AC 2011-599: APPROACHES TO ENGAGING STUDENTS IN ENGINEERING DESIGN AND PROBLEM SOLVING

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Approaches to Engaging Students in Engineering Design and Problem Solving

Introduction

This research reports results on the curricular, pedagogical, cultural, and organizational features of how six diverse engineering institutions embed design and problem solving throughout their undergraduate curricula. Findings are drawn from the *Prototyping the Engineer of 2020: A 360-degree Study of Effective Education* (P360) and *Prototype to Production: Processes and Conditions for Preparing the Engineer of 2020* (P2P) projects. P360's qualitative data from six case studies examines concrete examples of effective design curricula and co-curricular activities. P2P, which collected quantitative data from 31 four-year engineering schools to provide information on the structure of the design curriculum in nearly 120 engineering programs, augments the qualitative data from P360. Both projects collected data from multiple sources: faculty, program chairs, administrators, and undergraduate engineering students. The full study concentrates on three attributes of the engineer of 2020[1]: design and problem-solving skills, interdisciplinary competence, and contextual competence; this paper focuses specifically on effective strategies for teaching design and problem solving. The paper reports findings from the P2P quantitative study as well as the P360 six case study institutions of Arizona State University (Tempe & Polytechnic Campuses), Harvey Mudd College, Howard University, Massachusetts Institute of Technology, University of Michigan, and the Virginia Polytechnic Institute and State University.

Using the framework shown in Figure 1, we assume that learning is situated in social, cultural, and institutional contexts that strongly influence what is learned and how it is learned[2,3]. During our P360 data collection and subsequent analyses we identified several distinct ways that each of our case study institutions engage students in the process of engineering design and problem solving. Consistent with the framework, classroom experiences are only one way that our institutions engaged students in design. Other prominent co- and extra-curricular experiences include individual research experiences with faculty, design competitions, global overseas design projects, independent study, industry-sponsored design opportunities, and several other programs unique to the six respective institutions. The paper will provide detailed examples of how these varied design-focused learning opportunities are situated organizationally, and the different approaches for supporting and implementing the activities.

Results from this study provide a window into how several distinct institutions engage students in design and problem solving, from the student, faculty, and administrator perspectives. These detailed multi-perspective examples, organized around the features of the college experience as shown in Figure 1, provide concrete information for how engineering programs might implement, revise, or scale design activities at their own institutions.

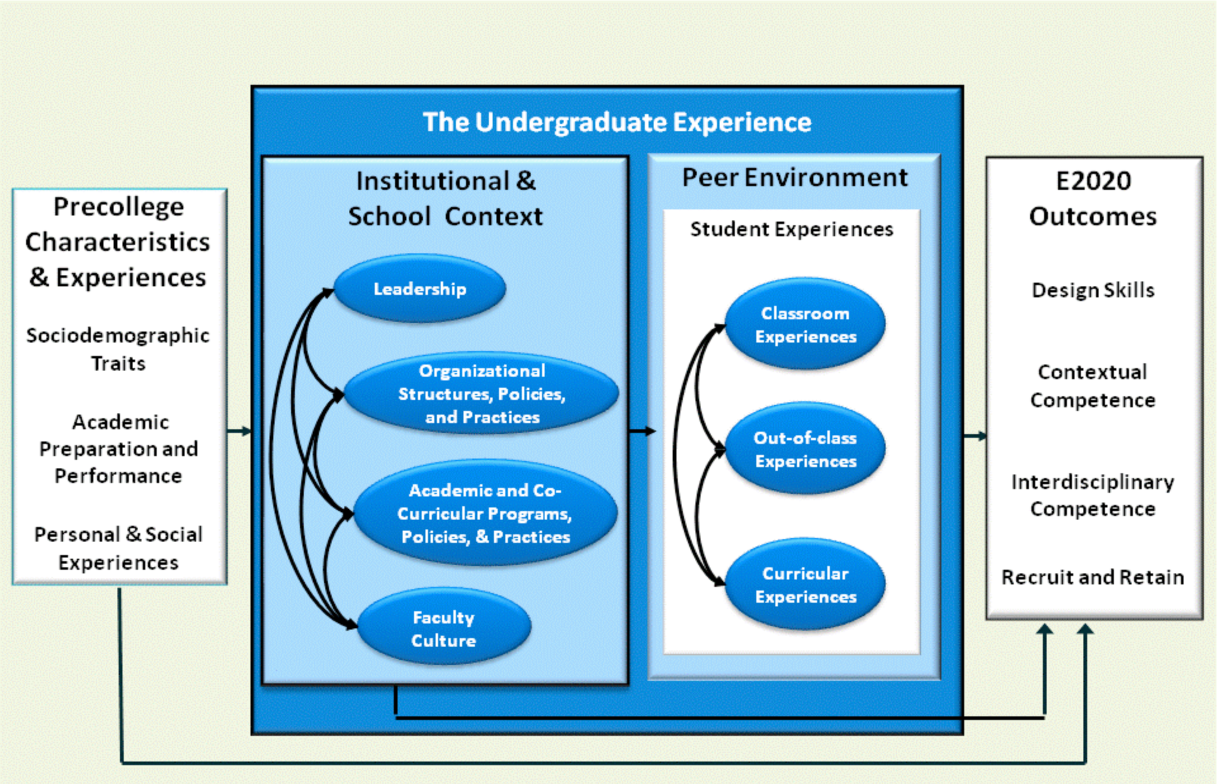

Figure 1. Comprehensive model of influences on student learning and persistence[4, 22].

Literature Review: Design and Problem Solving

Most engineers would consider *engineering design* as a central and defining activity for the field of engineering. The Accreditation Board for Engineering and Technology[5] (ABET, Inc.) defines design as "the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs"[6]. A similar definition comes from Clive Dym, et al.: "Engineering design is a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints"[7] (p. 104).

Design and problem solving skills are critical to an engineer's training; for example, Jonassen[8] states that STEM workers are hired, retained, and rewarded for problem solving. Cross[9] summarizes many different design process models. Bilén et al.[10] posit that the engineering design process may be thought of as having roughly four phases, often executed in an iterative fashion: (1) needs assessment and defining the problem; (2) generating concepts or solutions; (3) evaluating, and selecting a concept; and (4) implementing and communicating the design. Further, we also note that these phases have been referred to in similar but different ways in the literature across various engineering design texts (see the comparisons of engineering design processes across textbooks in Ogot and Kremer[11], pg.12).

Engineering problem solving has a broad range of functional definitions, from relatively narrow (solving engineering mathematical problems) to nearly synonymous with design. Most engineers would probably consider engineering design as the penultimate problem-solving activity; thus, all engineering design activities would be considered problem solving, but not all engineering problem solving would be engineering design. The two activities require some of the same steps: problem definition, gathering and evaluating resources for a solution, implementing a solution, and review; however, for most engineers, design connotes a broader, more encompassing landscape.

Popper[12] claims "All life is problem solving!" and hence all humans solve problems continuously. ABET, Inc. lists problem solving as a separate educational outcome from design in the a-k outcomes, stating that students must have: "(c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability and (e) an ability to identify, formulate, and solve engineering problems"[5].

Although we have stated that, in the engineering domain, problem solving is often experienced as design problems, we nevertheless opt to present prominent distinctions between problem solving and design. In its most generic form, problem solving is defined as "…find[ing] a path through the problem space that starts with initial states passing along paths that satisfy the path constraints and ends in the goal state[8]. The level of structure in a given problem (or its structuredness) and its situatedness are two important dimensions describing the type of problems.

Well-structured problems are those often encountered in educational settings – the textbook problems, and have "all the information needed to solve the problems in the problem representation; they require the application of a limited number of …rules and principles that are organized in a predictive and prescriptive way; and they have knowable, comprehensible solutions where the relations between decision choices and all problem states are known or probabilistic"[8] (p. 6). On the other hand, ill-structured problems are interdisciplinary in nature, with conflicting goals and multiple solution methods. Jonassen[8] argues that structuredness also relates to situatedness; that is, the more structured the problem is, the less context-specific the problem becomes. Typical engineering problems, which are mostly design problems, are classified as ill-structured and situated (context-specific) problems. Indeed, Jonassen[8] (p. 13) refers to a design problem as "perhaps the most ill-structured kind of problem."

Supporting the theoretical descriptions above, empirical studies of problem solving in design problem spaces versus non-design problem spaces showed clear differences between how subjects approached problem solving. For example, Goel[13] found that design problems required: (1) incremental development of an artifact (that is designed); (2) problem structuring with a relatively large percentage of time devoted to it (25%); and (3) existence of several problem solving phases: preliminary design, refinement (design iteration). None of these were applicable in non-design problem spaces.

For our case studies, we coded transcripts and other documents separately for design and problem solving, although most activities and comments that were coded as design were also coded as problem solving (but not vice versa). We think this approach most closely honors the definitions held by the engineering education community.

We offer a caveat at this point in regard to engineering design and problem solving. Clearly, these activities often involve other important engineering education outcomes, such as teamwork, multi-disciplinary teamwork, and communication. And, some of what we talk about in this paper will necessarily refer to these outcomes because the activity of design is so rich and encompassing.

Methods

This study draws on data collected from the *Prototyping the Engineer of 2020: A 360-degree Study of Effective Education* (P360) and *Prototype to Production: Processes and Conditions for Preparing the Engineer of 2020* (P2P) projects. The research design, data sources, and analytical methods are described in the following sections for each study.

Prototyping the Engineer of 2020: Conditions and Processes of Effective Education (P360)

The research team for P360 used a nationally representative dataset developed for the EC2000 study[14], which assessed the impact of ABET's outcomes-based EC2000 accreditation criteria, to empirically select six case study sites. Using the data from the EC2000 study, the research team identified institutions in which graduates reported a high level of ability in design skills, contextual competence, and interdiscipliary competence. In consultation with a National Advisory Board, the team identified five institutions that exhibited superior performance on the focal learning outcomes and/or in recruiting and graduating women and underrepresented students: Arizona State University (ASU), Howard University, Massachusetts Institute of Technology (MIT), the University of Michigan (UM), and Virginia Tech (VT). Upon the recommendation of the Board, Harvey Mudd College (HMC) was added to the study in recognition of its national reputation for graduating engineers with superior design and problem-solving skills.

Data Collection and Analysis

In 2007–08, the research team divided into three smaller teams, each comprised of four to five faculty and graduate research assistants from the fields of engineering and education. Each team was responsible for data collection and reporting for two case studies. Data collection relied on multiple sources of evidence: personal and group (or focus) interviews with faculty, administrators, students, and professional staff (e.g., student support services); observations of classes and events (e.g., Projects Day), archival records (e.g., meeting minutes), and other artifacts (websites, documents). Triangulation of these data sources enabled corroboration of facts and events at each case study site. In addition, the use of multiple investigators for each site (each team included at least one faculty member from engineering and one from education), contributed to construct validity[15].

Each case study site was visited at least twice to identify and study the factors shaping each institution's performance. The full team developed a set of protocols for different groups of interviewees for the first set of case study site visits. This visit examined organizational and curricular structures and policies identified from websites, engineering education literature, and discussions with academic administrators at each site. Researchers also identified additional individuals and educational experiences to be studied during the second site visit. For the subsequent visits, the teams customized protocols for the various groups of participants.

Data collection was completed by Fall 2008. Personal and group interviews were fully transcribed and entered into NVivo, a software program that supports the management and analysis of qualitative data. Each team analyzed the data from the two case studies it conducted. Coding and preliminary analysis of data began when each team completed its visits.

Processes and Conditions for Preparing the Engineer of 2020: Survey Data from the P2P Study

The quantitative component of this study assesses whether the activities (academic - classroom and curricular - out-of-class student experiences) have an influence on students' design skills by utilizing the data collected in the *Prototype to Production* (P2P) study.

The P2P study's institutional population was defined as all four-year U.S. engineering schools where the six engineering disciplines (biomedical/ bioengineering, chemical, civil, electrical, industrial, and mechanical) accounted for 70% of all baccalaureate engineering degrees awarded in 2007. Because the P2P study was also designed to inform analyses of the six case studies from the P360 study (one of which offered only a baccalaureate-level general engineering program, Harvey Mudd College), the sample was refined to include institutions offering a general engineering program. A 6x3x2 disproportional stratified random sample of institutions was drawn using the following strata: six discipline levels, three levels of highest degree offered (bachelor's, master's, or doctorate), and two levels of type of control (public or private). The sampling design ensured that the sample institutions are representative of the population with respect to type, mission, and highest degree offered.

Data Collection and Analysis

The analyses reported below are based on the responses of 5,249 students (a response rate of 16% overall) in 31 colleges of engineering during the 2009 spring and summer terms. Weights were developed to adjust for response bias (at the campus level) and for differences in institutional response rates. The weighting adjustments produced a nationally representative sample of students with respect to sex, race/ethnicity, class year, and engineering discipline. Missing data were imputed using procedures recommended by Dempster, Laird, and Rubin[16] and by Graham[17]. P2P staff imputed all missing data using the Expectation-Maximization (EM) algorithm of the Statistical Package for the Social Sciences (SPSS) software (v.18). Consequently, the adjusted sample can be considered representative of the population of engineering students (as specified) both on each campus and nationally.

Analytical Procedures

Multiple linear regression was used to determine the extent to which students' curricular experiences, classroom experiences, and out-of-class experiences variables explain engineering students' design skills after controlling for their demographic and pre-college characteristics. The Design Skills scale was first regressed on a set of students' individual characteristics (gender, race/ethnicity, parents' education, class-year, disciplines, and SAT scores) and then on measures of six academic (classroom and curricular) and ten out-of-class student experiences that the literature indicates are related to learning and skill development[18, 19].

Variables Used
The Design Skills scale is the criterion measure for this paper. This scale contained 12 items (alpha = .92) reflecting engineering students' reports of their self-assessed ability on design skills. Table 1 gives this scale's item-content and descriptive statistics.

Four sets of independent variables are used: sociodemographic (Table 2); classroom experiences (Table 3); curricular experiences (Table 4); and out-of-class experiences (Table 5). Students' sociodemographic information was mainly used as control variables which include gender, race/ethnicity, parents' education, SAT scores, class-year, and disciplines. Classroom experiences contain such experiences as students' reports of faculty classroom practices and pedagogical approaches. Two of the six were "classroom experience" scales (students' perception on their instructors' pedagogical approaches) among academic factors: student reports of student-centered teaching (five-item scale; alpha=.81) and active and collaborative learning (four-items, alpha=.77). The other four experiences were "curricular experiences" scales measuring students' perceptions of the curricular emphasis placed on particular engineering knowledge and skills. The scales reflect engineering students' reports on the extent to which their engineering courses emphasized professional skills (five-item scale; alpha=.81); professional values (five-item scale; alpha=.81); broad and systems perspectives (five-item scale; alpha=.81); and core engineering thinking (five-item scale; alpha=.81).

Out-of-class student experiences consist of five single-item measures of the number of months students reported spending in undergraduate research activities; engineering internships; engineering cooperative education experiences; study abroad or an international school-related tours; working on humanitarian engineering projects; student design projects/competitions beyond class requirements. In addition, out-of-class experiences included two single-items measuring the extent of graduates' involvement in an engineering club or student chapter of a professional society (IEEE, ASME, ASCE, etc.); and other clubs or activities (hobbies, civic or church organizations, campus publications, student government, Greek life, sports, etc.) during their undergraduate experience. Tables 1 to 5 list the control and predictor variables (including six scales) and their descriptive statistics.

Results

Engaging Students in Design and Problem Solving: Examples from Six Case Study Institutions

Through in-depth case study analysis for the P360 project, we employed qualitative interviewing and classroom observation techniques with collectively hundreds of engineering undergraduate students, faculty members, and administrators to identify the curricular, instructional, cultural, and organizational features that support innovative engineering education aligned with the Engineer 2020 goals. In addition, we performed document analysis of materials (e.g., syllabi, publications, institutional data) collected during the case study visits. This section provides an overview of the variety of ways each of the case study institutions engages students in design and problem solving activities through curricular, co-curricular, and extra-curricular experiences.

Arizona State University: Tempe and Polytechnic Campuses

Arizona State University (ASU) Tempe sits in an urban area rich with opportunities for connections to diverse industries solving technical problems. A large number of engineering and computer science students work part time or have credit-bearing internships or co-ops in the area. From faculty comments, we concluded that well over half of the senior students had engineering-related work experience, either an internship or a part-time job. In addition, a large number of the engineering students are non-traditional, returning to school after a full-time job or attending school while working full time. These industry experiences could prepare students to be more successful in design and problem solving activities in engineering academic programs and, in general, gain more from those programs.

The industry connections also provide a pool of adjunct faculty that has, historically, been engaged in teaching engineering at ASU, particularly at the capstone design level. These practitioners have the potential to provide a valuable connection for students in the areas of design and problem solving.

Another theme that arose from our study was instructional innovation, initially stimulated by involvement in the Foundation Coalition in the early 1990's. An education faculty member noted that the Foundation Coalition was very influential in the area of engineering design and "thinking about what that capstone design project should be. . .and they spent a long time working on it very, very hard." One outcome of the Foundation Coalition and two other large education grants was the Center for Research in Education in Science, Math, and Engineering Technologies (CRESMET). The center, which still exists, initially involved faculty from education, engineering, and the College of Liberal Arts and Sciences. The center offered workshops and professional development for faculty. The center also made available seed grants for between $5,000 and $10,000 to have faculty bring innovations to their own classroom.

In addition to the Foundation Coalition, engineering faculty were involved in other innovative education projects in the 1990's and early 2000's with faculty from education. The instructional innovations that resulted from this collaboration were mostly inquiry-based and project-based learning. Some of these innovative engineering faculty moved to the Polytechnic campus and started the heavily application-based general engineering degree program there. However, the effect of these innovations seems to have a firm foothold at the Tempe campus.

One theme that came through loud and clear was the effect of an engineering core curriculum that was in place from the mid-1990's to about 2005. This core, which was administered at the college level, included a first-year design course and another interdisciplinary design course at the junior level. When engineering programs were asked to limit their curricula to 120 credits, the first-year design course was absorbed by the individual departments (although the original objectives were mostly kept intact), and the junior-level interdisciplinary course was eliminated. The 120-credit curricula went into effect in 2006. The first-year core course was project and design focused, and provided a fairly intense design experience for entering students. Most programs kept that focus when the course was moved back to the disciplines.

Faculty from the many engineering programs at ASU-Tempe mentioned design education as one of the strengths of their academic programs, and we learned that ASU has a history of strong capstone design experiences at the senior level. Most of the engineering programs at ASU Tempe have a required two-semester senior capstone course, and students satisfy this requirement in a variety of ways. A large proportion of students participate in real-world, industry-sponsored projects. Nearly all programs have a strong connection with industry at the capstone level, leveraging their geographical location both to identify design projects and to involve people from industry as adjunct faculty in the classroom. In addition, there is interest among some faculty and administrators in allowing student credit for activities such as undergraduate research or competitive design projects sponsored by student organizations.

At the ASU Polytechnic campus, the Bachelor of Science in Engineering (B.S.E.) degree program enrolled its first students in fall of 2005 and graduated the first cohort of students in May 2009. A core group of engineering faculty from several disciplines moved from the Tempe campus to the Polytechnic campus to develop curriculum for the new program in 2004, after a year of research into innovative undergraduate engineering programs. The curriculum that these faculty put together is very hands-on, with a project every semester. Below is a description of the B.S.E. program at the Polytechnic campus from their web site.

> Arizona State University has created one of the most innovative new engineering programs in the country at the Polytechnic campus in the College of Technology and Innovation. This new program combines a focus on interdisciplinary project-based, studio-based learning with exceptional curricular flexibility. The program promotes agility, creativity, and innovation in a world-class engineering educational environment. (http://technology.asu.edu/node/17#/engineering, accessed 1-1-11)

The new B.S.E. program is seen as targeting a different audience and geared toward different objectives from the Ira A. Fulton Schools of Engineering at the Tempe campus. At the Tempe campus, the focus has been increasingly on higher levels of research on the part of faculty, which means attracting more graduate students and preparing their own students for graduate school. On the other hand, the Polytechnic B.S.E. degree was designed more for students heading directly for industry. In actuality, of the first graduating cohort, more students headed to graduate school than expected—around 50%.

When asked about the distinguishing characteristics of the B.S.E. program at the Polytechnic campus, one of the faculty members said:

> I think the biggest distinguishing feature is that we have projects all the way down here. And I was very persistent that I wanted projects every semester. . . . The problem I have with the traditional program is that they go to make something their very last year and they are supposed to apply all of this theory. . .but the problem is they've never made anything in their lives. And so they go to make something and they just fail miserably at it, which is fine. You're supposed to fail in school. . . . So, the idea is that if you led them through small projects, then bigger projects, then bigger projects, then they get to the capstone; you let them improve that process. . . . It used to be that students would fix cars, they would fix lawn mowers, they would fix bikes. Students come in now—they have never taken a thing apart. They don't know how things work. So if you don't know how basic things work, how are you supposed to design the next generation of things.

The projects that the engineering students work on vary, but they are always connected with the coursework until the students reach the senior level. Some of the project work is done in the Advanced Technology Innovation Collaboratory. This facility is aimed at connecting the faculty and student resources at the campus with small businesses in the valley. Students, with faculty mentorship, work on small-scale projects. The facility opened in 2007, and in the first year they grew from 5 to 15 projects.

In summary, the innovative, project-based B.S.E. program at the Polytechnic campus grew from faculty interest in alternative approaches to undergraduate engineering education. These faculty surely impacted the design education of students while they were still at the Tempe campus, and the two campuses continue to share ideas. One might say that ASU has, with the more traditional programs at the Tempe campus, and the new B.S.E. program, the best of both worlds. Certainly, they can offer students diverse pathways to learning about engineering design and problem solving and to an engineering degree.

Harvey Mudd College

At Harvey Mudd College (HMC), a third of the student body is National Merit Scholars. Across the 30 years starting in 1951, about 40% of graduates went on to earn a doctoral degree — the highest rate of any college or university at the time[20]. This trend continues today; Harvey Mudd had the highest rate of science and engineering Ph.D. production among all undergraduate colleges and second highest (Caltech ranks first and MIT third) compared to all universities and colleges, according to a 2008 NSF report[21]. Given the comparisons, for example, to MIT, one might think perhaps the obvious: good input yields good output. However, based on our interviews, observations, and analyses, we present two foundational principles that shape the curriculum, delivery, inquiry, faculty hiring, assessment, and the cultural setting within which all these happen. The first is the ***engineering practice focus***, which defines the core values for the curriculum. The curriculum is shaped "based on the recognition that there is a professional component best addressed through practice (working on real problems)," and the core values are systems, design, experiential learning opportunities, and professional practice. The second is the utmost importance put on ***teaching and learning effectiveness,*** with clearly defined faculty hiring, continuous improvement and reward structures.

The focus of the engineering department is not only to teach students the engineering fundamentals but also their application to problems, and hence, the development of students' problem-solving and design skills for practice (or the real world). One of the HMC faculty expressed the department's goals as:

> [F]irst and foremost, competence. And that is not just competence in attempting to solve applied math, applied physics, classic engineering science stuff, but competence as designers, able to work in the design environment, competent in terms of being able to work together in teams, competent in broader systems…design integrated systems. I think that, having a good solid work ethic, being ethical, straight forward.

Partly due to the broadness of the "general engineering" program, where the goals are not to have students become experts in an engineering field, students learn that a component of developing problem-solving and design skills is learning to become a life-long learner. This was expressed by one faculty as an unintended goal of the program:

> understanding very clearly that they don't know nearly even remotely what they are going to need to know the rest of their lives, and shouldn't expect to know that after four years, but they know enough to both know what they don't know and how to learn what they don't know when they have a need to learn it. And so it is an interesting thing, because I don't think it is one of our stated goals, but it is not one of the things I would have identified as one of the benefits of a broad curriculum, is where students quickly learn that there are not only limits to their own knowledge, but limits to our knowledge. … [T]hey understand that nobody knows everything and they have to learn to get through here and they have to learn for the rest of their lives.

The engineering curriculum is not specialized to any specific discipline, as students graduate with a baccalaureate degree in general engineering. The goals of the program are to provide students with the fundamentals in ***engineering science*** (i.e., chemical engineering, computer, electrical, and mechanical engineering), ***design skills***, and ***systems thinking*** (three major strands of the curriculum) so that they gain a broad perspective and flexibility in engineering. The integration of these three strands of engineering science, design, and systems thinking and the required courses needed to complete Harvey Mudd College's humanities and social science appears to be influential in developing students' problem-solving skills.

The common core (e.g., biology, chemistry, calculus) and the engineering science courses provide students with the fundamental engineering knowledge to solve problems. In the design sequence, students learn a process and an approach to solving problems by completing hands-on activities that involve open-ended problems. The systems courses develop the analysis skills by teaching students how to see the "big picture" and how to break down complex problems to simpler components. Just as important though are the humanities and social science courses that teach students to consider the non-technical issues when solving and designing solutions. By the time a student completes the engineering program, they are expected to design, build, and test a tangible product for a client, and hence, the curriculum is built around providing ample practice in open-ended, hands-on problem-solving skills.

A significant point is that even though HMC articulates three distinct sequences, the engineering curriculum should not be considered in separate strands that come together with a capstone experience; rather, the intention is for the three strands to be interwoven so that students not only see the importance of each component but also the importance with each other. For example, the engineering science and mathematics courses not only provide the foundational knowledge to solve problems but also opportunities to learn different approaches to solving problems. Systems sequence provides knowledge on how to apply mathematics for modeling the physical world systems using symbols while solving design problems.

The design sequence starts with Introduction to Engineering Design (E4). In the early 1990's, this course was redesigned to provide students a design methodology that was based on design theory. The objectives of this course are not only to introduce students to engineering, but also teach them how to approach and solve open-ended problems. A sophomore reiterated this point by saying, "What I got out of the class and what I think the major focus of it is, is just teaching you how to approach open-ended problems." This process and approach include defining a problem, generating ideas (e.g., using functions and means charts), narrowing down to a solution, examining the ethics to solving problems and developing communication skills while working in teams.

Students learn these design and problem-solving skills through hands-on activities that include a simple design project, a reverse engineering project, and a client-sponsored project. Some students commented how this was a fun course that allowed them to solidify their interest in engineering, because of the hands-on projects in the course. During the first project, students learn the whole design process. The introductory design project changes from year to year and has included building a dowel sorting machine and a rope-climbing machine that lifts an object. The reverse engineering project allows students to dissect a product (such as mechanical pencils) to teach students about functional analysis and modeling. Finally, students do a culminating project where they interact with a client in designing a product. One professor of engineering provides the rationale for this real-world simulation:

> We do a kind of capstone experience in that class where we bring in somebody, some local client,…and they do kind of a more real project for somebody. So they get to try it out early on, and then what we do as advisors in clinic is ask them to go back to that process. Because I think a lot of times when they are given a real world project in clinic, the inclination is just to kind of run out and find an answer, or whatever. But we really do try to make them sit down, analyze their problem statement, pull out objectives and constraints, and they'll resist it a little bit, because they'll think it is silly to do that, but in the end it makes them much more concerted, …thoughtful approach to the problem, and they will end up with a better answer.

In Design Representation and Realization (E8), students learn about the manufacturing processes by designing some common hardware tools such as hammers and screw drivers. Through these types of projects, students also gain hands-on experience using machines such as a drill press, and a lathe. By manufacturing these types of common tools, students learn how "making one thing to sell is easier than making ten things that are identical to it."

Students usually take the Experimental Engineering course in their second semester sophomore year. Early versions of this course involved twelve labs that introduced students to the various engineering fields. The course was redesigned in 2000, after surveying graduates who felt the course was more of an obstacle than a building block to their development as engineers. Two years ago, the class was redesigned to focus on building and launching rockets as opposed to measuring and collecting data about bridges. In this version of the course, two of the faculty explained that it "still has pretty much all the disciplines represented [in the course], the different varieties, but all of the experiments would be geared toward understanding some aspect of the rocket. So that there would be some overriding goal as to why you would need to learn all these different disciplines." The course provides opportunities for students to strengthen their knowledge about the field, but more importantly students apply their knowledge and further develop their engineering approach and thinking skills.

The Clinic is the culminating or capstone experience for the engineering students. In this course, students solve a multidisciplinary problem for a client for an academic year. Each team, usually a group of four, is expected to produce and provide a final report and prototype to the client. Companies not only provide monetary support, but also are required to dedicate at least one liaison who works with students in providing problem specifications and as a mentor to the project. The purpose of the liaison is not only to serve as the "voice of the client," but also as a resource for students to use when technical questions arise.

Past clinic projects have included designing surf boards to developing sensors for an Unmanned Aerial Vehicle (UAV). To prepare for Clinic, students "apprentice" by participating on a clinic project for a semester in their junior year. The objective of clinic is to provide students opportunities to gain some practical experience in developing and designing a product. In explaining the growth seen in the students, one liaison said, "You know, I think they found out kind of in a difficult way that something can work one way on paper and in reality be very, very different. So you know in that sense I think they have grown and matured somewhat."

A few people commented that the length of the capstone is a reason for its success in developing students' engineering skills. One senior faculty commented that these projects cannot be completed in three months (i.e., the normal length of an academic semester), because he thinks "It takes a while to get comfortable and figure out what the problem is. There is maturation time. … I also think some of these projects are way too complex to be done in shorter time." One liaison said the typical one-semester senior design course really does not prepare an engineer for the real world.

Clinic is an opportunity for students to showcase their design and problem-solving learning, but they are also held accountable to produce a final product. If the resources are limited (i.e., school does not have the equipment to build a prototype or conduct an experiment), students are expected to be resourceful in completing the project (i.e., find the equipment in the local area). Deadlines are also important, as one student relayed how professors did not provide her any slack when she had to miss class because of a clinic project. In other words, students are expected to operate as junior engineers at work already – an almost authentic real life engineering practice simulation, which is financed through a $40,000 charge per clinic project.

The success of the Clinic projects individually and the success of the overall program are assessed through sponsor, faculty, and student reviews. Anecdotal evidence is also at hand. For example, one faculty told a story about visiting a potential clinic sponsor and noticing the company had hired at least one HMC graduate for the past eight years. Another faculty shared a story on how a company did a cost analysis on money spent for clinic versus spending the money to complete the project in-house:

> . . .they are surprised by the quality of the work, and the fact they realize that it is as good as the work they could have gotten from in-house staff and resources. And then they realize that they have paid anywhere from one tenth to one half for us to do it as opposed to having it done in house, and it probably. . . gets done more quickly even though our students are only working on it part time, because there is just a lot of internal dynamics going on at these research institutions. And I am beginning to believe them.

Clearly, what makes the Clinic program and the overall student and sponsor experiences successful is driven by the rigorous preparation of the students in this three-pronged curriculum (engineering science, systems and design), where engineering science courses provide the technical knowledge; systems concepts enable modeling of the engineering systems to be designed; and design introduces the process of engineering problem solving in the context, with constraints. This success, however, cannot be sustained without the faculty who put utmost importance on ***teaching and learning effectiveness*** toward the ideals of the clinic, and hence the engineering practice focus.

Modeled after the residency of medical training, the clinic program (established in 1975) and the overall design teaching at HMC has been a model for many schools in the U.S. and abroad. In its current state, clinic sponsors are expected to pay a fee (~$43,000 per project), which covers the costs of running such a program and provides each student team with a budget between $10,000 and $20,000, depending on the project. The engineering department also provides a workspace/office for each team. Even the sustainment of such an extensive program should be considered as a testament for its benefits for all parties involved, particularly for students.

Howard University

Howard University is a federally-chartered, historically Black institution, located in Washington, D.C. Howard University's approach to education stresses the creation of leadership within a community of people who were historically excluded from many facets of American life; this approach is referenced in Howard's motto, veritas et utilitas, truth and service. Howard's core values are listed as: excellence, leadership, service and truth. Within this mission, the university prides itself on "building the nation through a culture of excellence in leadership, scholarship, and service" (Howard University Student Handbook, 2008-09).

Design experiences at Howard, therefore, embed aspects of service and leadership and take place in a variety of ways. Similar to the other case study institutions, design is prominent in the first-year program as well as at the senior level. In addition to these typical instantiations, Howard has incorporated several unique approaches to engage students in design. For example, they have the "Adopt a Team" program, which has strong industry connections. In the Adopt a Team program students engage with industry to work on design problems relevant to the particular industry. The program functions similar to a student organization where students participate based on interest. As one student explained "an organization on campus [is] Adopt a Team and I am part of the General Motors team adoption, and our project is building radio control cars from the ground up and we have to test it to make modifications like braking and drag…and then corporate members from GM come in and they look at our progress." This program provides students access to working professionals, as well additional design and problem solving experiences. In turn, the program affords industry access to students who may become future employees.

In addition, many of the design courses place a heavy emphasis on interdisciplinary collaboration. During our visits and interviews we found that many spoke of the importance of making a contribution (a "bigger footprint") and the context of engineering. Furthermore, there was an emphasis on teamwork in design; and even more prominent, there was a consistent and recurring discussion of the importance of developing excellent communication skills.

The first-year program underwent some revisions between our first and second site visits. During our first site visit, Howard was in the process of developing the first-year design course, and this was offered in conjunction with a first-year seminar. The idea behind the first-year seminar course was to put engineering into context, discuss professional skills, and provide students with examples from industry.

> During that seminar class, which uses the full semester, we have the opportunity to keep it real by bringing people from the outside to come to our class and to speak on ongoing issues in the field of civil engineering. Typical topics could be ethics, could be management, it could be design, it could be logistics, it could be finances, it could be preparation for becoming a professional engineer as well as our client and consultant firm interactions. (faculty)

The intent of the seminar course was grounded in providing students with access to "real-life" engineering topics. While this was still deemed important, the faculty found that embedding this in the design course experiences was more valuable.

> We basically made a completely project driven course this year. We used to have seminars on things like engineering in general and the different types of engineering: civil, chemical, mechanical, etc. We used to have the Dean come and talk to them about the college of engineering, college of computer science, just had a lot of background seminars that the feedback that we got from the students was just that they didn't really get the value of it, so this year we made it all projects. This year, from the beginning of the semester, we put the students into interdisciplinary teams. We have them do three projects all design and build…they get their hands dirty from the beginning and start to actually think about design and get to design a little, that's the main change. (faculty)

Design experiences at Howard not only emphasize design but also interdisciplinarity, teamwork and communication. One faculty says: "We emphasize design, design, design and we emphasize communication skills." Another echoes a similar sentiment: "Every professor pretty much is going to measure or going to stress communication both in a written and oral fashion in the presentation, and of course I'm notorious for a lot of class participation and discussion."

The design courses are also often team-taught: "the first-year students have to take that course. It's a team taught course--there are five of us, one from each department and we all teach the courses as a team." In addition to having engineering faculty from multiple disciplines co-teach, some courses are team taught by faculty from completely different schools at the institution. For example, the mechanical engineering capstone is quite innovative and is team-taught by faculty from engineering and art. The teams also comprise both engineering and art students.

> I think they enjoy just to work with the art student, as I said they have tremendous respect for each other. I saw engineer students try to work together with artists [on] how to do this, how to do that…I think the mechanical engineering students are impressed by the artist[ic] creativity… . We can even use wire frame 3-D modeling…do rendering…take it to the sculpture lab…so it is very interesting for the mechanical engineering students on how to model a car. (faculty)

Our interviews also shed light on how faculty at Howard think about design and what they conceive as the fundamental aspects of design. For example:

> …All necessary design process[es] like a problem formulation, problem solving, solution implementation, … evaluation and then demonstration… creative thinking …so I try to infuse that kind of [thinking in] my students 'cause designing is problem solving, so the problem is given to them, now ok, do your brain power.' (faculty)

In addition to design process skills such as problem identification and implementation, almost all faculty describe how professional skills are embedded in design: "we teach them about design, and we also work on communication skills, working in a team, some leadership skills, all those things wrapped up into one course."

The Adopt-a-Team program brings these professional skills to the forefront and provides students direct access to working professionals. As one high-level administrator describes, "our motto in the college years is give our students the world by design and the Adopt-a-Team project was one [example]." Design is considered one way to enable students to become a "complete person"; this concept is embedded in the culture as well as specific academic activities: "The importance of interacting and . . .the importance of being a complete person. . . we think that is kind of important to do. We try to institutionalize things in the program to help students develop these skill sets. It becomes embedded in a lot of the things that we do."

We found that at Howard design is intertwined with professional skills and is conceptualized as an inherently interdisciplinary activity. Communication, teamwork, and leadership are all considered aspects of design, so the design courses have been developed to explicitly embed these as central activities of the design process. Moreover, the interdisciplinary aspect of design not only comes through based on the nature of the project, but is explicitly modeled through team teaching as well as having students from multiple disciplines work together on projects.

MIT

The Massachusetts Institute of Technology (MIT) is located in Cambridge, MA, and is known as a pre-eminent institution of research, teaching, and learning in the sciences and technology. As an institution founded to impart practical knowledge, MIT implements education from a laboratory approach, stressing hands-on experimentation. This approach is congruent with the Institute's motto, *mens et manus* – mind and hand. The mission of MIT is to advance knowledge and educate students in science, technology, and other areas of scholarship that will best serve the nation and the world in the 21st century. MIT is dedicated to providing its students with an education that combines rigorous academic study and the excitement of discovery with the support and intellectual stimulation of a diverse campus community: "I think the main thing is we really focus on doing stuff. That is the real vicious [i.e., relentless] part of our culture. We do stuff " (MIT faculty).

Consistent with the mission, our findings show that at MIT there is an emphasis on providing context for learning, building intuition, and making connections across subjects—all of which come together in the context of design and problem solving. Moreover, this holds true for all disciplines, not just engineering. In particular, at MIT the departments recruit from the freshman class: "Freshmen are not admitted in a department like civil or electrical or even physics, they don't have to choose. All the freshmen have to take, even if they are in the humanities, more or less the same classes" (MIT faculty). This means that all students have exposure to, and are expected to be proficient in solving problems.

Overt value is placed on hands-on and "doing" with the recognition of how important building physical intuition is to developing a robust understanding of the more theoretical and analytical concepts: "Especially targeted at that first year, not sophomore year…is to provide a more in-depth experience to build intuition and provide a basis of hands-on experience that motivates and connects to the next round of subjects." (MIT faculty)

Students at MIT have "early and often" classroom design experiences. The first-year common core for all MIT students serves as a backdrop to understand the first-year design experiences in particular. That is, from one point of view, design is a mechanism for helping students build intuition, and gain an appreciation for how theoretical concepts can be applied in realistic settings. Furthermore, another aim is to "motivate knowledge acquisitions" (MIT faculty and department head).

In addition to gaining practical experience through design, as well as providing motivation, another theme that runs throughout MIT's first-year experience is to enable students to develop teamwork and to build a collaborative atmosphere:

> So you know, working in teams, being able to solve problems that are more diffused, less well defined, kind of that broader thinking and being able to work, not just *team work*, but work to really understand the strengths and weaknesses of people that you're working with to capitalize on that for a common good. (MIT administrator)

Students also describe teamwork and peer collaboration not only as a strength, but a necessity:

> I guess I've noticed MIT education is very good and geared towards innovation in that the whole idea of peer-to-peer collaboration, like the information that we received, the basic information that we received within our classes are kind of our foundation to go and discover something new and to go and solve world problems. I think one of the major strengths of MIT is just they are focused on building problem solvers and they do that by forcing us, or kind of like making things extreme. Like they give us extreme cases a lot of times and extreme problems that we have to go and solve. (student)

Many students acknowledged the intensity of the MIT curriculum and realized early on that it just is not possible to succeed without the help of peers. The rigor of the curricular experience serves as a catalyst for students to recognize the value of working together to achieve success.

Many MIT faculty even discuss the education process using metaphors from design. That is, the students are referred to as "products" and moreover, one of the best products at MIT: "It was pretty easy for me to conclude that we do many things at MIT, we do many things in this department, but if I had to pick one product it is undergraduate students. That's our best product" (MIT faculty).

In addition, "hands-on" is a pervasive theme throughout the MIT engineering curriculum, and is embodied by the institution's motto: "mens et manus."

> We also have the motto ‘Mens et Manus’ mind and hand. . .the idea of theory and practice, brought together very closely, so learning things through the lens of practice, not just being able to think them through an intellectual exercise. We also say ‘Now that I understand that, how do I build it? How do I see it in practice?’ and I think that is an old and unique experience for MIT. (MIT faculty)

It is clear that MIT engineering faculty value both hands-on and analytical experiences, and these two approaches inform each other.

> Our engineering students are really getting hands-on experience. For example they [have] built a radio or taken apart a CD player to see what is inside and that kind of thing. Beyond that. . . they have an opportunity to go in a lab and spend time there, break a few things. . .be innovative. (MIT administrator)

Students corroborated the emphasis on hands-on and building. One student noted:

> MIT is very conceptual and they are not just here to make you solve problems. They don’t give you a method and then you keep solving problems the same way; they give you the concept behind why the problem was solved this way and then you have to apply your skills to solving that problem… we build a lot of stuff. I think three out of our ten or twelve required classes we build a lot of stuff. (student)

The notion of design, that is developing innovative solutions to ambiguous, ill-defined needs or problems, applies to many aspects of the MIT engineering experience. That is, design does not necessarily reside in a “design course” or is even labeled as a particular design experience. For example, working on experiments in a laboratory setting is also seen as a process of innovation, and is approached as such. Furthermore, the experimental design is directly linked to learning some aspect of the subject matter or theory:

> Then the laboratory component where what they are really learning is the basics of bioprocessing and how to deal with instrumentation and how to make measurements of certain parameters… given a problem statement, then design a series of experiments that are supposed to test out some hypothesis… and so what we try to do is to give students both context and to then give them open access…you have this issue and then you have got to figure out how to solve it, and oh by the way there is not a single right answer…Nobody knows what the right answer, who knows if there is a right answer…the point is to get an answer and then understand what that means. (MIT faculty)

MIT actively encourages students to pursue their passions and to gain real-life experiences beyond the confines of the university. As one high-level administrator explains:

> We have the month of January off and we create a meaningful experience for them perhaps in a developing country or in a non-English speaking country where they can get a very different exposure [than] their day-to-day lives here. It is purely voluntary, but 80% of the students at MIT have done at least one semester of UROP (undergraduate research opportunity) before they graduate…. Here is a great opportunity to give international exposure, technology training, hands-on experience, cultural opportunities

> and also make them feel good about doing something called humanity.…This generation of students seem to be much more aware of global happenings and wanting to make a difference, and if there is an opportunity to do that in the context of science engineering that would be wonderful.

The quote illustrates several interwoven themes that permeate the culture and approach to design. Specifically, there are many opportunities for design to be situated within a broader social, global, business, environmental context. Design is more than just building a technical solution; rather, it is about making a difference in society for the better.

As is typical of engineering schools, MIT includes capstone experiences. What makes MIT's engineering design experiences stand out is not necessarily anything specific at the senior/capstone level, but how a focus on hands-on design and experimentation permeates the undergraduate education psyche. There are almost limitless opportunities for students to engage in some form of engineering design or problem solving activity beyond the walls of the classroom. For example, there are many opportunities to engage in design experiences through outreach, clubs, and the Edgerton Center:

> . . .we have a group, a sizable group, that does K12 outreach work, which involves some MIT students. The second group, which is our support for student clubs and, there are 360 student activities at MIT but there [are] 20 or so that are hands on, build things, compete in contests that kind of group. It is those students that are based at the Edgerton Center…strongest running team is a solar electric vehicle team (they have gone four times to Australia and raced solar cars across Australia), SAE Teams. . . robotics teams, underwater vehicle teams, those kind of things. They need shop resources, they need material resources, they need money, they need guidance, they need insurance, all of the kind of things that a support structure thing. We can make [it] easier for them. (MIT faculty and Director)

MIT supports and encourages students to pursue their passion. And, moreover, provides the infrastructure to enable students to do so. Emanating from this perspective is the unique feature that in-class experiences can derive from out-of-class opportunities. The following describes how this can happen at MIT:

> Three weeks in the field working on real problems, and really working with real people, they come back, some of them with just an incredible motivation and they keep doing engineering. The students come back and start their own courses. So we have a wheelchair design course, because a kid went to Tanzania and worked as a wheelchair engineer, came back with great ideas for how to improve on wheelchairs that are used in developing worlds. Another student who came back from working with an organization in India that does prosthetics and orthotic devices, he came back, we now have what we call a mobility lab and a new subject with largely student taught on devising prosthetics devices that could be made inexpensively and help people in the developing world. So, these kids come back motivated and just roaring to go. (MIT faculty and Director)

University of Michigan

Like many other colleges of engineering that try to partially fulfill ABET's design criterion, University of Michigan provides a first-year engineering course (Engineering 100) that not only introduces students to a certain engineering discipline but also teaches them a general design process. Even though the course is coordinated through the associate dean of undergraduate education office, each individual department is responsible for the content and pedagogy of the course. Students, thus, have many different options in selecting their Engineering 100 course, which can range from a strictly lectured-based course to a course with a few mini team projects to a course where students are actively designing and building a project (e.g., blimps).

The variety in the types of Engineering 100 courses demonstrates that University of Michigan is no different from other colleges that house multiple engineering disciplines in separate organizational units in that the emphasis of design skills can vary from department to department. For those disciplines that felt design was essential for their graduates (such as mechanical engineering), the design curriculum would build upon the first-year design courses and integrate design skills throughout the curriculum. While other departments may have felt it was important, providing opportunities to develop students' design skills is seen more challenging (e.g., materials). As one senior faculty member said:

> I think you can look at several disciplines where, and I tend to think of them as the process oriented disciplines, chemical engineering, nuclear engineering, where it is difficult, more difficult for those departments for those curricula to figure out how to do meaningful design. Materials science is a great example. Material scientists don't design things; they work with people who design things, and really to do design in material science, ideally it really does become multidisciplinary.

Perhaps it is due to curricular structures defined by disciplinary differences, some senior faculty members observe that students are great at solving well-structured problems, but have difficulty with more open-ended problems because of their inability to see the "big picture" although University of Michigan (UM) is a world-renowned university with a highly-ranked undergraduate engineering program (according to *U.S. News and Report*). One senior faculty member in mechanical engineering said:

> They knew how to do a beam analysis. But when you asked them to do something a little more complicated, they did not know because they really did not know how to abstract. So once you gave them the problem with the boundary conditions ... they could do it. But if you say I got this piece of equipment inside the machine, now do a load or a stress analysis, they did not know because they did not know to take it out and isolate it. ... You know why because they just were not connected with the real stuff and also another thing was happening which is even more so now students that came to engineering increasingly had no hands on experience from their previous lives.

The faculty, then, felt that students were developing the theoretical knowledge to solve problems, but not the practical knowledge needed to solve design problems.

The above issue illustrates that some of the challenges in providing students with design opportunities can be attributed to the organizational structure, and hence, disciplinary boundaries. Even though many of the University of Michigan faculty would agree that engineering is multidisciplinary in nature, having separate departments poses barriers in providing the multidisciplinary problems students need to develop design skills in the curriculum that colleges with a single engineering department like Harvey Mudd College can more easily overcome.

What some faculty (and administrators) did notice was that a large portion of their students were able to complement their in-class experiences with out-of-class curricular experiences. These include activities such as design competitions (e.g., solar car) and undergraduate research experiences. These opportunities provide students with open-ended problems, many of them multidisciplinary in nature that would allow them to build their practical knowledge needed for design problems. Until recently, even though many students participated in these activities, they were not formally recognized for their involvement, with the exception of co-op students whose transcripts and diplomas have the co-op seal if they completed a co-op. To capitalize on their student culture propensity toward these types of activities, faculty and administrators developed a minor in multidisciplinary design, which has become official in 2010. One senior administrator (and faculty member) describes the purpose of the minor as:

> this minor is intended to be the first step into this … to find a curricular way to help the students, but also to try to expand our opportunities for students. . . . To get the minor it is not just a one-term activity. It is really meant to be one year and really honestly a minimum of a one to two year activity that they are leading up to. They are not all just competitions. . . .Truly interdisciplinary having them work together on a real, a real problem.

The administrators and faculty at University of Michigan have recognized the importance of the out-of-class and co-curricular experiences and are making an attempt to better integrate them with the in-class experiences. In developing the minor, the College of Engineering is trying to promote the value of design and create the multidisciplinary opportunities students need to develop their design skills without major restructuring of the organization (i.e., the department barriers) and the curriculum.

What is also clear at UM is the importance of the material taught in classes and that it would not be sacrificed so that students would have more design courses in the curriculum. As most design faculty recognized, even though some schools are successful at providing a year-long design experience within the curriculum itself (see Harvey Mudd College), the difficulty in scaling up at larger institutions makes providing a meaningful design experience, where students can go through the whole design-build-test cycle, nearly impossible in a single semester. Even though the minor is optional, students now have a better opportunity to create a curriculum that will better allow them to develop their design skills without sacrificing the knowledge needed to solve such problems.

Virginia Tech

Virginia Tech's culture is permeated with a "design *is* engineering" mantra. As one high-level engineering administrator pointed out, "there has been a huge focus on hands-on learning here...more so than any place I've ever been" (administrator). Some at Virginia Tech think that

Virginia Tech's history as a military institution gave birth to the present-day focus on design in engineering education. This military history provided the school with a solid grounding in the hands-on, practical application of engineering, and when many schools moved toward the theoretical in engineering education, Virginia Tech did as well, but did not move as far and never lost those underpinnings of the applied side of engineering.

No discussion of design and problem solving at Virginia Tech would be complete without mentioning the Joseph F. Ware, Jr., Advanced Engineering Laboratory (Ware Lab) and how it contributes to design at Virginia Tech. The Ware Lab is considered a major strength by many at the institution. The Ware Lab was founded in 1998 with a gift from Joseph Fulton Ware, Jr. Another gift from Arthur Klages created the Klages Machine Shop soon after, and in 2006, the entire lab was remodeled with the help of the Virginia Tech Student Engineers' Council. One goal of this 2006 remodel was to make the lab friendlier to a diverse group of students. The lab is still expanding. As the lab's web site touts:

> The Ware Lab is the focal point for hands-on projects in the College of Engineering and is the best place on campus to view many projects developed by our undergraduate students. From autonomous underwater vehicles to radio controlled aircraft, engineering students, at all levels, are encouraged to become part of a design team that expands their view of what an engineer can accomplish before and after graduation. Companies frequently visit the lab and meet with students to discuss potential opportunities for internship, co-op or full time employment. The "hands-on, minds-on" philosophy of the Ware Lab promotes real-life experience with engineering concepts before students step out into the working world ("VT Ware Lab," 2009).

The Ware Lab Director told us that at the time of our data collection there were about 400 students using the lab, and these students were working on 11 large projects, five of which were based in mechanical engineering, five in aerospace engineering, and one in civil engineering. She estimated that about half of the students were getting academic credit and the other half were working as volunteers (administrator).

In a focus group of students who were currently working on projects in the Ware Lab, it was clear that some of the students made the decision to attend Virginia Tech after coming to campus and seeing the Ware Lab, and a few students work on projects in the lab for a full four years. One student remarked that "I've learned far more in Formula than I've learned in any of my classes…real world experience is what you really learn with these projects" (Student Focus Group). Another student, who is a member of a 19-member team, said that:

> It's a…social thing…you get in a leadership position [and] you learn a lot more…There's a lot of high technology that you really just don't learn in classes…You've got to learn it really quick. And they just don't really offer that many classes for that kind of stuff here. (student)

Team members recruit first-year students to their teams by talking to students in the engineering living/learning communities, doing tailgates at football games, and being present at other engineering events.

Most of the research team was able to visit the Ware Lab in person on one of the site visits. The lab is, indeed, a hub of activity, with numerous "bays" where groups of students are working on real-life design projects, some of which are for-credit, capstone projects and some of which are extra-curricular, competition projects such as the concrete canoe and the mini-Baja car. A facility like the Ware Lab offers students a host of learning opportunities.

As Dym et al. reported, "[t]here is a clear need to…create the facilities—such as design studios and associated shops—needed for modern, project-based design courses"[7] (p. 114). Many engineering programs now have the benefit of a facility similar to the Ware Lab; however, few have had such a facility for as long as the Ware Lab has been in existence, and few facilities are able to accommodate such a large number of students and projects. The lab is recognized by the Virginia Tech engineering community as central to its success in educating undergraduate students.

As we talked to people at Virginia Tech, we found that, across the board, from students to staff to faculty to administrators, the people in the Virginia Tech community expressed a desire to give students early and frequent experiences with engineering design and to produce students who were prepared to solve real-world, engineering problems. It is important to note that the focus on design and problem solving is integrated with decision making: Many administrators spoke of the Virginia Tech focus on design.

In regard to in-class design and problem-solving learning opportunities, the Department of Engineering Education (ENGE) at Virginia Tech is responsible for developing and offering courses that all first-year engineering students take. The department publicizes six outcomes for the First-Year Engineering Program, including "Demonstrate a basic understanding of and capacity for problem solving" and "Demonstrate a basic understanding of the engineering design process" (http://www.enge.vt.edu/Undergraduate/index.html, accessed 1-1-11). The Department of Engineering Education is also the organizational home of the Ware Lab and the Frith Freshman Engineering Design Laboratory, which is available to first-year students for the design and reverse engineering projects in their introductory classes.

At the senior level, nearly all of the engineering programs at Virginia Tech have a required two-semester senior capstone course. Students satisfy this requirement in a variety of ways. Many students participate in real-world, industry-sponsored projects. There are also some community service projects; for example, a group of students recently worked on a design project for the community animal shelter. Some of the projects span more than one year, and several groups of students will work on the project in sequence, with one group completing the early design group, another continuing the design work, and later groups taking the design work into the production stage. Competitions are popular, and the SAE and Baja SAE car projects, for example, can count for the senior capstone requirement for some programs.

In summary, the research team found that Virginia Tech lived and breathed engineering design and problem solving. The message was consistent, and it had clearly reached every part of the community: administrators, faculty, staff, and students. Most community members were excited about the design and problem-solving opportunities they were offering their students, and believed that they were doing a better job than most institutions in regard to preparing their students to solve real design problems on the job. Extra-curricular projects and experiences play an important role in the education of engineers at Virginia Tech. Some extra-curricular projects have become so central to the educational mission that faculty have become more flexible about allowing credit for participation, even to the level of allowing substitution for the senior capstone design course.

The P2P Study Findings

Multiple linear regression analyses indicate that engineering students' curricular, classroom, and out-of-class experiences significantly contribute to the development of students' design skills after controlling for their socio-demographic information and disciplines (Table 6). The overall regression model with the control variables explains 55% of the variance of design skills; without the independent variables, the control variables alone explain 23%.

Comparing the effect sizes for the academic experiences, this model shows that the program's curricular emphases on broad and systems perspectives (effect size = .69) has the greatest influence on engineering students' design skills. Other positive influences include the utilization of active/collective learning in the classroom (effect size =.36), participation in an humanitarian engineering project (effect size = .36), and having a curricular emphases on core engineering thinking (effect size =.32).

A diversity of out-of-class experiences have positive influences on students' design skills. For example, student's involvement in humanitarian engineering projects (effect size = .36), engineering internship (effect size = .12), an engineering club or student chapter or professional society (effect size = .09), community service or volunteer work (effect size = .08), design project/ competition beyond class requirements (effect size = .03) all have positive influences on their design skills. This provides support that activities beyond those in the classroom or in the curriculum can help students' develop their design skills. The effects may not be as strong as curricular emphasis on broad and systems perspectives, but the positive effects are also not trivial.

Even though out-of-class experiences are often beyond the control of engineering faculty (i.e., in-terms of content, activities), a diversity of these experiences have positive influences on the outcome. For example, student's involvement in engineering internships (effect size = .12), , non-engineering related), student design projects/competitions beyond class requirements (effect size = .09), community service or volunteer work (effect size = .08) and being active in engineering club or student chapter of a professional society have significant, positive influences on their design skills.

Limitations

In conducting the P360 study, we experienced certain constraints that in turn restrict the transferability of this study. Some factors involved time limitations. Given that our site visits needed to fit into two days each trip on certain dates, the number of people we could interview and classes we were able to observe were limited. Therefore, our findings do not provide a complete picture of all the classroom activities and perceptions of faculty, staff, and students.

Other considerations include our sampling procedures and resulting sample. We interviewed faculty, staff, and students whom we identified as likely to offer insights into the three focal learning outcomes of problem-solving and design, interdisciplinary competence, and contextual competence, plus the recruitment and retention of underrepresented students and faculty in engineering. Consequently, the sample included a greater proportion of participants from some engineering disciplines than others. In addition, we communicated the goals of the project to our liaisons who helped us to identify and contact some individuals (students in particular to whom we did not otherwise have access), which impacted to some degree whom we ended up interviewing. Also, students and alumni self-selected to be interviewed individually or as part of a focus group; thus, we may have attracted individuals who were particularly motivated to share their views about their institution. It is further important to mention that although we targeted student leaders and underrepresented minorities for individual interviews for the first visit and conducted focus groups during the second visit, we felt that our contact with the students was still limited.

Finally, the last group of limitations relates to the source and nature of our data, including the types of conclusions we can draw from their analysis. The original data from which our "exemplary programs" were chosen has its own limitations: (1) the data are self-reports from students and (2) the response rate varies from institution to institution and from program to program. Finally, it was difficult to "recreate" the environment that existed during the period when the original data were collected in 2004. We had to assume that the earlier environment, through the continuation of programs, activities, and philosophies, persisted to the present day. Nevertheless, some people we interviewed were not at the institution at the time the original data were collected. With regards to the P2P data, the use of self-reported data for student ability in design skills may be considered a limitation. Although direct measures of learning would be preferable to self-reported abilities, there is no widely used standardized test of the engineering learning particularly for key learning outcomes such as design skills[14]. Until such tests are available, self-reports of engineering abilities are a reasonable proxy, but should be interpreted cautiously. Another limitation is that the P2P findings are generalizable only to engineering graduates in the disciplines studied. Although these fields award more than 70% of all undergraduate engineering degrees annually, engineering graduates in other disciplines may or may not have experienced curricula and co-curricula similar to those reported by respondents in this study.

Summary

This paper reported in-depth details about how six distinct institutions engage students in design and problem solving from the student, faculty and administrator perspectives. These detailed multi-perspective examples, organized around the features of the college experience as shown in Figure 1, provide concrete information for how engineering programs might implement, revise, or scale design activities at their own institutions. Consistent with the framework, we found that classroom experiences are only one way that our institutions engaged students in design. Other prominent co- and extra-curricula experiences include individual research experiences with faculty, design competitions, global overseas design projects, independent study, industry-sponsored design opportunities, and several other programs unique to the six respective institutions. The P2P, which utilizes a national samples, provides evidence that these activities do indeed help students with their design skills and support the findings and initiatives from the institutions in the P360 study.

Our findings also shed light on how an institution's mission and values shape how courses are designed and how faculty teach and engage with students. During each of our case study visits the institutional culture was palpable and present in almost all of our interactions with students, faculty and administrators. Results from our study suggest that in many ways the institutional culture defines how design and problem solving occurred, even more so than any particular pedagogical, assessment, or theoretical approach. Moreover, the statistical data as well as our case studies make a strong argument for the need for flexibility in the curricular approach based on institutional characteristics, and faculty and students needs and interests. We found that "one size does not fit all" and there are a range of effective approaches to educate and to engage our engineering students in design and problem solving.

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Table 1: Dependent Variable

	Mean	Std. Dev.
Design Skills*[1.] *(alpha = .92)		
Evaluate design solutions based on a specified set of criteria.	3.72	0.96
Generate and prioritize criteria for evaluating the quality of a solution.	3.62	0.97
Producing a product (prototype, program, simulation, etc.).	3.33	1.13
Apply systems thinking in developing solutions to an engineering problem.	3.45	1.07
Brainstorm possible engineering solutions	3.83	0.93
Take into account the design contexts and the constraints they may impose on each possible solution	3.55	1.03
Define design problems and objectives clearly and precisely.	3.75	0.91
Ask questions to understand what a client/customer really wants in a "product."	3.67	1.08
Break down a design project into manageable components or tasks.	3.77	0.97
Recognize when changes to the original understanding of the problem may be necessary.	3.76	0.91
Develop pictorial representations of possible designs (sketches, renderings, engineering drawings, etc.).	3.67	1.09
Undertake a search before beginning team-based brainstorm	3.51	1.07

[1] Question stem for items in scale from student survey: "Please rate your ability to apply…" Responses were given using a five-point scale, where 1= "Weak/none" and 5= "Excellent"

Table 2: Independent Variables - Classroom Experiences

	Mean	Std. Dev.
Student-Centered Teaching Scale*[1] *(Alpha = .84)		
Set clear expectations for performance	4.18	.68
Conveyed the same material in multiple ways (in writing, diagrams, orally, etc.)	3.76	.73
Explained new concepts by linking them to what students already know	3.88	.77
Used examples, cases, or metaphors to explain concepts	3.98	.78
Answered questions or gone over material until students "got it"	3.56	.86
Active/Collaborative Learning Scale*[1] *(Alpha = .77)		
Provided guidance or training in how to work effectively in groups	3.00	.94
Provided hands-on activities and/or assignments	3.48	.88
Used in-class, small group learning	2.98	.94
Assigned group projects	3.58	.93

[1] Question stem for items in scale from student survey: "In your engineering courses, how often have your instructors …" Responses were given using a five-point scale, where 1= "Never" and 5= "Very often"

Table 3: Independent Variables - Curricular Experiences

	Mean	Std. Dev.
Program Emphases on Core Engineering Thinking[1] ***(Alpha = .85)***		
Generating and evaluating ideas about how to solve an engineering problem	3.80	.89
Defining a design problem	3.78	.93
Emerging engineering technologies.	3.50	1.04
Creativity and innovation.	3.72	1.03
How theories are used in engineering practice.	3.72	1.00
Program Emphases on Broad and Systems Perspectives[1] ***(Alpha = .84)***		
Understanding how non-engineering fields can help solve engineering problems	2.61	1.05
Applying knowledge from other fields to solve an engineering problem	2.86	1.06
Understanding how an engineering solution can be shaped by environ, cultural, econ, and other considerations	3.00	1.07
Systems thinking	3.23	1.07
Program Emphases on Professional Skills[1] ***(Alpha = .88)***		
Leadership skills	3.33	1.09
Working effectively in teams	4.02	.89
Professional skills (knowing codes and standards, being on time, meeting deadlines, etc.)	3.59	1.12
Written and oral communication skills	3.74	.92
Project management skills (budgeting, monitoring progress, managing people, etc.)	3.32	1.06
Program Emphases on Professional Values[1] ***(Alpha = .82)***		
Examining my beliefs and values and how they affect my ethical decisions.	2.62	1.15
Ethical issues in engineering practice.	2.99	1.12
The value of gender, racial/ethnic, or cultural diversity in engineering.	2.54	1.15
Current workforce and economic trends (globalization, outsourcing, etc.).	3.15	1.10
The importance of life-long learning.	3.67	1.02

[1] Question stem for items in scale from student survey: “How much have the courses you’ve taken in your engineering program emphasized…” Responses were given using a five-point scale, where 1= “Little/no emphasis” and 5= “Very strong”.

Table 4: Independent Variables - Co-curricular Experiences

	Mean	**Std. Dev.**
Undergraduate research activities[1]	3.69	6.30
Engineering internship[1]	3.33	5.72
An engineering cooperative education experience[1]	1.54	4.52
An engineering club or student chapter of a professional society (IEEE, ASME, ASCE, etc.)[2]	2.19	1.21
Other engineering-related clubs or programs for women and/or minority students (e.g. NSBE, SHPE, SWE, WISE, etc)[2]	1.61	1.00
Other clubs or activities (hobbies, civic or church organizations, campus publications, student government[2]	3.36	1.32
Study abroad or on an international, school-related tour[3]	.99	3.90
Humanitarian engineering projects (Engineers without Borders, etc.)[3]	1.04	4.66
Non-engineering related community service or volunteer work[3]	4.13	8.13
Student design project(s)/competition(s) beyond class requirements[3]	2.94	7.10

[1] Question stem for items in scale from student survey: "Since starting your engineering program, approximately how many <u>months</u> have you spent…"

[2] Question stem for items in scale from student survey: "During the past year, <u>how active</u> have you been in . . . .?" Responses were given using a five-point scale, where 1 = "Not Active" and 5 = "Extremely Active (hold a leadership post)."

[3] Question stem for items in scale from student survey: "During the past year, about how many <u>weeks</u> did you spend participating in (each activity)."

Table 5: Control Variables

	Percent
Gender	
Male	72.8%
Female	27.2%
Race/ Ethnicity (Dummy coded, 1=yes, 0=no)	
African American	2.8%
Asian American	8.1%
Hispanic/ Latino American	5.8%
Other[1]	19.3%
Caucasian American (reference group)	64.4%
Discipline (Dummy coded, 1=yes, 0=no)	
Bio-medical or Bio-engineering	6.0%
Chemical Engineering	10.0%
Civil Engineering	17.3%
Electrical Engineering	18.1%
General Engineering/Engineering Science	6.4%
Industrial Engineering	4.7%
Other engineering discipline	4.1%
Mechanical Engineering (reference group)	33.3%

Table 5: Control Variables (con't)

Class Standing (treated as interval scale)		
Sophomore	19.4%	
Junior	34.5%	
Senior	35.8%	
More than senior year	10.3%	
Highest level of education attained by father (treated as interval)		
Did not finish high school	3.9%	
High school graduate/GED	13.1%	
Attended college but did not receive a degree	9.9%	
Vocational/technical certificate or diploma	3.8%	
Associate or other 2-year degree	13.7%	
Bachelor’s or other 4-year degree	32.9%	
Master’s degree (M.A., M.S., M.B.A., etc.)	18.6%	
Doctorate degree (Ph.D., J.D., M.D., etc.)	4.1%	
Highest level of education attained by mother (treated as interval)		
Did not finish high school	3.7%	
High school graduate/GED	11.4%	
Attended college but did not receive a degree	8.4%	
Vocational/technical certificate or diploma	4.3%	
Associate or other 2-year degree	8.3%	
Bachelor’s or other 4-year degree	30.0%	
Master’s degree (M.A., M.S., M.B.A., etc.)	21.9%	
Doctorate degree (Ph.D., J.D., M.D., etc.)	11.4%	
	Mean	**Std. Dev.**
SAT Composite Score	633.42	80.65

[1] The category includes Native American; Middle Eastern American; Multi-race; Foreign National; Naturalized Citizen; and other racial/ethnicity.

Table 6: Results of Regression Exploring Unique Contribution of Students' Classroom, Curricular, and Out-of-Classroom Experiences on Their Design Skills (N = 5405)[1,2]

	Effect Size (a)[3]	
Control Variables		
Gender		
Male	.03	**
Race (reference group = White)		
African American	-.11	***
Asian American	-.08	***
Hispanic/Latino/a American	-.11	***
Major (reference group = Mechanical Engineering)		
Chemical Engineering	-.04	***
Civil Engineering	-.10	***
Electrical Engineering	-.19	***
General Engineering/Engineering Science	.20	***
Class Standing	.22	***
Mother/Guardian's highest level of formal schooling	.13	***
Classroom Experiences		
Student-Centered Teaching Scale	.04	*
Active/Collaborative Learning Scale	.36	***
Curricular Experiences		
Program Emphases on Core Engineering Thinking Scale	.32	***
Program Emphases on Professional Values Scale	-.21	***
Program Emphases on Professional Skills Scale	-.25	***
Program Emphases on Broad and Systems Perspectives Scale	.69	***
Co-curricular Experiences		
Undergraduate research activities	-.05	***
Engineering internship	.12	***
An engineering cooperative education experience	-.02	*
An engineering club or student chapter of a professional society	.09	***
Humanitarian engineering projects	.36	***
Community service or volunteer work	.08	***
Student design project/competition beyond class requirements	.03	**
Constant	.63	***
Adjusted R^2	.55	

[1] Only significant variables reported in Table

[2] Effect size is an unstandardized regression coefficient/SD of outcome (0.82)

[3] The number of respondents were weighted by gender, race/ethnicity, discipline, and adjusted for institutional response rate.

*p < .05 **p < .01 ***p < .001