to then work on a major design project for an external client. The authors explore the role of the physical space and its effect on student learning. It was noted that the most common spaces used for design instruction were classrooms or laboratories – spaces very different from studios that are used to explore the visual arts. Their review suggests that modeling engineering design workspaces on visual arts studios would have a positive impact on the learning experience. The pedagogy used in architecture studios is presented as a model where the open format encourages frequent desk-reviews of the works in progress. This approach promotes the instructor as a guide to an active learning process with the students gaining the greatest understanding of things they taught themselves.

Assessing design skills has been examined by Atman (et al.) with comparisons between freshmen and senior engineering students, as well as with practicing engineers.[8] Their work investigated the skill differences between the test groups in five areas: problem scoping (and information gathering), project realization, generating alternative solutions, iteration effectiveness, and the quality of the solutions. Their findings recommended stronger design instruction to help students adequately scope a design problem before progressing into a detailed design, improving students' abilities to gather information during the initial problem review phase and throughout the design process, and increased attention on the aspects needed to bring products to fruition.

The concept of active learning is a common thread in the history of design education, first applied to the learning and teaching styles in engineering education by Felder and Silverman.[9] Active learning encourages not only high levels of physical engagement with course content (such as physically experimenting with concepts) but also reflection on the results of that activity. Teaching styles that are correlated with prevailing learning styles lead to higher success and greater fulfillment. Engineers are more likely to be active learners and engaging learning environments have a significant impact on this segment of learners. The role of active learning through the use of cooperative learning environments and project-based exercises has also been endorsed by other researchers as means to improve design education.[10] It is our thesis that higher education makerspaces are environments that cater to this style of learning.

Higher Education Makerspaces: History and Opportunities

Having appeared on the academic landscape over the last decade, the history of higher education makerspaces and their impact on engineering education has yet to be fully studied. A few explorations have detailed the origins, attributes, and impact of higher education makerspaces. Tapping into the increased accessibility and affordability of design and fabrication tools, higher education makerspaces integrate some aspects of traditional machine shops with modern manufacturing methods and techniques. The arrival of makerspaces on college campuses was preceded by grassroots efforts to create community-based workshops for discovery, collaboration, design, fabrication, coding and assembly.[11]

Lacking a formal definition, higher education makerspaces typically combine access to tools and information to form supportive creative communities. Makerspaces are not simply locations, but rather the entirety of the operation which commonly includes scheduled activities such as tool training, design tool workshops, and social events, as well as the community of maker-members. Some higher education makerspaces host for-credit courses (the subject of this specific paper). The combination of equipment and culture provides a powerful catalyst for formal and informal learning. Higher education makerspaces generally have few restrictions on the use of their resources (much like libraries do not restrict how patrons apply the accessed information from their facilities). As such, university students, faculty and research staff are often invited to use higher education makerspaces for academic, curricular, extracurricular, and personal design activities.

As community-centered spaces, the open and supportive components of higher education makerspaces are factors that increase their value on college campuses. With low barriers to entry and missions to help members learn, higher education makerspaces tend to be welcoming environments that foster imagination, support education and community engagement, promote collaboration, encourage cooperation, and are self-sustaining where members contribute to the learning, discovery, and creative environment.[12] Social programs are also common to higher education makerspaces and allow community members to deepen their relationships with one another. As promoted by active-learning advocates, community members learn from each other when working in the spaces and participating in workshops.

The physical layout of a makerspace is an important factor that often determines whether academic courses can be hosted in the facility. Further, building such courses into the mission of a higher education makerspace determines how the facility is staffed, supported, and administered.[13] Typical staffing models include student-managed, faculty-managed, and staffmanaged, with the latter two staffing models being more conducive to supporting academic courses within the facility.[14]

The impact of higher education makerspaces on engineering education and the acquisition of design skills are subjects of on-going research. One study of 50 survey participants quantified the value of the space for enhancing design with nearly 90% experiencing a positive impact. Other factors common to more than 50% of those surveyed in this study were increased outlooks on engineering (>80%), stronger manufacturing skills (>80%), and an increased understanding of safety (>80%).[15] Further research is underway to examine the influence of a higher education makerspace environment on at-risk student retention, fostering diverse learning environments, and promoting multi-disciplinary teamwork.[16]

Makerspaces were proposed by Barrett (et al.) as a partial solution to increasing student design skills that are often delayed to the end of a degree program.[14] The authors positioned the use of makerspaces for extracurricular activities to bolster skill development, noting that makerspaces can serve as a compliment to existing offered design courses. It is proposed that the primary benefit of working in higher education makerspaces is an increased visceral understanding of engineering principles. This is obtained from the process of constructing physical models and is amplified by the informal learning environment and the supporting community within higher education makerspaces.

It is proposed that many of the historical design education challenges are addressed when credit-awarding design courses are hosted in higher education makerspaces. As presented in this section, the historical challenges of design education include:

- Learning practical engineering skills (in an educational lab setting)[2,4]
- Infusing design throughout the curriculum (beyond cornerstone and capstone experiences)[3,4]
- Improving cornerstone and capstone experiences (by immersion in a collaborative environment)[4,5]
- Increasing the number of interdisciplinary design courses[3,5]
- Using exercises to build confidence and skills to solve an open-ended problem[7]
- Enhancing the design talents expected of engineering professionals[8]
- Meeting the needs of active learners[9,10]

While others have suggested that many of these challenges are addressed by student experiences gained from extracurricular activities conducted in higher education makerspaces, it is proposed that all of the challenges are readily addressed by hosting design courses within higher education makerspaces. These credit-awarding courses can occur not just in the first and last years, but can span all four years of a student's education. The courses also have the possibility of being multidisciplinary, thereby introducing a larger number of students to the values of diverse backgrounds for innovative problem-solving. The value of design and build experiences has been documented by others, but the recorded impact predates the recent arrival of higher education makerspaces.[17,18, 19] The details associated with such courses conducted within higher education makerspaces are presented in the following section.

Addressing Design Education Challenges: Teaching in a Higher Education Makerspace

The Yale Center for Engineering Innovation and Design (also referred to as the Yale Design Center) hosts over 2,000 members of the Yale student, faculty and staff communities in the 8,700 square foot learning, meeting, design, fabrication, and assembly space. A 45-seat instructional area adjoins (but is not physically separated from) the center's open-studio, workshops, and meeting rooms. Four full-time staff members manage and operate the facility, develop the center's programming, and train all users on equipment located within the makerspace. Two of the staff are (non-ladder) members of the faculty who teach academic courses in the center. The center hosts a number of credit-awarding courses each year, spanning all four years of the undergraduate programs. The course content is aligned with the computer science, biomedical engineering, electrical engineering, environmental engineering, and mechanical engineering disciplines.

Figure 1. Yale Center for Engineering Innovation and Design Center

Students in these courses benefit from being taught within the Yale Design Center by having all aspects of the lectures, laboratory activities, design activities and shop training located in a single location. With the entirety of the courses taught in one location, ready access to Yale Design Center resources, including tools, equipment and support staff, is always available. The courses also benefit from contributions provided by the collaborative and diverse community of users who willingly assist student design teams. Given this framework of openness and collaboration, the barriers for developing new design courses are reduced, thereby easing the way for adding design courses to the curricula.

Access to tools and equipment is a primary benefit of hosting design courses in the Yale Center for Engineering Innovation and Design. The facility houses CNC mills/lathes, a CNC router, an injection molding press, CAD/CAM stations, 3D printers, a vinyl cutter, 3D scanners, laser cutter, and a sewing machine. Hand tools, power-tools and electronics equipment are also provided. Members are trained to use each piece of equipment and provided with the requisite amount of staff oversight and assistance. A complete list of equipment and the physical layout of the space is posted on the center's web site.[20] Access to tools, technology, and training in a central location has proven to be a key benefit of learning design skills within the Yale makerspace.

The availability of design-trained employees to assist students is an additional benefit of teaching design courses in the Yale Design Center. As full-time employees, the staff is readily available to assist students (with it not being unusual for these employees to work schedules that align with student work schedules). Staff members provide equipment training and certification. They also offer design guidance to student teams, especially during course work periods, thereby leveraging the ability of the course teaching staff to address multiple issues simultaneously.

Students in design courses held in the Yale Center for Engineering Innovation and Design also benefit from learning technical content and design skills in an environment that promotes collaborative learning. The center encourages individuals working on specific projects to seek help from their peers and offer assistance to others in their own areas of expertise. This culture of collaboration is facilitated by the openness of the facility where nearly every square foot of area is visible (and unimpeded). This openness encourages cooperation as individual work is always on display for others to observe, thereby making it easy for members to offer assistance and suggestions that improve the work of others. Forcing the serendipitous collision of ideas was an important factor behind the space's open architecture.[21] Informal learning from each other is further facilitated through workshops and social events that are regularly held in the center.

Diversity is yet another benefit to students enrolled in the Yale Design Center courses. The 2,000 students, faculty, and staff members come from all departments and programs at Yale as the center is open to all at the university. Once members are oriented and trained on policies and procedures, they are provided with 24/7-access to the facility. Beyond the typical resources within their individual disciplines (when taking a design course housed within a specific department), students in Yale Design Center courses have access to a spectrum of talent in the center's membership, including physicians, curators, researchers, artists, and farmers, to list a few.

Because of the above reasons, teaching cornerstone and capstone design courses in the Yale Center for Engineering Innovation and Design enhanced the design education experience for students enrolled in these courses. The presence of the Yale Design Center has also prompted the development of new design courses. With the supporting infrastructure of a higher education makerspace, course developers were spared many of the logistical details involved with establishing hands-on design courses.

These new courses were topic-focused (such as medical device design, musical instrument design, sustainable design, and entrepreneurship). As electives, the courses were open to as many students as possible with a diversity of academic ages and disciplines (provided that individual students had skills/abilities that contributed to the design explorations). The addition of these mid-level design courses created a design continuum for students, thereby enabling a larger number of students to gain further design skills and experience.

Teaching Design Courses in a Higher Education Makerspace: Examples

Examples of three design courses taught in the Yale Center for Engineering Innovation and Design are presented in this section. The courses include lecture and design (lab) components, and use one of three distinct design approaches:

- *Theory-Skills-Project Methodology*
- *Design Immersion Methodology*
- *Product Development Methodology*

It is proposed that there is no single best method to teach design, but rather the method should align with the purpose of each course. In this context, courses using the *Theory-Skills-Project Methodology* augment theory with a design experience that increases student comprehension of the theory. The *Design Immersion Methodology* emphasizes the role of the design process as a problem-solving tool. The *Product Development Methodology* applies the traditional capstone design course process as a means of demonstrating competency in an engineering discipline.

Despite the different methodologies, the courses share a number of common elements: lectures on disciplinary topics, presentation of a course-pertinent design process, equipment training, an open-ended design project (that results in the fabrication of a product), and final student presentations. Typically the term projects are client-posed problems completed by teams of students. The courses require a broad synthesis of ideas and an integration of the laws of science with engineering practices. The physical products produced in these courses include physical devices and computer/mobile applications.

All of the courses institute elements of design thinking to ensure that the correct problems are identified before solutions are pursued. Concept development and prototyping are also common to all of the courses, as is the process of iterating to optimize solutions. The courses require criteria (such as feasibility, safety, and manufacturability) and realistic constraints (including specifications, economics, and environmental concerns) to define the problem, with the final solution determined after evaluating alternatives.

These courses can be considered typical analyze-design-test-build courses (or similarly as Conceive-Design-Implement-Operate courses).[3,13] What is unique is the fact that the entire course (including lectures, training sessions, and workshop sessions) is housed in a higher education makerspace, with the benefits of this arrangement detailed in the previous section. In addition to these benefits, conducting these design courses in a higher education makerspace amplifies student understanding of the iterative nature of design and the value of frequently seeking input and assistance. The higher education makerspace environment is energizing and inspiring, with the collective culture supporting the concept that significant amounts of time and energy are needed to produce high-quality products.

Course examples illustrate how these three methodologies have been applied across a variety of disciplines, ranging from cornerstone to capstone courses.

The Theory-Skills-Project Methodology presents theory using lectures. Skills related to elements of that theory are then taught hands-on activities, and interim and final projects are used to show how the theory and skills can be integrated and applied to solve real-world problems. Problems are solved using the available expertise and manufacturing capabilities of the higher education makerspace. At the Yale Design Center, this methodology has been used in four separate courses: Introduction to Engineering Innovation and Design, Musical Acoustics and Instrument Design, Green Engineering and Sustainable Design, and Environmental Technology in the Developing World. The first two of these courses are profiled in detail to illustrate the application of the *Theory-Skills-Project Methodology*.

The cornerstone course Introduction to Engineering Innovation and Design is open to all undergraduates and provides an introduction into each of Yale's engineering and applied science majors (biomedical, chemical, electrical, environmental, and mechanical engineering, and computer science). Figure 2 illustrates a version of the engineering design process (developed by *Design for America)* that is applied in this course.[22]

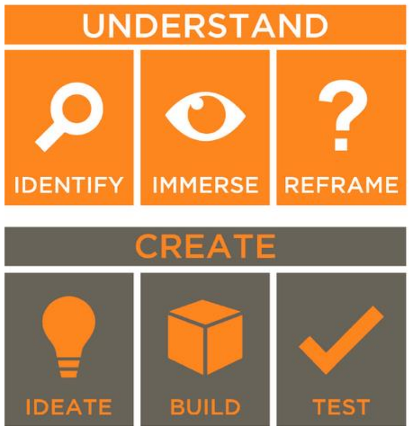

Figure 2. Design for America Process

The first half of the course is devoted to "theory and skills" while the second half is devoted to a client-based "project." For each engineering discipline, part of a lecture is devoted to discussing the discipline in general, and then a specific theoretical aspect of the discipline is covered in detail in 1-2 additional lectures. This specific area is reinforced in a lab session (in the makerspace studio) where students engage in guided hands-on activities to learn useful skills. Associated with the lab are homework assignments that often challenge the student to do something innovative and creative outside of class time. These assignments further enhance the students' skills while preparing them for more open-ended design tasks. For example, the computer science discipline is introduced in a series of lectures (and homework assignments) on computer programming using the open-source "*Processing*" language. Although brief, this introduction challenges the students with some relatively complicated tasks and gives a glimpse into the power and structure of programming.

For mechanical engineering, the students are taught in class about motor power curves and the basics of gears; in lab the students measure the power curve and electrical efficiency of a motor and are then challenged (as homework) to design gearing systems (with a simple set of kit parts) to raise different weights with maximum speed or efficiency.

Where possible, the theory and skills-based elements of different disciplines taught in lecture/lab/homework are all coordinated to build upon or relate to each other: Processing (for computer science) is used because it is also the language used for programming Arduinos, the microprocessors that are taught as part of electrical engineering. The Arduinos are used in later labs to control thermoelectric systems with various kinds of feedback, and this simple system is used to demonstrate process control in chemical engineering. In the lab the students actually use the device to temper chocolate, as a realistic example of a chemical process. The wooden and metal box housing the thermal device is constructed in the very first lab in the course that introduces the students to the use of simple hand tools. The use of various materials (and associated mechanical and thermal properties) in the box are discussed in a materials lecture (as part of MechE). In addition to the confectionary rewards, the series of lab activities illustrate that connectivity between disciplines is useful to solve real-world problems.

In all cases, the makerspace environment embodies a unique role - it supports all of the class activities with facilities, materials, and staff expertise, but also becomes a comfortable and familiar space to the students where they begin to see that they are empowered to design and manufacture almost anything they can conceive. This view is reinforced by all the *other* activity they observe around them from students in other classes and independent/club projects as described earlier.

These course activities serve as the foundation for open-ended problem solving. At this stage of the course (roughly mid-term), students are presented with (vetted) design challenges by clients from across the university. Working in teams, the students reduce the challenge to a well-specified problem and then develop a solution. The students meet frequently with the clients to present concepts, refine prototypes, and develop working solutions. Examples of these projects include:

- Design and construction of a hippo-proof device to measure the turbidity of the Mara River. The client was a researcher from the School of Forestry and Environmental Studies who used the device in Africa a month after the team's final presentation.
- Concept development and fabrication of a device that used light as a form of art. In this example two student teams worked with a conservator from the Yale University Art Gallery who was preparing an exhibit of Thomas Wilfred's pioneering work using colored glass and light sources as an art medium.
- Creating and coding a digital platform to explore nature aspects surrounding a remote campus research facility. The client for this application was the campus sustainability officer with the product being a mobile device that guides visitors on nature tours around the research campus.

The *Theory-Skills-Project Methodology* has also been used in a similar fashion in the Musical Acoustics and Instrument Design course taught in the Yale Design Center. Here the course theory presented the concepts of instrument acoustics (originating from bars, strings, and tubes) and electronic sound production.[23] The skills portion of the course was conducted in the makerspace studio where students applied the theory to fabricate and assemble percussion, wind, and string instruments. Standard designs were used to teach skills associated with computer modeling, 3D printing, electronics, power tools, and laser cutting. After completing the prescribed fabrication exercises, students were challenged to design and fabricate their own string instrument as a mini-design exercise.

Similar to the project-based-learning component of the previous course, the students apply the theory and skills by designing and constructing unique musical instruments in the last 5 weeks of the term. In this course students work as individuals on a project of their choice. The projects spanned a range of musical dimensions and included a computer controlled string instrument, a string-synthesized instrument, and a piano-tine device that used keyboard input to actuate frequency-tuned wooden tines.

In both of these examples the courses were team-taught. For the cornerstone course, one instructor was from the Department of Mechanical Engineering and the other a center staff member (Ph.D. Physics). The musical instrument course was taught by the same center staff member and a faculty member from the Department of Music. This level of teaching support ensured that the theoretical, skills, and design aspects of each course were adequately covered.

The Design Immersion Methodology is used in a number of courses taught at the Yale Center for Engineering Innovation and Design. Using this methodology to teach design, students are introduced to design process while simultaneously working with a client on a real-world, open-ended problem. In this manner students are not only applying design principles to meet a client's needs, but are also developing critical communication and organizational skills. The design framework, displayed in Figure 3 used in this methodology is a modified version of IDEO's Human Centered Design Process (HCD).[24] Examples from two courses illustrate how this framework can be applied to various types of problem statements and design opportunities, ranging from well-defined to ill-defined. In both cases students begin working in the 'concrete' space, where they build capacity through fundamental research, interviews, and a thorough examination of the problem topic. Armed with this knowledge, the students then enter into the 'abstract' space of concept generation, refinement, and selection, before returning to the 'concrete' space of prototyping, testing, refinement, and plans for deployment.

In the course Medical Device Design and Innovation, students work in small teams with clinician mentors/clients to tackle an unmet clinical need while they are simultaneously introduced to, over the course of the semester, various topics relevant to medical technology (regulatory affairs, intellectual property, healthcare economics, etc.). Projects are chosen based on scope, nature, and scale prior to the start of the semester. Clinicians present these unmet medical needs during the first class period, and students then align themselves with a clinician and project of interest for the remainder of the term. The clinician pitches are intended to introduce students to the unmet clinical need and the impact of addressing this need. However, in effort to allow sufficient creative and design freedom, clinicians refrain from presenting potential solutions. Student teams use these descriptions to learn specific information about the posed problems by observing individuals, conducting primary and secondary research, patent searches, identifying prior art, and through interviews and observations of key stakeholders.

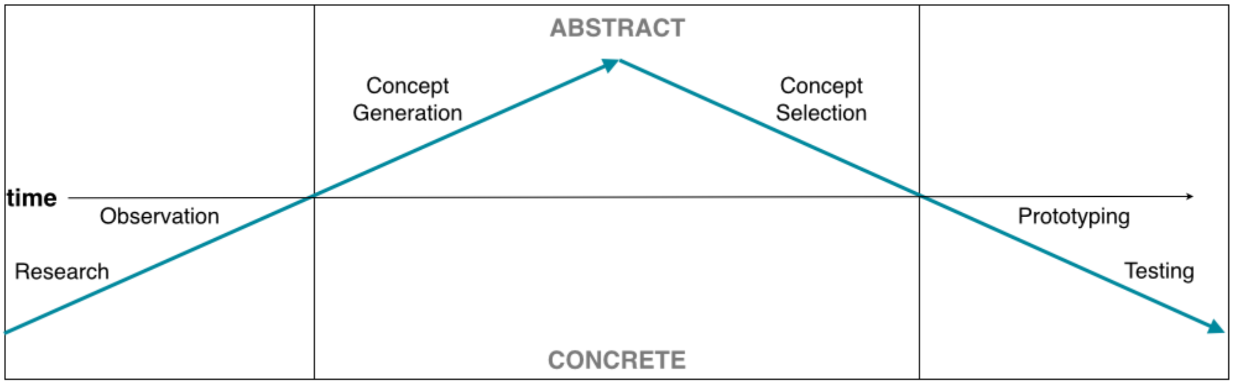

Figure 3. Design Immersion Process (modified from the IDEO HCD Design Process)

After developing foundation knowledge in their respective projects, students clearly define their problem statements and review them with the course instructor and clinician mentors. Well-structured problem statements are presented in a fashion that does not suggest nor limit possible approaches to a solution. At this point students enter into a mode of abstract thinking and begin the process of concept generation. The peak of the curve is the point at which students have generated a multitude of ill-defined concepts. Then, various concept refinement and selection tools, such as decision matrices and Pugh charts, are applied until a final concept is selected.

Finally, the design team returns to the concrete space to develop their concept. Prototypes are developed to test particular functions and also to collect feedback from clinician mentors on usability, ergonomics, workflow, etc. Here, a heavy emphasis is placed on iteration and the development of prototypes that will allow for robust experiments. Simultaneously, students are generating plans to develop and deploy their designs in the real world, in addition to exploring whether or not they have developed novel intellectual property.

The lecture area of the Yale Design Center serves as the meeting space for lectures on the medical device industry and the design process. These lectures are augmented by skills training in the first third of the course to equip students with the knowledge to explore and investigate their yet-to-be-defined problems (and the later designed solutions). With these fabrication skills in hand, students are better equipped to form insights and frame problem opportunities by investigating systems and gaining a better understanding of the underlying engineering fundamentals. The studio and accompanying fabrication tools then support the concept and prototyping phases of the design process that lead to the final solution.

The design process is practiced in real-time over the course of the semester during weekly meetings with the project clients. Early meetings define the issues around the problem being pursued, mid-semester meetings identify the specific problem to solve, and the remaining meetings review the concepts, prototypes, and final product.

When using the *Design Immersion Methodology*, a deep dive into the technical discipline is accompanied by a simultaneous deep dive into the design process (for each particular problem). Inherent to the process is identifying the correct problem to solve, generating multiple concepts and prototypes, and testing ideas to identify an optimal solution. Lectures are augmented with hands-on activities, all centered on the actual problems that are being solved. Students realize that design is a creative, non-linear process that relies on deep research and empathy to integrate all aspects of a solution into a viable product.

One example of this process being applied in the course was a project that originated when the client radiologist introduced the issues surrounding bone marrow biopsies in an initial discussion. That discussion allowed the students to pursue independent research into the process to collect bone marrow samples, including the science behind the process, current methods being practiced, the existing technology used to collect samples, and the complications of the current methods. Equipped with this information, the students were positioned to frame the problem to improve the current practice of collecting bone marrow samples. Ideas were refined and devices prototyped, with the physical models shared with the physician during the weekly review meetings. The deep immersion into the two worlds of medical technology and the design process set the stage for detailed explorations of both domains that ultimately lead to viable solutions.

This same instructional methodology is applied in the course Appropriate Technology for the Developing World. In this course students develop technological solutions to various challenges faced in resource poor settings around the world. The theme of the course, which might range from clean water to access to electricity to agriculture, changes annually. Similar to the medical device design course, students follow the design process and produce similar deliverables, however, the design challenge is far less defined. In the former case, an individual client is addressing the students with a particular need, while in the latter case, students, through extensive research, are tasked to identify their own design challenge and develop requisite external partnerships. As such, a far greater period of time is spent in the initial ‘concrete’ zone than compared to the medical device design course.

As an example, in one year the general exploratory concept was the word “Ebola." Through the process of observation and the discovery of narratives, various themes and opportunities emerged, followed by the identification of specific problems for student teams to investigate during the remainder of the semester. Expertise in the topic area was obtained by infusing the course with health care, social change, and public health professionals who delivered lectures and served as project consultants for the student teams. After a period of working on concepts and prototypes, the course concluded with the presentation of solutions that addressed the principle concept of Ebola. The solutions included a shared-economy model for distributing medical supplies in a region inflicted with an Ebola outbreak, a portable cooling system integrated into medical protective garments, and a paperless product to record and monitor health in a rural community.

In each of these courses, two instructors taught the course with one specializing in the design thinking process and the other having expertise in the discipline. The Assistant Director of the Yale Design Center (Ph.D. in Biomedical Engineering) was the design specialist in each course. A research scientist from the medical school and a social entrepreneur served as the second instructor for the medical device design and appropriate technology courses, respectively. The courses are noteworthy in that they are neither introductory (cornerstone) nor ultimate (capstone) courses within a discipline, but rather are mid-level courses open to all students from all majors. The diversity of students who enroll in these types of courses is a significant strength.

The Product Development Methodology is the third model of design education taught through courses in the Yale Center for Engineering Innovation and Design. In this application an engineering discipline is emphasized with an application of the design process used to frame the exploration. This methodology follows the product development process that is used by many programs, with much of the course content and deliverables aligned with demonstrating student obtainment of engineering accreditation objectives.[25] The emphasis of many capstone courses is the demonstration of proficiencies expected of an engineer in that specific discipline. The courses also provide students with experience in product design, a skill expected of engineering professionals.

The capstone course in mechanical engineering has been taught for the last four years at the Yale Design Center. The course is structured around solving a client-based design problem using teams of 3-6 senior mechanical engineering students. Three phases of the design process (Concept Design, Prototype Design, and Detailed Design) are used to progress from a client's need to an engineered solution. Concepts such as design iterations, constant improvements, and informed decision making are applied during each of the three design phases, as illustrated in Figure 4. This process becomes the format for the course with the lecture components and design activities modeled using this sequence of events. Concept designs represent the earliest solutions to the identified need. These preliminary solutions are improved and refined into working prototypes. These systems then progress to the detailed design phase that when constructed becomes the engineered solution to the problem.

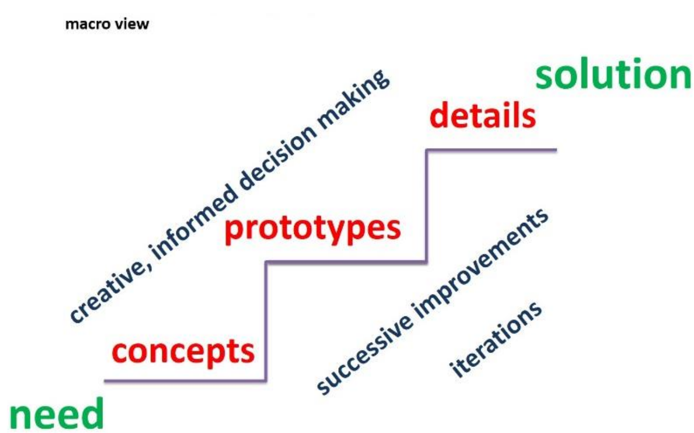

Figure 4. Capstone Design Process

The course's content is structured using a series of deliverables as milestones along the design journey. These deliverables are aligned with accreditation requirements and document the students' abilities achieving specified objectives (illustrated in Figure 5). These objectives include the topics of safety, manufacturing, material selection, engineering standards, project planning and ethics, as well as the engineering practices of analysis and experimentation (to collect data for making design decisions). While these objectives span each of the three design process steps, the deliverables are only assigned (and retained for assessment purposes) at specific stages of the design process. The deliverables include physical artifacts of concepts, prototypes, and final designs, as well as oral and written reports. The collected portfolio is a record of the design process.

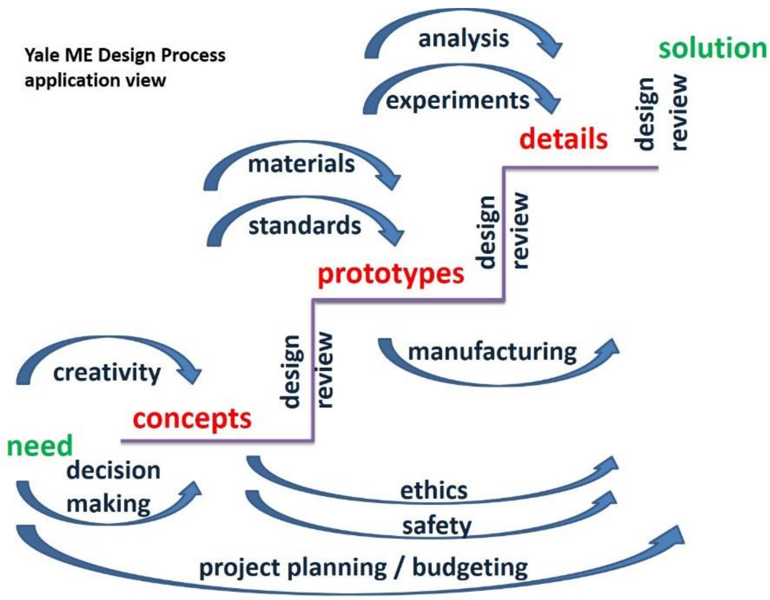

Figure 5. Demonstration of Proficiency within Capstone Design

As examples of the scope of projects pursued, students have designed and constructed a motorcycle-powered dynamometer (and the associated power control system) to address rural electrification needs, a device to analyze ice-core samples, and a system to measure an athlete's propensity for ACL injuries. The development of these products required high levels of mechanical engineering analysis and testing to ensure the integrity of the selected components and the utility of the designed system. It is noted that this model of instruction is fairly standard across most accredited engineering programs with the local application being conducted within a higher education makerspace.

Observations and Conclusions

It is proposed that the ability to teach design principles is enhanced in each of the three methodologies because the courses are taught within a higher education makerspace. With the elimination of physical and program boundaries between theory and application, the ability to learn practical engineering skills in an educational lab setting is increased by the availability of tools and technology. Since the students are embedded in an active "making" site that is not limited to just their class, students have the support of an extended community to help them learn manufacturing, coding, and testing skills.

Each profiled course has unique learning outcomes. The goal of the Introduction to Engineering Innovation and Design course is to understand that design is a process. The utility of design as a disciplinary-based, problem-solving tool is the goal of the Medical Device Design course. Gaining competency in practicing design within a professional context is the goal of the capstone course. Within each course, the level of completion of the course project is an assessment instrument to evaluate the achievement of outcomes.

Because the courses are housed in a location that supports teaching, meeting, and manufacturing, the barriers to entry for new courses are dramatically reduced. As such it is much easier to infuse design throughout the curriculum (beyond cornerstone and capstone experiences) when a facility is readily available for students and faculty to work in. The infrastructure is not limited to a worksite and access to the tools and equipment, but rather extends to include the availability of training resources and staff support for the residential design courses. With such support, design courses beyond entry and exit classes can be created to explore not just the theory of disciplines but also the applications of that theory to produce products. These courses can be interdisciplinary and open to students in each of the four undergraduate years.

Similarly, the cornerstone and capstone experiences are improved for students who are enrolled in courses housed in higher education makerspaces. The immersion in a collaborative environment is a benefit that promotes creativity and increases the ability to solve problems (with the assistance of a larger number of individuals from diverse backgrounds). Students who are active in higher education makerspaces continually improve their design skills by practicing elements of their profession – be that computer aided design, electronics, fabrication, or testing – through hands-on problem solving. In the course of their work (in curricular, extra-curricular, or personal project activities), these students develop and enhance the design skills that are expected of engineering professionals. This form of learning aligns with the most effective comprehension modes for active learners.

As Dym (and others) reported, "Design is a mechanism for learning and in itself is a learning process."[3] Teaching design courses within higher education makerspaces facilitates this learning process by providing access to opportunities that otherwise are not readily available.

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