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Special Issue
Clive L. Dym Mudd Design Workshop X
Design and the Future of the Engineer of 2020

Guest Editor
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This paper is a brief resume of the presentations and vivacious interactions during the Clive L. Dym Mudd Design Workshop X: "Design and the Future of the Engineer of 2020," at Harvey Mudd College in June of 2017. This paper also describes both the key ideas that emerged from the presentations and discussions of the participating engineering design educators, practitioners and researchers.

In design learning and practice, feelings of surprise and doubt are ubiquitous due to the inherent nature of design as complex, ambiguous, and uncertain. For design learners, engaging in surprise and doubt in a productive manner may be a challenge. For design educators, it may also be challenging to scaffold learning environments that support learners in constructive ways when confronted with uncertainty. To support learners' development and educators' teaching practice, we introduce transformative learning theory and draw a connection to design activities through a lens of surprise and doubt. Transformative learning theory emphasizes students' engagement in critical reflection to challenge their beliefs and assumptions and formulate new ways of thinking and being. We use the context of a graduate learning course on design cognition to illustrate how transformative learning theory may be enacted as an approach for capitalizing on experiences of surprise and doubt. This paper contributes to design teaching and learning by providing a conceptual approach for productively engaging in students' experiences of surprise and doubt during design learning and practice.

Keywords: surprise; doubt; transformative learning; critical reflection; design experiences

The central thesis of this paper is that prototyping abilities are important for engineers in 2020 even though prototyping is not prominent in the Engineer of 2020 reports. While design itself is not cited as a separate attribute in the Engineer of 2020, its role is clear through several attributes such as "practical ingenuity" and "creativity." Prototyping and making skills, on the other hand, are not even hinted at as an important skill of the engineer of 2020. We assert that one reason for the lack of focus on prototyping is the context and timing of the report, which was published in 2004. Not only was the report written as engineering education continued its movement away from the hands-on and towards the mathematical and theory-based, it was also written when a technological revolution that made prototyping quicker and more accessible was only in its infancy. In this paper, we present results from a study of how engineering students design. Thirty-six undergraduate engineering seniors worked on teams of four for three hours to design a product while being video recorded. The students were provided with a space to work, a whiteboard, and prototyping supplies ranging from office supplies to more technological items such as sensors. One of the most surprising results was that teams spent over half (56%) of their time either building or testing prototypes. Working to better understand the problem and doing conceptual design work only accounted for 44% of their time. While prototyping can be used for many reasons, teams in this study used prototyping as a primary means of evaluating performance of designs. This activity—evaluating performance—is linked only to analytical skills in the Engineer of 2020 report. As we look to the engineer of 2040, we should embrace the idea that hands-on prototyping also plays a critical role.

Keywords: prototyping; engineering design; verbal protocol analysis; Engineer of 2020

In conjunction with the drive towards human-centered design in engineering education, questions arise regarding how students build and engage a socially-aware engineering identity, and how this identity points towards beliefs about the nature of reality. In this paper, we describe how students in a transdisciplinary undergraduate program struggle to engage with ontological and epistemological perspectives that draw on this social turn, particularly in relation to human-centered engineering approaches and sociotechnical complexity. We use a critical qualitative meaning reconstruction approach to deeply analyze the meaning-making assumptions of the students. Our findings reveal characteristic barriers in engaging with other subjectivities, and related epistemological and ontological claims implicit in these subjectivities. Specifically, we show that students' observable behaviors often mask misalignments between their epistemic beliefs and the designerly practices they employ—failing to account for the multiple subjective realities that the tools are designed to uncover. For these students, that misalignment makes the learning or practice of designerly behaviors less formative of a designerly identity. We conclude with implications for encouraging socially-aware identity formation in engineering education.

Keywords: epistemology; critical theory; transdisciplinarity; designerly identity

Innovation is critical to our economic and social prosperity. Faculty and administrators have undertaken resource-intensive efforts to foster innovation in engineering education, yet we inadequately understand the impact these interventions have on individuals' judgment of their own innovation ability. This exploratory study developed a comprehensive instrument to measure an individual's self-efficacy toward innovation. Creation of the instrument began with a literature review and expert interviews with practitioners and academics specializing in engineering innovation. Subsequent tests with experts (n = 22) and students in engineering innovation (n = 681) were used to provide validity and reliability evidence for an initial set of items. The resulting Innovation Self-Efficacy Measure (ISE) consists of 29-items within 9 clusters: creativity, exploration, iteration, implementation, communication, resourcefulness, synthesis, and vision. Factor loadings revealed through exploratory factor analysis ranged between 0.715–0.899 with reliabilities ranging between a Cronbach's Alpha of 0.743–0.864. Implications for evaluation within engineering education are discussed.

Keywords: innovation; self-efficacy; instrument development; assessment

A hands-on learning module was implemented at Marquette University in 2012 to teach biomedical engineering students about basic manufacturing processes, lean manufacturing principles, and design for manufacturability. It incorporates active and student-centered learning as part of in-class assembly line simulations. Since then, it has evolved from three class periods to five. The module begins with two classroom presentations on manufacturing operations and electronics design, assembly, and testing. Students then participate in an in-class assembly line simulation exercise where they build and test an actual product per written work instructions. They reflect on this experience and suggest design and process changes to improve the assembly line process and quality, save time, and reduce cost and waste. At the end of the module students implement their suggested design and process improvements and repeat the exercise to determine the impact of their improvements. They learn of the importance of Design for Manufacturability, well-written work instructions, process design, and designing a product not only for the end user, but also for the assemblers and inspectors. Details of the module, and its implementation and assessment are presented along with student feedback and faculty observations.

Keywords: design for manufacturability; assembly; process design

The recent reform efforts in K-12 education urge for the integration of engineering with other subject matter such as science. Design, a core practice in engineering, is new to many K-12 students, and thus, little is known about their design strategies and conceptions. One design strategy, making trade-offs, is a necessary design practice, and is a key performance dimension in student design. However, research on K-12 students' conceptions of balancing trade-offs is limited. Such research is essential as we attempt to understand how students become informed designers and how we can support their transformation. Understanding how students prioritize design strategies after taking part in a design activity allows an opportunity to see how students' conceptions of design activities change. In particular, this multi-method work addresses students' use and prioritization of the term "balancing trade-offs" in design through the following research questions: (1) Do students report changes in their perceived importance of "balancing trade-offs" after engaging in a design project, and (2) How students' *conceptions* of "balancing trade-offs" change after introduction of a design activity. This survey was administered as a pre- and post-test assessment in three middle schools with over 700 students. We performed McNemar tests to quantitatively understand changing conceptions and qualitatively analyzed open-responses to get a deeper understanding of students' rationale. Results suggest that after a design activity, "balancing trade-offs" became a statistically more important concept to students, but that students still did not have a sophisticated understanding of the term without dedicated instruction.

Keywords: engineering design; K-12; trade-offs; design decisions

At the University of California at Berkeley, the vision of a 2020 Engineer with the skills to solve the global challenges of today is being realized through an emergent program focused on design for social impact. A minor for Ph.D. students, Development Engineering (DevEng) is a degree program and accompanying ecosystem that aims ". . . to create technology interventions in accordance with the needs and wants of individuals living within complex, low-resource settings." This paper explores how the competencies conveyed through the DevEng program overlap with and go beyond the criteria laid out for the Engineer of 2020. Today's engineering student engages with a wide variety of global problems, only some of which are addressed by solely technological solutions. Academic programs across the country, including DevEng, have recognized that a unique skillset is needed to address these complex challenges. As a result, there is a growing collection of academic programs (e.g., DevEng, Design for Social Impact, Humanitarian Engineering) that train technologically adept engineers to work in multifunctional teams while attempting to have a positive social impact on the world. In this paper, the authors examine the skill development activities that students in the DevEng Program are exposed to and whether they meet or exceed the goals and principles of the 2020 Engineer. The paper further describes the DevEng learning objectives and accompanying ecosystem opportunities to determine whether the program is on track in providing students with a multidisciplinary set of skills and diverse experiences that effectively train the Engineer of 2020.

Keywords: 2020 engineer; development engineering; 21st century skills; education ecosystem analysis; skills analysis

Engineering leadership skills have been identified as a hallmark of the engineer of the future. In addition, employers seek to hire engineers with not only solid technical grounding but also strong non-technical skills. This study sought to understand which competencies of entry-level engineers were sought by recruiters during on-campus career fairs. Themes identified included participation in meaningful experiences, ability to connect these experiences to potential employment opportunities, and key behaviors such as strong communication, humble confidence, initiative, and collaborative problem solving. Beyond simply taking part in an experience, successful engineering leaders should be able to clearly articulate their contributions to these experiences and how they have solved problems (both technical and interpersonal) as well as align their combined competencies to the potential job. Cornerstone engineering design courses offer students the opportunity to develop many of these non-technical skills, such as teamwork and communication, through project-based learning in teams. Therefore, these courses are uniquely positioned to impact how a student reflects upon, and ultimately articulates, these experiences. In addition, since these courses often provide an introduction to engineering as a profession, the course is also able to help the student align their selected experiences to their career path. This paper suggests incorporating a three-part module based on career development theory into cornerstone design courses to better prepare students for their future engineering careers. In the first module, students develop self- and occupational-knowledge through interviews and discussions. The second module allows students to apply the engineering design process to a career problem by developing a career plan. Finally, the third module invites students to reflect on their experiences and plan and deliver an introductory speech, as would be expected at a career fair. By intervening early in their educational career, this type of module enables engineering students to meaningfully design their future.

Keywords: engineering design; engineering leadership; career development model; professional development; student-recruiter interactions

Free-hand sketching is an essential skill for engineering communication and visualization. Sketching provides many benefits to engineers. This paper compares two approaches for teaching engineers to sketch. The traditional engineering approach was compared with an approach borrowed from industrial design, which emphasizes learning to sketch in perspective. The Perspective approach was expected to provide greater free-hand sketch ability and sketching confidence, but its impact on spatial visualization has not been explored. Pre- and post-course evaluations measured design self-efficacy and spatial visualization using the Revised Purdue Spatial Visualization Test and the Mental Rotation Test (MRT). Both sketching approaches improve MRT scores but had no differences between the groups. For initially low scoring students, similar trends are observed as when comparing the full sample size. The results show that the Perspective approach adds additional free-hand sketching skills while preserving the critical impacts on spatial visualization. Across the course, for both groups, design confidence and expected success both increased with reduced anxiety about doing design. The Perspective approach is as effective as the Traditional approach while also including additional skills in the same amount of course time.

Keywords: sketching; spatial visualization; visual communication; engineering curriculum

Capstone design courses often provide authentic learning opportunities and real-world responsibility at the conclusion of students' undergraduate engineering education, helping prepare them for their career and life trajectories after graduation. Cultivating the broader capstone design ecosystem can further enrich students' learning, expand student connections, and facilitate acquisition of the Engineer of 2020 attributes. This paper presents a framework and associated strategies for a capstone design ecosystem that extends across the capstone design course, across the engineering department, across the institution, and across the alumni community. The paper discusses implementation of the proposed ecosystem approach as a case study supplemented by student testimonials and survey results from students and alumni regarding impact. Capstone educators are encouraged to try these strategies, in part or in whole, within their own institutions so as to improve capstone design experiences and better prepare students for engineering in 2020 and beyond.

Keywords: capstone design; ecosystem; Engineer of 2020; shadowing; alumni engagement

The National Academy of Engineering (NAE) has argued that an "Engineer of 2020" should be able to situate engineering work in broader global, societal, economic, and environmental contexts. As part of the Academic Pathways Study—a longitudinal mixed-methods study of engineering students as they move into, through, and beyond undergraduate education—we asked students to react to the NAE argument and found that students did not take an especially broad view of the context of engineering. At the same time, students described significant learning experiences that suggest a framework for curriculum development to target the broader context of engineering design as a learning outcome. This framework is exemplified in a "Perspective and Art" assignment that has been carried out in several offerings of a design seminar and a Professional Teamwork and Communication Skills course. The goal of the assignment is for students to first see and then examine their own perspectives, as well as those of others. Acknowledging multiple perspectives is one step toward broadly considering the multiple contexts in which perspectives are formed.

Keywords: engineering design; context, perspective; engineering education; instructional design; art

Peer feedback during design reviews in engineering design courses can be limited in its effectiveness due to time limitations to solicit and respond to feedback and to self-censorship of comments. These actors tend to be prevalent in the traditional question and answer period following most in-class design reviews. The net effect is a reduced quantity of feedback on which the designers may take action. Prior work has shown a significant increase in the quantity of feedback offered in writing compared to that offered in a traditional question and answer (oral Q&A) format. The focus of this research is to investigate the ability of the instructors to manipulate the quantity of feedback offered by students during a design review by manipulating the expected number of comments during a design review. The quality of the feedback as a result of this manipulation is also evaluated by the design teams in terms of comment importance, professional tone of the comment, comment originality, and ease of use of the comment. The authors manipulated the expected number of comments upward from 2 to 4 across 3 sections of an introduction to design course over three design review exercises. The number of comments closely matched the number that students were told would be expected. The quality of the comments did not substantially differ across the sections, implying a greater quantity of comments can be obtained at negligible expense of quality by setting a higher expectation on the quantity of comments.

Keywords: peer review; feedback; written feedback; student comments; feedback quantity

Designers are accustomed to solving problems that are provided to them; in fact, common practice in engineering is to present the problem with carefully delineated and detailed constraints required for a promising solution. As a consequence, engineers focus on creating feasible solutions rather than exploring novel perspectives on the presented problems. However, the Engineer of 2020 needs to respond with innovations for multiple and dynamic user needs, diverse users and cultures, and rapidly changing technologies. These complex demands require engineering students to learn that problems are not "fixed" as presented, and to build the habit of exploring alternative perspectives on the stated problem. Creative innovations in problem understanding may lead directly to more innovative solutions. While previous research has documented the "co-evolution" of problem and solution during the design process, the present work aims to understand how designers intentionally explore variants of problems on the way to solutions. Summaries of two empirical studies provide initial evidence about how stated problems are altered within successful solutions in open design challenges, along with evidence of problem think aloud protocols. Analysis of qualitative changes in problem perspectives reveals systematic patterns, or cognitive "heuristics," and these same patterns are evident as student engineers solve problems. By exploring diverse perspectives on a stated problem, engineers can incorporate innovations into *both* problems and solutions during the design process.

Keywords: engineering design; problem exploration; innovation; co-evolution

We contend that, for the engineer of 2020, the ability to adapt to changing circumstances, technologies, and paradigms will be among the most important competencies to possess. We further contend that students can develop the competency to adapt by engaging in continuous learning through reflection on doing. Additionally, we hypothesize that this critical self-reflection can be implemented in engineering 'Design, Build, and Test' courses. In this paper, we present the 'Learning Statement' (LS) as an

instrument for learning through reflection while providing instructors an instrument to assess that learning holistically. We explore a framework for implementation of the LS in a senior-level mechanical engineering design course and a method for evaluating the data collected through its use. Using LS data from 76 students in the Fall 2016 AME4163: Principles of Engineering Design course, we implement a version of the bisecting K-Means algorithm to text mine student LSs for patterns in subject matter frequently written about, changes over the course of a design project, and levels of insight demonstrated. We note that students largely focus in their LSs on keywords linked to principles associated with team formation and management as well as prototype construction and testing. Furthermore, we find that student LSs for assignments strongly correspond to targeted themes. Additionally, we find that LSs assessed as more insightful preferentially focus on areas related to team organization, concept generation, and critically analyzing the design process. We find that text mining analysis of LSs confirm patterns in student learning identified in our earlier work while greatly reducing analysis time. Further, we find that students are challenged by the team-based design process and thereby learn lessons dealing with planning, organizational structure, and delegated responsibility in such structures. Finally, we find that effective self-assessment occurs when students connect their learning to specific future utility.

Keywords: experiential learning; design, build and test; text-mining; learning statements

Knowledge capture and reuse systems, such as interactive table surfaces or smart whiteboards, have long enabled designers to review and revisit the knowledge artifacts generated by their creative work. Advances in data sensing and computation now allow near real-time analysis and feedback to be added this toolbox. In this paper, we outline our exploratory application of real-time speaker identification, audio transcription, linguistic analysis, and proactive content retrieval to design team meetings. We highlight the potential benefits and limitations of tools available to collect and analyze real-time design interactions and identify areas of future exploration for engineering educators and designers. In addition, we consider the implications of these tools for design research; automatic data analysis makes it possible to instrument several design workspaces simultaneously, increasing the chance of capturing critical moments, and increasing the opportunity to draw comparisons and contrasts across teams.

Keywords: design, knowledge capture, teams, team dynamics, interactive spaces, meetings, collaboration

Design experiences offer opportunities for students to develop a wide range of technical and professional skills. Community-engagement or service-learning is becoming more pervasive in engineering and offers opportunities for students to engage in designs that address human, community and environmental needs. Connecting engineering with these areas is cited in the literature as a means to potentially enhance diversity and retention. Analyses in this paper indeed show a positive impact on the retention of students who engage in the EPICS Program early in their academic program and female students in particular. Furthermore, there are many benefits of extended design experiences and the data shows that participation over multiple semesters has a significant impact on the depth of the experiences. In addition to the personal benefits, the participation of students over multiple years also offers opportunities for mentoring younger students within the course and can further impact the diversity and retention efforts.

Keywords: service-learning; community engagement; retention; multidisciplinary design

Over a twenty-five-year period, we have created, modified, and enlarged two first year graduate courses which introduce new PhD prospects to research via written construction and oral presentation of two research proposals. In addition to these writing and speaking tasks, we included professional development topics such as research ethics, advisor-advisee relations, the laboratory notebook, intellectual property and patents, and research group citizenship. The evolution of these formal elements I describe here as a series of curricular design challenges, each involving the classical design sequence of need identification, conceptualization, feasibility, production, and acceptance by our stakeholders: our graduate students, our faculty, and implicitly, employers of our graduated students.

Keywords: design; graduate curriculum; research; proposal

Undergraduate women are more likely than their male peers to leave engineering majors because they do not feel that they belong in the engineering classroom. The growth of university makerspaces provides a potential opportunity to establish new patterns of interactions that provide female students with a sense of community. But we cannot realize this potential to retain female engineering majors, due to our limited understanding of their sense of community in these new university makerspaces. A critical examination of how females experience community within makerspaces through an equity lens is needed to identify what interventions are needed to facilitate the successful participation of a diverse student body. During a 13-month qualitative study, we performed 27 interviews with undergraduate female university engineering students and leaders of university makerspaces and engaged in participant observation of university and independent makerspaces to identify ways to support and limit a sense of community among female students. Our findings inform design principles for university makerspaces to support a sense of community including supporting project assessment, member assessment, perspective taking, signals of approachability, structured help-seeking, and credentialing. Theoretically, we contribute an emergent framework for understanding what mechanisms undergraduate women take into account when evaluating their sense of community in makerspaces.

Keywords: makerspaces; university makerspaces; engineering education; sense of community; gender diversity; design; design communities; equity; women in engineering

The design process is often introduced with project-based learning employing ''authentic'' or ''real world'' design projects. This paper explores the educational potential of a design project with authentic outside-of-the-classroom impact. Students designed and built single-burner alcohol stoves that were used to cook meals on a four-day wilderness expedition. Half of the students used stoves that they designed and built for themselves, experiencing the impact of their own decisions. The other half of the students designed stoves that were used by classmates, experiencing the responsibility of designing for an external user. There was no difference in the style of stove chosen or the technical complexity of the stoves built between the two groups of students. Stoves students made for self-use were more likely to be reported as working in the wilderness than stoves made for an external user (Fischer's exact test, $p = 0.012$). However, there was not a significant difference if we only consider stoves as ''working'' when used to cook food regularly while on the expedition (Fischer's exact test, $p = 0.401$). Interviews revealed differences between the motivation expressed by students, the challenges experienced, and the understanding of the perspective of the user. An unexpected finding was that students often did not believe the stove would be used for the full four-day expedition. We find that the authentic integration of use into the learning environment may help increase students' understanding of human-centered design principles.

Keywords: human-centered design; project-based learning; authentic

We have developed an experiential learning global health design program that emphasizes direct interactions with stakeholders and first-hand exposure to the contexts in which solutions will be implemented. Students in the program gain practical hands-on experience identifying and defining unmet global health needs in low-resource settings and apply human-centered and co-creative design approaches. Device designs that incorporate rigorously collected and analyzed first-hand data from diverse users and stakeholders rather than anecdotal or poorly represented information are more effective at meeting true needs. To date, more than 100 undergraduate student participants have identified hundreds of needs in collaboration with sub-Saharan and Asian healthcare providers. Approximately 400 students from the U.S., Ghana, Ethiopia, and Uganda have contributed to the generation of technology concept solutions to address these needs. Program outcomes include approximately 100 student design projects completed at multiple institutions, student-led design-based conference publications and journal articles, device commercialization, and peer-to-peer mentoring within traditional capstone design courses. In this paper we describe the curricular elements of the clinical immersion and design ethnography experience. Additionally, we describe programmatic best practices that have emerged over the past 10 years and challenges students encounter when performing this front-end design work.

Keywords: global health; engineering design; needs finding; immersion; project-based learning; experiential learning

This paper codifies a form of expertise that is tailored to framing and addressing the classes of complex, multifaceted, multistakeholder challenges affecting organizations and society, here termed ''major challenges''. This type of expertise tends to be elusive because of the divergent schools of thought used to characterize major challenges, the seemingly serendipitous nature of the innovations needed to respond to these challenges, and the tacit and situated nature of the design knowledge and practices required to frame and address them. We develop a framework for this qualitatively distinct type of design—termed ''Design for Big X''. Our framework codifies a set of conceptual shifts in patterns of thought and action aligned with the properties of major challenges, relative to generic design practices. The framework provides new constructs for research on innovative thinking and the cultivation of talent in educational institutions and organizations working to address major challenges.

Keywords: innovation, systems; major challenge; design behavior; design pattern

This research describes and compares the interviews of practicing engineers and designers in industry regarding their collaboration on design projects with how academic textbooks teach design. An empirical study was conducted that centered around live interactions between the researcher and the interviewees to retrieve targeted information specific to collaborative design research that may be more difficult to attain in written documents. A total of ten interviewees from three companies volunteered to participate in an interview with topics related to design projects, processes, tools, and meetings. Interviews were then deconstructed to quantify results based on specific topics discussed (e.g., informal and formal meetings) and collaborative tools used throughout a project. Insights into when, why, and how the interviewees typically undertake design projects at their respective companies were elucidated. Results show that only one of the interviewees mentioned the benefits of a design tool, which they did not however use during their projects. This finding contradicts the textbook suggestions of using design tools as the means from which to collaborate. The purpose of collaborative design from the perspective of the interviewees is also discussed through formal and informal meetings. According to the interviewees, each meeting type employs a different set of needs when used in the design process. To better equip students for work outside of academia, preparation for meetings would be beneficial as they would begin to develop soft skills and project management skills required for industry. Such training is useful in concurrence with the teaching of design tools by enforcing student teams to compile meeting minutes, begin with stating the project problem statement, or limit meetings to a specified duration. These tips were useful in providing students with skills in managing meetings to ensure the ultimate success of the engineering design project. Additional research questions are posed for purposes of further study of other firms regarding their design practices and what resources academia can provide for individual designers.

Keywords: industry collaboration; practicing engineers; interviewing; interview-based study

Making is a social phenomenon that encourages the adoption of many of the practices, skills, and knowledges associated with STEM (Science, Technology, Engineering, and Mathematics) disciplines. It also incorporates many of the key personal attributes of the Engineer of 2020. Although educators have started to institutionalize this connection through the establishment of makerspaces and Maker-based curriculum, less effort has been made to understand how the current population of ''grassroots'' Makers have come to identify with this movement. In this qualitative research study, we analyze critical incident interviews of young adults who frequent shared-use community workshops, or makerspaces. Employing a theory-driven thematic analysis, we developed an initial process framework for Maker identity formation that could provide educators with a useful perspective when implementing Maker-based programs in their institutions.

Keywords: Maker Movement; identity formation; STEM education reform, future engineers