Systemic Convergence Education in Undergraduate ECE Programs

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***Abstract*— This work in progress paper addresses one of the future challenges facing academic disciplines—traditional STEM as well as the social sciences and humanities—of how to prepare students to address complex problems that require a range of disciplinary perspectives. The goal of such preparation is termed convergence. Convergence captures both how different sets of expertise become focused in solving a problem as well as the network of connections that is built in undertaking these activities. Efforts at convergence are usually focused at practitioner, post-graduate, and graduate levels and engage multiple disciplines. Here the authors report on early-phase development of an effort to integrate convergence education into an undergraduate disciplinary-based degree program in electrical and computer engineering focused on integrating problems and projects across the curriculum. Key challenges faced were how to distinguish engineering topics from societal concerns in ways that were meaningful for students, balancing discipline-specific skills with fostering systemic understanding, and identifying relevant projects with attainable goals. Existing frameworks serve as a foundation for students to understand systemic and convergent issues. Framework development by individual students is scaffolded by expanding grading practices to provide feedback on skills believed to support convergence, developing ways to elicit student narratives about how courses and projects relate to individual interests, and adopting learning technologies that can support more emphasis on projects throughout the curriculum. Initial results on changing grading practices and introducing projects that are grounded outside of disciplinary context are presented. The relevance of this work to engineering education arises from the relatively small amount of empirical work exploring how to prepare engineering undergraduates to address convergent problems as well as the importance of such problems. The innovative potential of the work is that the effort will eventually become curriculum-wide and supported by structural changes to grading practices.**

Keywords—convergence, undergraduate, development as freedom

I. INTRODUCTION

Engineering was founded as, and still is, a technical discipline dedicated to addressing meaningful problems [1]. However, while engineering at the start of the 20th Century sought to marry science and industry for production, today's challenges—inequities in access, increasing recognition of the environmental costs of high levels of production, and economic turbulence—arose in part from this vision of efficient production. A purely technical education does not adequately equip students to address challenges related to social justice, ecological sustainability, and tectonic shifts away from the goods-based economy engineering education was designed to support [2], [3]. Today's problems are more systemic [4]–[6], wicked [7], and convergent [8]–[10].

This paper reports early-stage efforts to create a learning environment that fosters solving convergent problems in an undergraduate degree program through NSF RED [11] support. The effort adapts Sen's development as freedom, or capability framework [12], focusing on student development (personal, economic, educational, intellectual) as enabling individuals to live a life they value. Sen's framework was chosen for several reasons: it recognizes the role that individual freedoms play in development; it takes a long view by acknowledging that the opportunities that individuals have (or lack) across their lives affects their development; and the framework is systemic, that is freedoms—both freedom to and freedom from [13]—have societal as well as individual impacts which align with convergent challenges. Sen's framework has been further developed by Nussbaum [14]. The emphasis on developing capabilities within an individual's environment makes Sen's framework more all-encompassing than theories that focus on specific aspects of student development such as cognitive, moral, etc. [15]. The recognition of environment as well as characteristics of the individuals also align with intersubjective and interobjective teaching frameworks [16] that are hypothesized to be important to convergent problems.

In Sen's development as freedom framework the things a person values, what they are and can do (determined by their opportunities, experiences, and cultural affordances) are 'functionings', and each individual has a unique functionings vector based on what they value. Although an individual's functionings vector indicates valued goals, they will be unsuccessful in achieving their goals unless they have the 'capabilities' to do so. Capabilities are the set of functionings that are actually available to a person and include access to needed resources and learning how to effectively utilize those resources to enact desired functionings. In this model an engineering education serves two goals. The first is to enhance students' capacity to achieve functionings (expanding their capabilities) by providing resources such as knowledge, skills, a social network, etc. The second is to expand students' set of possible functionings by giving them new perspectives and experiences, thereby growing their functionings vector. It is through expanding the functionings vector that the ability to address more convergent problems is assumed to be developed. In terms of educational change, this framework refocuses the goal of education from economic utility or workforce preparation to maximizing a student's future freedom by trying to increase their capability (what they can do) in a way that is aligned with their functionings vector (what they value). It thus stresses student agency and autonomy [17]. Because convergent problems [8]–[10] are both emic and etic in nature, they align with the goal of expanding functionings and building capabilities and serve as central element in this project [18].

II. Background and Prior Work

A. The Age of Convergence

The problems facing tomorrow's engineering graduate are daunting. They are global, complex, and will require teams composed of individuals from a variety of backgrounds and experiences that span and transcend traditional disciplines. These problems wear many names: convergent, confounding, wicked, and transdisciplinary. Examples include curing and preventing diseases like cancer, providing clean water, infrastructure, and proper nutrition to every individual on the plant, conserving and sustaining the resources on the planet, and addressing global health concerns like COVID-19.

While definitions of convergent problems often focus more on trying to describe what will be needed to address such problems instead of being able to identify a convergent problem from one that is not, there are some consistent aspects of definitions. The definition used here is aimed at specifying convergent problems for undergraduate students and has been informed heavily by definitions from national agencies [8]–[10]. First, since the problems are socially relevant and impact multiple peoples across the planet in a significant way, by solving them we significantly improve the human condition for many. Second, the problems themselves cannot be specifically bounded and solutions cannot be easily evaluated making uncertainty unavoidable. Third, addressing the problems requires teams that cross multiple and diverse disciplines, multiple sectors and individuals with a range of experiences, knowledge, skills, and perspectives. Fourth, approaches require new ideas which permeate traditional boundaries and cross-pollination and active exploration of others' paradigms and perspectives is required. Individuals must work to educate each other and learn from each other with the goal of creating new and hybridized approaches.

B. Open Problems in Engineering Programs

Convergent problems have been highlighted over the past 10 years through "grand challenge" lists such as the National Academy of Engineering's 14 Grand Challenges [19] and the UN Sustainable Development Goals [20]. Other lists, however, exist from mathematics [21] to assessment [22]. Two coordinating organizations have brought schools together around convergent problems. The first is the Grand Challenge Scholars Program (GCSP) which is built around the NAE's Engineering Grand Challenges. The GSCP has about 100 participating schools from across the world which are mostly opt-in; i.e. available to students but not required. Each participating school has a public facing document that defines various aspects of the school's program including, but not limited to, vision, student selection, and specific requirements. The student requirements run the gamut from taking specific courses or types of courses to service learning projects to Grand Challenge related research. The second is the Principles for Responsible Management Education (PRiME) which is built around the UN Sustainable Development Goals. The PRiME initiative is built around Six Principles: Purpose, Values, Method, Research, Partnerships, and Dialog. Participating schools "sign on" to the PRiME initiative and become part of the network. Each submits a public "Sharing Information on Progress" every two years that details specific ways in which they are connecting with the Six Principles. These initiatives tend to affect entire programs or schools, impacting all students in those programs.

III. Convergence Framework

In transitioning an undergraduate electrical and computer engineering degree program to focus on student capabilities and functionings through addressing convergent problems it is necessary to go beyond traditional change efforts which typically focus on curricula or courses. This project seeks more structural changes since the goal is to educate student to tackle problems that extend beyond the boundaries of a single degree program. As used here structures are accepted and embedded processes which form an interconnected system that an organization, e.g. university, relies on to accomplish day-to-day activities. Structures have large and often unnoticed effects on what an organization can accomplish – for example how grades are determined and assigned. Changing an organization's structures requires creating new ways to see its purpose [5], in this case to shift faculty and students' conceptions of what it means to be an engineer to one that addresses challenging convergent problems. This structural change is being attempted through five synergistic interventions that are hypothesized to impact students' abilities to address convergent problems later in their careers and are described below.

A. Introduce Convergence in Undergraduate Courses

The first hypothesis, drawn from the literature on problem based learning [23] is that students need to undertake convergent problems in order to learn how to address them. Three methods are being introduced to bring convergent problems into existing courses. The first is enhancing students' functioning vector by making convergent challenges visible to students, especially those that they do not encounter every day [24]. The second is to support student choice and agency under the assumption that some subset of convergent problems will intrinsically motivate students [25] and pique their interest which they will then explore further through research, interviews, and personal experiences. The third is being able to identify relevant expertise and build a team since a major aspect of addressing convergent problems is working with a diverse team. Some data suggests that engineering students disengage from non-STEM topics as they move through engineering programs [2]. Given the siloed nature of the degree program building inter-disciplinary teams is a structural challenge. To address this challenge the degree program is developing a minor for non-engineering students that will expand enrollment in what are current engineering-only classes. While at this point in time attempts to integrate convergent problems are in the early stages, the eventual goal is to have students address convergent problems in some form across the entire curriculum.

B. *Opportunities for Reflection*

Introducing undergraduate students to broader convergent and systemic problems is not effective unless students are able to make systemic connections between their various educational experiences [26]. Because no single convergent problem can be covered in a single course, students must intentionally bring together experiences from the wide range of courses and opportunities accessible to them at a liberal arts university. In this project the authors use electronic portfolios [27] to provide a structure in which interdisciplinary connections are promoted, seen, and valued. Portfolios provide a support structure for students to integrate and reflect on both their educational and life experiences, helping student narrate their journey as they deepen existing passions and discover new ones.

A university supported e-portfolio system is being used to capture narratives in projects across the curriculum to build skills in reflection and curation. Portfolio development assignments are currently being integrated into a professional skills course students take in their junior and senior years. The assignments under development are to provide students an opportunity to develop and shift their narratives by broadening their perceptions of an engineering identity. Prompts will be developed to encourage students to reflect on experiences and explain in their own voice how their experiences developed new functionings and enhanced capabilities [12] to expand upon their ability to integrate engineering with their interests and goals to build a life they value.

C. *Modifying Structure – Grades*

Despite modern criticisms of grades and grading structures [28]–[30] as well as other reforms [31] , grades remain "the coin of the realm" [32] that faculty use to reward (or punish) students and communicate tacitly what is important in a course. The near-universally implemented grading practices within the United States can be traced back to the year 1897 [33]. Despite noting in 1913 that "very great stress is laid by teachers and pupils alike upon these marks as real measures or indicators of attainment, we can but be astonished at the blind faith that has been felt in the reliability of the marking system" [34], the system has remained mostly unaltered.

Grades play a large role in establishing student expectations, and grading structures indicate what is valued. In this project the authors are changing grading structures to better communicate that success as an engineer depends on developing a variety of abilities to provide feedback on skillsets needed for addressing convergent problems by mapping student work to align with program goals and our institutional mission.

Traditionally in engineering, a course grade is largely determined by few high-stakes, timed exams, and a moderate amount of weekly assignments which reflect mostly technical and quantitative skills. In this project grades are defined by a set of categories or vectors that is used to assign students a more holistic grade which are derived from department and university mission statements. The vectors align both with the degree program's identity as a liberal arts institution and with skills currently in demand for engineering leadership [35] and convergent problems, as shown in Figure 1.

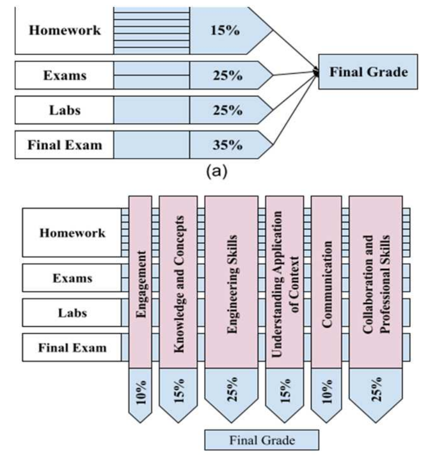

Figure 1: Extracting skillset scores from assignment

Changing grading structures has the potential to better communicate that success as an engineer depends on developing a variety of abilities; the authors hypothesize that such change can affect the behaviors of both students and faculty by providing feedback on skillsets that are needed for addressing convergent problems. Since structural change is inherently tied to culture change, the pilot effort as designed to address all three levels of Schein's organizational culture framework [36]. At the artifact level expanding grading structures across the curriculum to provide multidimensional feedback to students and faculty builds needed structural support for introducing convergent projects. At the level of values, this effort will enable a shifting of departmental narratives and espoused values around what it means to become an engineer. At the assumptions level, the holistic grading system enables students to develop a wider range of functionings and understand how these enable career pathways that lead to desired capabilities [12].

D. *Addressing Time/Effort*

The efforts to provide convergent problems, enable reflection, and shift grading structures are all subject to faculty time constraints, a seemingly intractable problem since time is effectively conserved. However, one of the major changes in the higher education ecosystem in the last decade has been the rise of education-based startups. As there is increasing market stability and wide-spread adoption [37] of such services, a goal of this project is to integrate educational software and data analytics strategically to: create value for faculty by reducing time committed to repetitive tasks, provide new insights into student learning, and provide effective learning support that is time- and place-independent. The last year of the pandemic gave this last item a significant jumpstart by making faculty more familiar with both affordances and challenges of such software.

An internal survey of faculty indicated that if the time spent on disliked activities such as grading could be reduced by approximately five hours per week it would become possible to support projects. This grant ise seeking to leverage technologies to reduce time commitments without reducing (and perhaps improving) the effectiveness of student learning by reducing the time they spend on mundane activities. Because software and data systems, and the affordances they do and don't offer, are integral to university structures in future years the authors will build structures to collect, analyze, and display data in support of developing skills in addressing convergent problems. This effort began over summer 2021 with a comprehensive review of available educational software such as GradeScope [38], Perusall [39], Zybooks [40], and many others.

E. Building Community

The four activities described above will require faculty to change established practices; to support such change the project is establishing communities of transformation (CoT) [41]. CoTs are built from a compelling philosophy, in this case Sen's Development as Freedom framework; integrate that philosophy through practice; and place members in a networked community. The project is in the early stages of establishing CoTs to support bottom-up rather than top-down changes. To support faculty and student engagement, the CoTs are being organized around a relevant text, e.g. *Development as Freedom*, for participants to read and discuss. These groups are open to all faculty, staff, and students at [Institution name deleted] and are building on existing campus initiatives in areas such as sustainability, design justice, and service learning to broaden their appeal. The project also is planning half- or full-day workshops to support bottom-up development of project activities.

IV. Early Phase Implementation

A. Initial Implementation

While this project is in the early stages, which have been further delayed by the pandemic, several actions have been taken in the program's four-year design sequence. In the first year design course the grading practices outlined earlier were implemented on a trial basis. A pilot program implementing the grading structures was then introduced in the first year, second, and third year design courses. In these design courses, a rubric-based approach was used to provide students feedback throughout the design experience. Each assignment identified components mapped to one of six grading categories: applying engineering skills, learning the knowledge and concepts needed to understand and solve problems, clearly communicating ideas and the results of one's work, acting professionally and collaboratively, understanding the larger systemic context of one's engineering work, and being deeply engaged to finding joy in what you do. As an example, a homework assignment might have ten points of the engineering skills categories across several questions, a question with five points mapped to knowledge and concepts and two points mapped to communication for overall clarity, legibility, and organization.

While still in the pilot stage, instructors report that mapping course activities to holistic categories makes strong value statements to students and stimulates conversations that center on growth and improvement rather than merely maximizing points on an assignment. Additionally, instructors are able to more fully reflect on course activities and how assignments align with overall course and instructional objectives. The activities are targeted at different class years with first year students learning the new grading structure, gaining understanding of roles in the discipline to expand possible functionings, and cohort building. Activities in the second-year course focus on providing students capabilities which support their role as engineers in collaborative teams, and the third-year course introduces a project couched in one of the NAE Grand Challenges. An initial pilot of e-portfolio systems is underway with a small group of students and will be reported.

V. Summary

In summary, adapting Sen's Development as Freedom framework around convergent problems provides engineering students increased opportunities to bring in knowledges from outside engineering. The project assumes that since convergent problems are systemic, a systemic approach is needed to develop student interest and capabilities in these challenges. A five-pronged approach—introducing convergent problems across the curriculum, reflection and portfolio development, changing grading structures, introducing new educational technologies, and community building—is being tested to better prepare students to address the changing problems of the 21st Century. At this point in time the project is in its early phases and it is not clear the extent that changing these five elements will have on student learning around convergent problems and impact needs to be assessed. Another limitation of the approach outlines is that while convergence is relatively well defined for practitioners, but the capabilities and functionings that lead to eventual expertise in convergent problems are not yet fully determined at the undergraduate level [8].

As this is a work in progress paper, future efforts are to implement each of the five elements outlined in section III and evaluate the impact on students using social cognitive career theory [42].

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