Paper ID #23184

Convergent Approaches for Developing Engineering Leadership in Undergraduates

Dr. Meagan R. Kendall, University of Texas at El Paso

An Assistant Professor at The University of Texas at El Paso, Dr. Meagan R. Kendall is helping develop a new Engineering Leadership Program to enable students to bridge the gap between traditional engineering education and what they will really experience in industry. With a background in both engineering education and design thinking, her research focuses on how Hispanic students develop an identity as an engineer, methods for enhancing student motivation, and methods for involving students in curriculum development and teaching through Peer Designed Instruction.

Prof. Debbie Chachra, Olin College of Engineering

Debbie Chachra is a Professor of Engineering at Olin College of Engineering. Her education-related research interests include self-efficacy, design, intrinsic motivation, and gender. She speaks and consults on curricular design, student-centered learning, and gender and STEM.

Dr. Kate Roach, UCL
Mrs. Emanuela Tilley, University College London
Dr. Kyle G. Gipson, James Madison University

Dr. Kyle Gipson is an Associate Professor at James Madison University (United States) in the Department of Engineering (Madison Engineering) and the Director of the Madison Engineering Leadership Program. He has taught courses focused on first-year engineering students, materials science and engineering, engineering design, systems thinking and engineering leadership. He has a PhD in Polymer, Fiber Science from Clemson University. His research background is in the synthesis of polymer nanocomposites and engineering education. He was trained as a Manufacturing Process Specialist within the textile industry, which was part of an eleven-year career that spanned textile manufacturing to product development.

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Abstract

Here we describe a shared approach to engineering leadership that provides the foundation of four disparate engineering programs, all of which undertake to support and develop undergraduate leadership either explicitly (University of Texas at El Paso and James Madison University) or implicitly (Olin College of Engineering and the Integrated Engineering Programme at University College London). All four programs have independently converged on similar pedagogical approaches to engineering leadership that include both a broad conception of technical excellence and elements of interpersonal interaction. This emergent model of engineering leadership bears striking similarities to some recent top-down models of engineering leadership.

In taking our programs as case studies, we demonstrate a focus on both student academic and personal development. These cases probe some of the shifts that have taken place in engineering education on both sides of the Atlantic in response to calls from professional policymakers and educators for technical education to include the development of professional and interpersonal skills, and consideration of the broader social context of technical work. Collectively, these four case studies also illustrate how intentional, carefully-scaffolded learning experiences in collaborative project-work and design lay the groundwork for our students to continue to develop as engineering leaders after graduation.

Introduction

For at least the last fifteen years, the engineering education community has engaged in the development of a suite of professional and interpersonal skills within engineering curricula, as a response to calls from professional bodies and industry for these skills in graduates [1] – [5]. A recent example of this is the proposed ABET Student Outcome 7, which is related to functioning effectively as a team [5]. This increased emphasis on non-technical outcomes has also led to a reevaluation of the concept of 'engineering leadership', and how it might be effectively taught to undergraduate engineering students. As educators continue to create learning experiences to develop a host of professional, interpersonal, and entrepreneurial skills, multiple definitions and models for engineering leadership have emerged [6].

One common approach to teaching 'engineering leadership' at the undergraduate level is to adapt existing theories of leadership, drawn from organizational psychology or management studies. At their core, most such theories define leadership as influence (e.g., [7]) and focus on developing a framework of behaviors or competencies of the kind that have been used across the industry for decades (e.g., [8]). At the other extreme, engineering leadership is sometimes taken as shorthand for the purely technical, where an 'engineering leader' is a person or company that is the most technically advanced in a given field, with no explicit acknowledgment of anything beyond engineering considerations [9].

In the engineering education literature to date, there has been relatively little attention paid to the increasing importance of leadership education as an element of engineering programs, although interest in engineering leadership has been growing. Rottmann *et al.* [10] have begun a process of filling this gap with empirical work that explores the perspectives of working engineers and maps them to conventional definitions of leadership. Their work is an important advance for engineering leadership education because it moves toward demonstrating how leadership is perceived in engineering-focused professions, and how leadership roles are embedded within them. The reevaluation of engineering leadership in higher education also provides an opportunity for engineering educators to demonstrate, in a substantive way, the role of leadership in engineering. Indeed, as Rottmann *et al*. point out, "The acceptance and implementation of engineering leadership education depends on widespread recognition of engineering as a leadership profession." [10, pp. 352]

In this paper, we report on four disparate engineering programs, all of which have embedded elements of leadership education. The four programs are structurally diverse and include a new engineering college, a new degree program, a new program that cuts across engineering disciplines and degrees, and a co-curricular program of academic enrichment. In two of these cases, the development of engineering leadership in students is an explicit focus. However, we will argue that, in all four programs, the foundations of engineering leadership among our students are laid by scaffolding the development of a host of professional, interpersonal, and personal skills [8]. While these programs were developed independently of Rottmann *et al.*'s 2015 work, there is a convergence between the explicit and implicit models of leadership that emerge from these four programs, Rottmann *et al.*'s model, and other recent models of engineering leadership, as discussed further below.

The four programs that serve as case studies here have curricula that were developed, in engineering leadership and more broadly, from a similar starting point: careful consideration of the skills and abilities required of 21^{st}-century engineering graduates in response to calls for engineering education reform from professional engineering bodies over the preceding decade. For example, the National Academy of Engineering's report "The Engineer of 2020" [2] describes the ability to frame problems within a sociotechnical and operational context as an essential part of the engineers' toolkit, along with other professional skills, such as good communication, business and management aptitude, high ethical standards and leadership abilities. Similar reports from professional bodies conveyed that graduates are also expected to be dynamic, agile, resilient, flexible, and to work with a strong sense of professionalism [1] - [4]. So, while none of the programs had an *a priori* commitment to engineering leadership, they all developed curricula that were at least in part a response to globalization, the increasing complexity of engineering challenges, and the rapid pace of change in technosciences, all of which requires engineers to work in (and lead) diverse, interdisciplinary teams. By focusing on the development of a range of personal, interpersonal, professional, contextual, and lifelong learning skills, these programs, effectively scaffolded a model of engineering leadership, implicit or otherwise. Furthermore, the model is developmentally and pedagogically appropriate for undergraduate students.

Here we report on how our four programs converged on a shared approach to engineering leadership development in undergraduate students, despite their diverse structures and nominally different educational goals. Some of the areas that our teaching approaches have converged towards are elements of leadership that have typically been a part of industry frameworks and are well described within the organizational psychology literature [8]. We go on to further consider leadership in an engineering context, and how ideas of engineering leadership may, or indeed *should,* be reflected in learning experiences for undergraduate students.

Leadership in engineering practice

Professional leaders and individuals leading engineering teams often resist conventional definitions of leadership [10], [1], such as the definition in Northouse's well-known text: “Leadership is a process whereby an individual influences a group of people to achieve a common goal” [7]. The emphasis on interpersonal influence runs counter to certain engineering norms that see decision-making as a product of objective or scientific information, which is often couched in terms of whether an idea, product, or function is effective [10]. Making things work is the core activity of engineers, and it legitimately calls forth structured, systematic thinking informed by science. This can seem to run contrary to the challenge of developing leadership practices which are by definition ill-defined, people-centered, and socially-focused.

Interestingly, Rottmann *et al.* also reported resistance to the term ‘leadership’ among their sample of professional engineers, but when the term is grounded in engineering practice or practices that are seen as relevant to engineering, it becomes acceptable and desirable [9]. They go on to define three areas of leadership that resonate with working engineers: technical mastery, collaboration based on teamwork and leading teams, and organizational innovation.

Our case studies touch on all three of these areas in various ways, but perhaps the category which is most interesting and elusive is the ‘organizational innovator’. In Rottmann *et al.*’s work, this emerges as an entrepreneurial function with a technological orientation, which incorporates a diverse set of skills, such as understanding markets, needs, values inherent in the goal, and likely impacts of the goal.

Hartmann and Jahren [11] provide a slightly different view on ‘engineering leadership,’ as they reported on industry employers who specifically request leadership skills as part of the suite of requirements they stipulate for entry-level graduates. The authors investigated what is meant by ‘leadership’ in this context by analyzing job postings for full-time, entry-level positions for engineering graduates. They identified five key leadership themes in the job postings, which coincide with many of the themes described by the National Academy of Engineering [2], Royal Academy of Engineering [12], and other engineering policy-makers [4]. The five leadership themes that emerged in this study were: initiative/confidence, communication skills, interpersonal skills, teamwork skills, and engagement.

Four of the five skills address leadership of the kind described in management and business journals. The only place where employers raised the idea of social responsibility is within a category of skills that the authors labeled ‘engagement’, which referred to the need for graduates who have undertaken extracurricular activities, such as volunteering. The employer quoted as typical of this category is the only one to raise the need for, “the social responsibilities of whatever [graduates] are doing…giving back…a person who tends to be engaged.” [11, pp. 17].

Both the Rottmann *et al.* and the Hartmann and Jahren studies find a number of leadership elements that are common to engineering and industry in general. While these tend to be behaviors and abilities, such as communication or teamworking, they also highlight a few leadership skills that are more specific to professional contexts. This includes the idea of social responsibility, as identified in Hartmann and Jahren's job postings, and in the understanding of contexts and impacts required to be an 'organizational innovator', in Rottmann *et al.*'s terminology. These ideas share some common ground with ideas of 'upstream' and 'downstream', terms which are used in the literature about responsible innovation that emerges from the field of science and technology studies (STS). The 'upstream' elements of an engineering project refer to the motives, values and initial scoping frameworks that drive the project, while the 'downstream' elements are related to the impact of the project (e.g., [13]). Upstream and downstream considerations of engineering projects are not generic leadership skills, and they require particular knowledge and understandings of the human-technical interface.

The 'responsible innovation' literature, which sits between policymakers and social scientists (e.g., [13]), harmonizes with calls for a more 'humanistic' engineering from within sections of the engineering profession itself [6]. Rottmann *et al.* describe these drives as "rooted in the idea of professional service" [10, pp. 353], one in which engineers have a professional responsibility to take leadership roles in addressing 21st-century challenges to create sustainable, safe futures. They also report that the few definitions of engineering leadership that exist are focused more on leading engineering teams than on engineers as professional leaders. This suggests that there is a conceptual gap between drives for a professional level of responsibility, the rise of engineering leadership in higher education programs, and any significant attempt to make a domain-specific definition of leadership.

Conversely, we can begin to close this conceptual gap by recognizing this as an opportunity to create learning experiences for undergraduate students that explicitly address the social context of their engineering work, both upstream and downstream, and the role that engineers can play in our shared future. In parallel with this, the calls for engineering education reform have led engineering educators to think more intentionally about creating learning experiences that incorporate reflective practice for students, in areas such as teamwork, communication, and lifelong learning. These areas collectively comprise not just a model of engineering leadership, but also a set of pedagogical approaches that can be used to develop an undergraduate experience that serves as a foundation for future engineering leadership development once students enter the workforce.

Approaches to teaching engineering leadership

Over the past decade, a number of institutions have begun to develop engineering leadership programs aimed at undergraduate students. These programs vary in size, scope, focus, and context. Klassen *et al.* categorize fourteen engineering leadership programs from across North America along three axes: focus, delivery channel, and pedagogy [14]. Program foci, according to Klassen *et al.*, include entrepreneurship and innovation, personal and professional growth, or global citizenship. Delivery channels, i.e., methods for integration of courses in educational programs, include integration via the use of core courses, curricular minors, or co-curricular programs. Like the focus and delivery channels, pedagogical approaches vary considerably, though many emphasize active learning and team-based projects.

As part of the creation of their programs, institutions have wrestled with the idea of engineering leadership, and a number have crafted their own frameworks for engineering leadership development [14] - [18]. For example, the Gordon Institute of Engineering Leadership at Northeastern University uses a fourteen-point framework for leadership development [17], illustrated below (Figure 1).

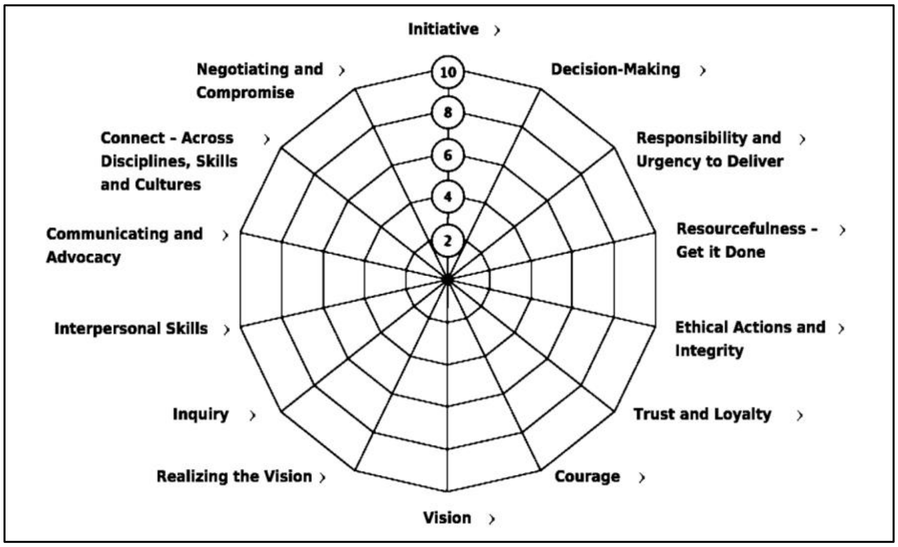

Figure 1. Northeastern University's fourteen-point framework for leadership development [17]

Similarly, Iowa State University's Engineering Leadership Program developed a Leadership Model via a collaboration between engineering faculty, staff, and students [18]. It includes eight learning outcomes:

1. An ability to function on interdisciplinary teams
2. An understanding of professional and ethical responsibility
3. An ability to communicate effectively
4. The broad education necessary to understand the impact of engineering solutions in a global and societal context
5. A recognition of the need for, and the ability to engage in, life-long learning
6. An ability to create a vision, articulate it, and inspire others to share and implement it
7. An ability to effectively influence and innovate to deliver results
8. Recognition of the need for actively encouraging diversity and creating an inclusive environment

Note that the first five of these outcomes are familiar to many American engineering educators, as they are drawn directly from the accreditation requirements for engineering degrees [5].

Both of these models appear to have borrowed heavily from models of leadership that arise from organizational psychology or management studies; for example, the sixth outcome on the Iowa

State list maps closely onto, the Northouse definition given earlier. However, these models are intended to go beyond a model of leadership based on influence, focusing on developing a larger framework of behaviors or competencies that their creators believe are pertinent to 21st-century engineers.

Programs that explicitly seek to develop engineering leadership skills in undergraduates have utilized a variety of pedagogical approaches. As is increasingly common across engineering education, many programs use direct instruction, problem-based learning [19], Kolb's experiential learning cycle [20], and reflective practice [21]. However, few validated instruments exist to assess the development of engineering leadership directly. While an instrument to assess leadership, change, and synthesis in engineering undergraduates was recently developed [22], programs tend to rely on traditional student leadership assessments, such as the Student Leadership Practices Inventory [23].

The four programs described here were developed independently in response to calls to develop behaviors and competencies for 21st-century engineers within the context of engineering leadership, as outlined above, along with including an emphasis on the responsibility of engineers to address the upstream and downstream requirements of their projects. We argue that the commonalities between these otherwise disparate programs collectively comprise an emergent, bottom-up model of engineering leadership, one which maps closely onto some of the recent top-down models of engineering leadership. All four of the engineering programs have taken an approach to leadership that provides opportunities for students of different leadership orientations to develop their leadership practices, whether they are engineering team leaders or professional leaders of the future. All of the programs are also explicitly student-centered, and provide a foundation for future leadership development by supporting a bedrock of behaviors and understandings that are developmentally appropriate to undergraduate age groups.

Research approach

In this study, we follow a qualitative assessment approach based on an iterative reflection process, focused on four engineering programs as case studies. Using an approach analogous to that used for extracting product design heuristics from practicing product design engineers [24], representatives from each institution (also authors) collaboratively generated a list of prompts related to the key features of their respective engineering leadership (EL) programs (Table 1).

The same representatives then independently generated responses to the prompts for their programs. These responses were then reviewed by the group to extract themes. We then iterated on the responses for additional depth and sought documentation for specific examples for each theme from each institution. From these themes, a shared definition and framework for teaching engineering leadership were extracted.

Table 1. Engineering Leadership (EL) Program Prompts

"What is(are) the…"
1. Size and type of EL program/track at your institution
2. History of your EL program's/track's development
3. Basic leadership philosophy in your program (For example, are 'leadership' and 'engineering leadership' considered to be synonymous?)
4. Key frameworks used in teaching/framing your engineering leadership development approach (such as Expectancy-Value Theory, Entrepreneurial Mindset, etc.)
5. Materials used in courses or other EL development activities (such as the Northouse textbook)
6. Cornerstone activities/learning experiences used in EL development
7. The role of value in your program
8. Level of explicitness of EL development as a goal of your program/track
9. The role and amount of leadership theory and practice in your program
10. Key pedagogical approaches implemented in teaching EL

Case Studies: Descriptions of engineering leadership teaching and learning at four institutions

The four engineering programs described here are all relatively new, and were all defined and developed in an effort to produce a more holistic engineering graduate by explicitly fostering different types of engineering learning and practice. None of the programs initially had a stated goal of developing engineering leaders. Rather, after reflecting on the skills and competencies which were considered to be crucial to engineering practice, those involved in designing and delivering the programs recognized that behaviors relevant to engineering leadership were an integral part of the curricula; in two cases, this was articulated and emphasized in the programs.

The four programs that serve as case studies here, from which themes of engineering leadership emerged, have very different structures (Table 2). One is a new engineering school which addresses engineering leadership implicitly through innovative teaching and learning practices (Olin College of Engineering, Needham, MA) while another is a new engineering degree program that explicitly focuses on engineering leadership (University of Texas at El Paso, El Paso, TX). A third is a co-curricular program in engineering leadership that selected students can take in addition to their disciplinary engineering program (James Madison University, Harrisonburg, VA). The final program included here is a teaching framework that includes a series of required practical and skills-based learning experiences which are embedded into

Table 2. Characteristics of institutions and programs described in the case studies

Characteristic	UT El Paso	James Madison Univ.	Olin College	Univ. College London
Institution type	Large public, 4-year	Large public, 4-year	Small private, 4-year	Large public, 3- or 4-year
Program size	15-20 UG students/year	24 UG students/year	90 UG students/year	750 UG students/year
Program type	Bachelor's degree	Satisfies credits for engineering electives within bachelor's degree	Engineering college offering three bachelor's degrees	Integrated credit-bearing courses within bachelor's or integrated master's degrees
Accredited program	Seeking accreditation in 2019	Yes	Yes	Yes
History	Established in 2014, first graduates in 2017	Established in 2014, first graduates in 2015	Chartered in 1997, first graduates in 2006	Established in 2014, first graduates in 2017
Engineering leadership (EL) philosophy	An effective engineering leader has a deep understanding of who they are, what they are doing, why they are doing it, and have the necessary skill sets needed to bring the right group of people together to carry out their shared vision.	Taken together, "engineering leadership" is an actionable phrase where individuals build relationships by working artfully to bring about something of value through using processes to achieve a common goal.	Not explicitly articulated, except in isolated courses. The mission of the institution is to produce, "exemplary engineering innovators who recognize needs, design solutions and engage in creative enterprises for the good of the world."	Not explicitly articulated but embedded in the skills and authenticity of the program components. We engage students with upstream and downstream considerations of engineering design and with leadership skills.
Explicitness of EL	Explicit	Explicit	Implicit	Implicit
Engineering Leadership cornerstone teaching and learning activities	Teamwork, mentoring, design projects, reflection, immersion activities	Teamwork, workshops, mentoring, design projects, leadership project/practicum	Teamwork, reflection, communication, discipline-specific and interdisciplinary design projects	Teamwork workshops, reflection, small group facilitation, strength-based individual assessment, discipline-specific and interdisciplinary team design projects
Pedagogical approaches	Project-based learning, flipped classrooms, peer- and self-assessment, student-centered active engagement strategies	Project-based learning, learner-centered approaches, near-peer mentoring, peer-led learning, reflection, 360 evaluations	Project-based learning, student-centered approaches for engagement and motivation, development of lifelong-learning skills	Self and peer-assessment, authentic and experiential learning, problem/project-based learning, design workshops, reflection

existing disciplinary engineering degrees (University College London, London, UK).

Short descriptive case studies for each of the programs follow, highlighting the aims of each program, how leadership has arisen in the context of the engineering program, the learning experiences that incorporate engineering leadership, and whether or not upstream and downstream elements of engineering are included in leadership teaching and learning. Background information about each of the four programs, including student enrollment, program type, and history, is provided in Table 2.

Case Study 1: Engineering Leadership degree program at The University of Texas at El Paso

The development of engineering leadership in students is a specific goal for the relatively new Bachelor of Science in Engineering Leadership (E-Lead) degree at the University of Texas at El Paso (UTEP). The E-Lead program aims to educate students to become 'Renaissance Engineers', who are more than their technical depth, who are holistically educated, and who can practice engineering in a variety of contexts (http://e-lead.utep.edu/). In the development of this program with its vision based, in part, on Duderstadt's *Engineering for a Changing World* [25], early engagement with key stakeholders (including students, faculty, industry, and academic partners) established leadership as one of the three core principles of the program, alongside business acumen and design/innovation.

Within the E-Lead program, the framework for engineering leadership development is based on that of the United States Military Academy (West Point) [26], [27], which can be summarized as the 3 C's: Character (who you are), Capacity (what you can do), and Competence (what you know). It describes an effective leader as one who has a deep understanding of who they are, what they are doing, why they are doing it, and who has the necessary skill sets to bring the right group of people together to carry out a shared vision. The team leading this program recognizes that graduates are not likely to attain leadership roles immediately upon graduation; however, the program is intended to accelerate the potential for students to lead in a variety of environments, based on their passion and values, as well as their knowledge and abilities. Furthermore, the program is designed to provide opportunities for students to understand who they are and what they value before they take on leadership roles.

Engineering leadership development in the E-Lead program is delivered in a tiered model, with development activities designed for all students, many students, or a select few students, based on their level of interest. For all students, the program relies heavily on a combination of leadership theory applied to engineering design team experiences, with a focus on leadership texts such as Northouse's *Leadership: Theory and Practice* [7] and Arora and Baronikian's *Leadership in Project Management* [28]. Examples of in-class activities include group discussion of case studies and application of concepts in ongoing engineering projects. Extracurricular activities are available for many students, such as participating in a Ropes Course challenge (in which students learn to work as a team by navigating a physically demanding obstacle course), serving in leadership positions of on-campus student organizations, and attending leadership workshops. Further opportunities, including teaching assistant roles, mentoring opportunities with community members, and off-site leadership conferences, are available to students who demonstrate interest and commitment.

All teaching of leadership is done in the context of engineering projects. At the core of the program is human-centered engineering and design. In this approach, students learn to understand the needs of the user before the generation of solutions and business models. In doing so, students are often made aware of how the upstream (in this case, stakeholder values, project requirements, and motives) and downstream elements of engineering projects are closely integrated. They also recognize how their leadership efforts can impact their design solution and the project outcomes, as well as their project experience.

Case Study 2: Upper-Level Engineering Electives in Engineering Leadership at James Madison University

Engineering at James Madison University (JMU) is a four-year interdisciplinary Bachelor of Science degree program that was crafted to educate engineering versatilists. The curriculum allows the students to engage in authentic project work and provides opportunities to enhance their awareness of how and why consideration of values, viewpoints, and actions can assist them in developing into adaptive, creative, empathic engineers who create value and make an impact in the world. The Madison Engineering Leadership Program includes a required two-year-long capstone project experience that provides a platform for customized learning in a focused area of interest. There are eight semesters of authentic project work which facilitates project-ready graduates and prepares individuals for the flexibility and resilience needed in the rapidly changing work world.

Stakeholders from industry and other sectors have suggested that a modern engineer requires a perspective across many fields to meet the complex demands of 21st-century opportunities. This curriculum provides an engineering education rich in design, systems thinking, project management, and opportunities to customize learning through engineering projects. One area of focus for the department is the inclusion of leadership principles in undergraduate engineering education.

The engineering leadership program strives to link the practices of engineering and leadership in an inclusive environment. Part of the teaching philosophy is to have students recognize that engineering encompasses more than creating solutions for industry. Engineering is about creating ideas and transforming them into real solutions for the betterment of the planet and society. In this context, leadership is a process that hinges on relationships and relationship management, rather than a practice that is centered on power and influence. These concepts of engineering and leadership are brought together in ‘engineering leadership’, which is taught as an actionable phrase, where individuals build relationships by working artfully and using processes to create something of value and achieve a common goal.

Each year, approximately twenty-four students are selected from an applicant pool of upper-level students to participate as part of the leadership cohort. The year-long program underscores mindsets and skills critical to engineering, including self-awareness, emotional intelligence, empathy, and ethical decision-making. Pedagogically, it is a combined curricular and co-curricular experience with six phases: leadership workshops, mentor training, design challenge facilitators, leadership theory, a leadership practicum, and a leadership project. The collection of experiences is designed to prepare the next generation of engineering leaders through a pathway of personal exploration. This is facilitated, in part, by providing all of the students selected for the program with the opportunity to explore their identities as potential leaders and to serve as near-peer mentors for first-year engineering students. The technical mastery required in engineering is blended with the value-added skills of building character, understanding core values, working in/leading teams, relationship management, and inspiring others in every aspect of the program.

The program is designed to help students learn and develop knowledge through a greater understanding of themselves, the interconnectedness of the world, and leadership theories and practices, so that they become effective, ethical and empathetic leaders. The activities within the courses are aimed to assist the student in achieving their greatest potential to adapt and to adjust to a diverse and ever-changing world, to lead effective change, and to create positive impacts. The program activities are structured through three major frameworks to aid in engineering leadership development: emotional intelligence, expectancy-value-cost theory (motivation), and entrepreneurial mindset. The desired outcome is that students become aware of themselves and others, as well as the needs of their stakeholders, in order to deliver effective action that brings about value, impact and productive change.

Case Study 3: Engineering Leadership as Implicit in Student Learning at Olin College

Olin College of Engineering is an engineering college that offers three degree programs in engineering; of note, it has an institutional commitment to gender parity among all students enrolled. Its aims, as embodied in its mission, are twofold: to educate engineering innovators who incorporate an understanding of human needs into design and creative enterprises, and to catalyze change in engineering education both by developing effective new educational approaches and by collaborating closely with other institutions. Engineering leadership is not explicitly identified as part of the vision or mission of the institution and its programs, which focus on advancing educational approaches and on graduating engineering innovators.

There is considerable overlap in the three engineering degree programs offered, offering many opportunities for interdisciplinary collaboration. Student learning experiences emphasize project-based learning, hands-on experiences, and self-directed learning, with conscious attention paid to fostering motivation and engagement. Teamwork and collaboration skills are explicitly scaffolded and developed in a wide range of courses throughout the four-year programs, culminating in a senior engineering design project carried out for an external client (typically either a company or an underserved community). Students are exposed to gender issues and concepts, such as implicit bias, in required first-year courses, with additional opportunities to develop their understanding throughout the curriculum. All students are required to take a series of courses in design that generally emphasize team-based project work: engineering design courses that emphasize design methods and developing a prototype; a user-oriented design course that focuses on using anthropological and ethnographic techniques to co-design products with a specific user group; depth courses that focus on specific aspects of design, including sustainable design; and the senior engineering design project. Students are also required to take a foundational entrepreneurship course that draws from agile methodology, emphasizing ideation and testing the value (monetary and non-monetary) of ideas under development by experimentation, particularly by interacting with potential users, and of self-discovery. The use of project-based learning across the curriculum develops lifelong learning skills, and this culminates in a required self-directed learning experience. Communication (particularly visual, graphical, spoken and written communication) is emphasized in many courses. Finally, contextual understanding (i.e., the upstream and downstream elements) of engineering work features in many courses, sometimes implicitly as a component of the motivation for self-directed projects, but also explicitly in a number of design and humanities courses.

Few learning experiences are directly identified as addressing engineering leadership. However, elements of engineering leadership, as identified in the Iowa State and Northeastern models described earlier in this paper, are key features of the undergraduate degree programs. In addition to technical engineering skills (including quantitative analysis, design, and diagnosis), the five elements of the Iowa State model that overlap with accreditation objectives (including teamwork, professional responsibility, communication, contextual awareness, and lifelong learning) are intentionally scaffolded and developed extensively across a wide range of learning experiences, as described above. Two of the remaining items (innovation and inclusion) are directly addressed in the mission of the college and reflected across the curriculum.

Case Study 4: Engineering Leadership is Developed by a Teaching Framework Across Undergraduate Degree Programs at University College London

The Integrated Engineering Programme (IEP) at University College London (UCL) was implemented in 2014. It was designed to break down educational silos created by eight discipline-focused departments, each of which offers their own bachelors and masters-level degrees. The new program offers students opportunities to engage in interdisciplinary study, project work and skills-based learning alongside their studies in their chosen disciplines [29]. Authentic learning opportunities have been built into the undergraduate curricula across the eight disciplines, so that all students are given ample time and space to work in teams, improve their technical knowledge, and develop their professional skill-sets by putting theory into practice while exploring and shaping their sense of self.

The real-world authenticity of the projects is what the IEP students most enjoy and also identify as being the most important contributor to their development of positive personal attributes for effective leadership. They have reported developing interpersonal skills for effective teamwork; self-awareness of strengths and weaknesses and understandings of the diversity amongst teammates [30]; the ability to take initiative to achieve shared goals; and the resilience to overcome obstacles [31].

Central to the vision of IEP is our definition of what engineering is: “[Engineering is] the art and practise of changing the physical world for the benefit of all.” Its main relevance to our leadership philosophy is that it frames engineering as a creative profession that has an impact beyond the profession itself. We emphasize this framing during the first two years of the program through authentic, active-learning opportunities in the form of nine problem-based/project-based learning (PBL/PjBL) activities that run in parallel with and connect closely to discipline-specific core technical, applied mathematics, and professional skills modules.

The cornerstone and capstone projects of the program, the "Engineering Challenges" and "How to Change the World", are design-based activities that students undertake in interdisciplinary teams. Students are challenged with unusual problems and contexts that require them to consider the impact of engineering on stakeholders both upstream and downstream of implementation. The Scenarios, which comprise the rest of the program's PBL/PjBL framework, are different in that they test the students' ability to apply their discipline-specific technical understandings during week-long intensive projects. Scenarios are also team-based and linked to a concurrent skills-based module, providing students with further opportunity to develop their practice and understanding of working in teams.

Support for building and leading teams is available to students in their first two years, on a diminishing scale. In the first few weeks of their time in the program, students engage in team-building activities, teamwork and leadership workshops, a profiling tool and associated coaching session, and they have the offer of tutor-led support for teamwork should they need it. The materials provided are purposely designed to be light-touch in order to make them an appropriate fit for the developmental stage of the majority of students. Our teamwork syllabus arises out of literature on effective teamwork (for example, [32]) and our leadership support is based on team leadership at the outset, and differentiates leadership from authority, by emphasizing the need for self-awareness, commitment to one's values and the needs of others, where 'others' may mean other engineers in the team, or end users, or society.

Results and Discussion

We have described four programs that supplement technical engineering education with social, communication, and project-based skillsets of the kind described in the Iowa leadership model [18] and the Northeastern University descriptors [17]. Notions of leadership have been commonly used in industry and organizational psychology for many decades, but their move into engineering undergraduate curriculums is relatively recent.

While engineering leadership was the explicit goal of only two of the four programs described above, we nevertheless realized that there were significant commonalities between them, expressed as the four themes described below. Together, these four themes comprise a view of engineering leadership that emerged directly from programs that were focused on rethinking what it means to be an engineer in the 21st century. These four themes also overlap considerably with the models of engineering leadership that were defined at Northeastern and the Iowa State University, as described in the introduction, and include the themes identified by professional engineers as reported by [10].

One key element of these programs is that they provide students with opportunities to understand both the upstream and downstream elements of the engineering process. This leads us to suggest that we are not only providing the potential for undergraduate development of the generic skills required to lead a team of engineers on a technical project, but we are also introducing ideas about context and impact that are required for the professional service model of leadership described by Rottmann *et al*.

Emergent themes: Technical mastery, teamwork, contextual awareness, effectual behavior

Each of these programs acknowledges ***technical mastery*** as a defining skill of an engineer, and a necessary element that distinguishes engineering leadership from leadership more generally. Technical skills are developed as not just quantitative analysis but also as design and diagnosis. Despite this, all four of these programs recognize that technical skills do not and should not exist in isolation: they are manifested within groups, are informed by their social context, and have an impact on the world around them. Even the most technically-focused engineer needs to be able to communicate with others to move their work forward; more broadly, however, engineers need to be able to work effectively across disciplines and to understand and communicate the larger impacts of their work.

At the undergraduate level, therefore, ***teamwork*** is a key foundational practice for leadership. These programs explicitly scaffold the development of teamwork skills through learning experiences, including the development of communication skills and by explicitly addressing factors such as implicit bias. In these programs, students have the opportunity to work across engineering disciplines and with non-engineers, rather than in narrow technical areas. This manifestation of leadership as teamwork involves contributing, facilitating the contributions of others, and creating structures that help the team function effectively. Teamwork is also a mechanism for promoting and supporting the development of personal and interpersonal leadership styles, as expressed in the two programs that explicitly focus on engineering leadership.

In encouraging our students to engage in realistic technical design projects on teams, we are encouraging leadership development, but these experiences also provide students with opportunities to begin understanding the context in which their innovations lie. Traditionally, leadership has focused on the characteristics and behaviors of the leader, and not on the characteristics of the stated goal that the group is focused on meeting. But a key element of professional leadership is the alignment of the upstream values inherent in the goal with those of the participants who sit downstream; that is, engineering projects being designed with eventual impacts in mind. Value is a social and emotional construct and as such has been an arena that engineers may have seen as outside their remit. It is understandable that individuals who build expertise in the rational, objective material world feel unprepared to deal with the subjective, emotional world of value, and indeed this is what Rottmann *et al.* [10] report in their sample of working engineers. Two of the programs include language on the impact of the engineering work on the larger world in their self-description: "changing the physical world *for the benefit of all*" or "engage in creative enterprises for the good of the world." To understand the values implicit in goals, including engineering goals, students must develop ***contextual awareness***.

This ability to build contextual awareness means encouraging students to think about the larger social context and impact of their work. For students, this means engaging in engineering ideation and implementation in ways that take people into account. At UTEP, JMU, and Olin, entire courses emphasize the importance of user engagement in a collaborative design process.

UCL's IEP intentionally incorporates interdisciplinary projects into their curriculum to encourage students to explore other perspectives and approaches to address a common goal. Contextual awareness also involves thinking about the context of engineered work, be it social, environmental, financial, etc. One key way in which all programs support the development of contextual awareness is by providing opportunities for authentic project-based learning, in which students are challenged with different design contexts, allowing students to envision diverse designs and their impacts and usefulness. This allows them to experiment with their values and it encourages them to ask 'what if' questions. By moving away from the idea that engineering is divorced from upstream and downstream elements, and is politically- or socially-neutral, our students begin to grasp the complexity of leadership as professional service.

Finally, ***effectual behavior*** stems from self-awareness, the awareness of others, and the contextual environment. Being able to understand what one does not know in a given situation, and having the ability to decipher and articulate what additional information is needed, is a learned process. Through ideation, iteration, and testing, students become accustomed to adapting goals to fit the needs of the stakeholders and the project objectives. Effectual behavior includes the confidence to advocate for, curate, and prototype ideas in the world, in order to obtain and analyze the feedback so that they can create appropriate policies for the given tasks. Effectual behavior is often informally developed in project-based courses as students ideate and test in teams, but it is formally developed in courses in the programs described here; for example, in the required foundational entrepreneurship course at Olin College.

One way of thinking about the three non-technical themes is that, while they connect in multiple ways, they are each primarily focused at a different social scale: effectual behavior is at the level of the *individual*, teamwork occurs at the level of *small groups*, and the contextual awareness at the level of *larger groups and society broadly*. While the context of the work is engineering, these different social scales make clear the need to reach beyond working only with peers with similar technical backgrounds.

Towards a converging model for engineering leadership

The four programs described here are united by being established in the 21st century with the goal of educating engineering students more broadly than the 20th-century norms, but are structurally disparate and have different approaches to what 'engineering leadership' means (including not explicitly addressing it). In particular, all four programs focus on what is developmentally and pedagogically appropriate for undergraduate engineering students.

It is striking, therefore, that the emergent themes map quite closely to the models of engineering leadership that came out of Iowa State University [18] and Northeastern University [17]. For instance, technical mastery, teamwork, contextual awareness, and effectual behavior encompass several of the points in the Iowa State leadership learning objectives, such as teamwork, ethical responsibility, impact on a societal level, influence, diversity, and inclusion [18]. Note that the Iowa State University model does not directly address technical mastery, which seems essential in any domain-specific definition of leadership.

Similarly, the four themes encompass the sixteen descriptors in the Northeastern Universities framework [17]. Our contextual awareness theme emphasizes the need for inquiry, ethical actions, and integrity, yet pushes to a deeper level on the responsibility of the engineer to understand the impact of their innovation. Teamwork also encompasses the points of interpersonal skills; communicating and advocacy; vision; connecting across skills, disciplines, and cultures; negotiating and compromise; and decision-making. Effectual behavior encompasses those personal character points related to taking initiative; responsibility and urgency to deliver; trust and loyalty; and courage. Technical mastery, while not explicit in the Northeastern framework, does include elements of resourcefulness and the ability to apply technical engineering skills to “get it done” or realize the vision.

The four themes we have identified are high-level descriptors of the domains in which we expect actual engineering leaders might operate. Such specifics as life-long learning and the ability to communicate a vision are skills that sit within each of these themes. Central to our themes, except for technical mastery, is the focus on engineering as a people-centered activity. We have all converged on the view that these domains are vital for engineers at an undergraduate level. How far individuals take their expertise within each domain may then be a matter of choice and inclination. The graduate who goes on to excel in technical mastery and is a leader in their own, albeit narrow, field, will benefit from having some basic understanding of the people-centered aspects of the profession, even if only at the level of teamwork. Those individuals who go on to excel in all of the domains we identify are more likely to become the kind of engineering leaders who will tackle 21st-century problems of sustainability and global equality.

Future work

In thinking about engineering leadership for undergraduate engineering students, it is important for us to consider what is pedagogically and developmentally appropriate. The primary elements of engineering leadership for undergraduate students, beyond their technical focus, is continued personal development in the form of fostering effectual behavior, the development of teamwork and collaboration skills, and growing contextual awareness of their engineering work. Rather than the perhaps-hubristic notion that our undergraduate students must be engineering leaders upon graduation, we focus on lifelong learning: that we need to collectively develop the foundational underpinnings for a model of engineering leadership that is collaborative, inclusive, and socially situated.

Based on the themes that describe our shared framework for engineering leadership at the undergraduate level, our next focus will be on further developing and validating this framework. As it stands, it incorporates a perspective on four engineering programs; our future work in this area will endeavor to incorporate additional perspectives. This could include other institutions as well as other stakeholders, such as industry and students in the programs. Our ultimate goal is to help the engineering education community to continue towards a common definition of engineering leadership, one that takes into account the developmental stage of undergraduate students and pushes past the traditional, and often unstated, understandings of engineering and leadership.

At present, this framework of engineering leadership is an idealized picture of an engineering leader. Now we begin the process of pulling this down to the practical elements of pedagogy and assessing the impact of this framework on engineering leadership development. Using the framework, we intend to develop an instrument for assessing engineering leadership development in our students across the four themes identified.

Conclusion

As discussed earlier, engineers often resist notions of leadership [10]. Therefore, it is important that engineering educators be able to articulate and define different types of leadership roles that are available to graduates in engineering-related professions, and how these differ from generic understandings of leadership. Only then can leadership be presented to our students through the lens of engineering, rather than as a set of behaviors designed to have generalized influence. This also gives us the opportunity to define new, intentional models of engineering leadership that capture a broader perspective and reflect the challenges we collectively face in the 21st century. In this paper, we described how four disparate engineering degree programs have fashioned support for the development of engineering leadership in undergraduate students. The four programs have converged on a pedagogical approach which supports reflective practice in essential elements of engineering leadership: *teamwork*; the development of engineering *technical mastery*; the development of *contextual awareness*, and *effectual behavior*, including articulation of values and an understanding of impact, i.e., the upstream and downstream elements of the engineering process. Similar descriptors have emerged from engineering professionals (e.g., [10] and [11]), who have identified team leadership, technical expertise, and contextual understandings as important facets of engineering leadership. Further, this work is situated against a background of a developing practice and literature on engineering leadership, which has begun describing and differentiating similar leadership elements to the ones we describe above (e.g., [6], [10], [11], [17],[18]).

In taking our programs as case studies, we demonstrate a focus on student academic and personal development. These cases probe some of the shifts that have taken place in engineering education in the US, the UK, and elsewhere, in response to calls from professional policymakers and educators to supplement technical education by supporting the development of professional and interpersonal skills, and of fostering an understanding of the broader social context of engineeering work. Collectively, these four case studies illustrate how intentional, carefully scaffolded learning experiences in collaborative project-work and design can lay the groundwork for our students to continue to develop as engineering leaders after graduation.

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