Implementing Integrated Project-Based Learning Outcomes in a 21st-Century Environmental Engineering Curriculum

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Abstract

Engineering education research and accreditation criteria have for some time emphasized that to adequately prepare engineers to meet 21st century challenges, programs need to move toward an approach that integrates professional knowledge, skills, and real-world experiences throughout the curriculum [1], [2], [3]. An integrated approach allows students to draw connections between different disciplinary content, develop professional skills through practice, and relate their emerging engineering competencies to the problems and communities they care about [4], [5]. Despite the known benefits, the challenges to implementing such major programmatic changes are myriad, including faculty's limited expertise outside their own disciplinary area of specialization and lack of perspective of professional learning outcomes across the curriculum.

In 2020, Montana State University initiated a five-year NSF-funded Revolutionizing Engineering Departments (RED) project to transform its environmental engineering program by replacing traditional topic-focused courses with a newly developed integrated and project-based curriculum (IPBC). The project engages all tenure-track faculty in the environmental engineering program as well as faculty from five external departments in a collaborative, iterative process to define what students should be expected to know and do at the completion of the undergraduate program. In the process, sustainability, professionalism, and systems thinking arose as foundational pillars of the successful environmental engineer and are proposed as three knowledge threads that can be woven throughout environmental engineering curricula.

The paper explores the two-year programmatic redesign process and examines how lessons learned through the process can be applied to course development as the team transitions into the implementation phase of the project. Two new integrated project-based learning courses targeting the 1st- and 2nd-year levels will be taught in academic year 2023-2024. The approach described in this work can be utilized by similar programs as a model for bottom-up curriculum development and integration of non-technical content, which will be necessary for educating engineers of the future.

Background

Beginning in 2020, Montana State University (MSU) launched an initiative to transform its environmental engineering program with support from a National Science Foundation's Revolutionizing Engineering and Computer Science Departments (RED) grant. The rationale for this programmatic overhaul is the recognition that the current approach to environmental engineering education is inadequate to the task of preparing graduates to be successful innovators and change agents in a complex world facing existential global environmental challenges. The prevalent engineering education model, described by Villanueva and Nadelson as the "stasis of engineering curriculum" [4, p. 639], has remained largely unchanged since its introduction in the nineteenth century. In this model, students are introduced to common math, science and engineering fundamentals during the first three years and receive more discipline specific instruction only in their fourth year of study through professional electives. Application of core knowledge and skills to real-world problems and projects is confined primarily to the fourth-year senior design capstone project [4].

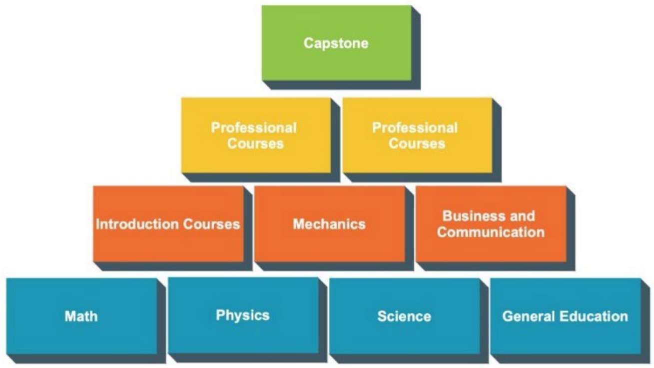

Figure 1. Current topic-focused undergraduate engineering curriculum model [6]

There is extensive literature highlighting the deficiency of this approach. First, the timing and progression of knowledge acquisition in the "stasis" model means that students are not exposed to the scope of professional roles and responsibilities available in their chosen discipline until quite late in their programs of study. Since engineering, unlike liberal arts, is a professional program of study, the failure of programs to connect students early on with the purpose, expectations, and desired professional attributes of their chosen field is problematic and contributes to attrition [4].

Second, the current topic-focused model tends to minimize opportunities for explicit instruction aimed at situating engineering practice within broader social, economic, and environmental contexts. Development of students' *contextual competence*, defined as "an engineer's ability to understand the constraints and impacts of social, cultural, environmental, political and other contexts on engineering solutions and vice versa" [7, p. 1], is an inherently interdisciplinary process. While engineering practice is increasingly interdisciplinary in nature—requiring the synthesis of knowledge, methods, and perspectives from multiple disciplines—interdisciplinarity presents a challenge to faculty as there are no existing guidelines on how multidisciplinary faculty can work together to build consensus around multidisciplinary outcomes [8], [9]. Compartmentalized learning in topic-based courses therefore remains the rule rather than the exception. Students are largely left on their own to make connections between what they learn in foundational math and science courses and other multidisciplinary coursework (e.g., core courses in writing, humanities, social sciences, etc.), and how to transfer and apply that knowledge to engineering courses, projects, and professional experiences [3].

Despite accreditation criteria elevating contextual competence and other professional practice outcomes (e.g., effective communication, teamwork, ethics and leadership), as well as a plethora of national studies calling for a different approach to engineering education, institutional and structural issues continue to complicate curricular change [10], [2], [5]. One issue stems from a lack of incentive for faculty collaboration across departments to develop consensus around multidisciplinary outcomes appropriate to a specific program [9]. A second major challenge concerns the time and resources required of departments to design and implement curricular enhancements without burdening students or faculty with unsustainable course or workloads [1].

Project-based learning (PBL) is a teaching approach that addresses many of the noted deficiencies in the current engineering education model while enhancing, rather than competing with, technical content [3]. Literature on PBL articulates a variety of educational benefits applicable to the desired professional formation of engineering students [1], [2], [3], [5]. Notably, project-based learning:

- Requires students to connect knowledge and skills from multiple disciplines to address open-ended, complex problems.
- Brings real world experiences into the classroom that highlight how engineering solutions impact and are impacted by economic, social, environmental, and other contexts.
- Provides students with opportunities to develop and practice their professional skills in the context of authentic tasks (e.g., project management, communication, teamwork).

By integrating PBL activities into coursework, faculty can enhance students' ability to apply learning from multiple disciplines, foster their contextual competence, and simulate professional practice without increasing course load burdens or lessening the technical rigor of the program.

In light of these findings, the MSU RED project, titled "Sustainable Transformation of Environmental engineering Education for Modern society (STREEM)", has embarked on the transformation of its curriculum from a hierarchical, topic-focused course structure into a model in which integrated, and project-based learning courses are delivered in every year of a student's program of study.

Conceptual Framework for the Program

The STREEM project engages a core team of all seven tenure-track faculty in the environmental engineering program in a multi-year curriculum design and implementation effort. It also involves faculty with expertise in philosophy, public policy and administration, sustainability, engineering management, and communications to support the core team in defining multidisciplinary competencies needed by environmental engineering graduates and in effectively integrating content from other disciplines into environmental engineering coursework.

The authors previously presented an overview of the outcomes-based approach the project team undertook to develop specific and detailed multidisciplinary outcomes for the program at the curricular level and a conceptual framework for grouping outcomes [6]. To highlight our focus on interweaving competencies, we adopted a nomenclature of "threads" and "strands." The top-level *knowledge threads*, envisioned as the foundational roots supporting the emergence of successful 21st century environmental engineers, were selected as: systems thinking, professionalism, sustainability, and disciplinary competencies (Figure 2).

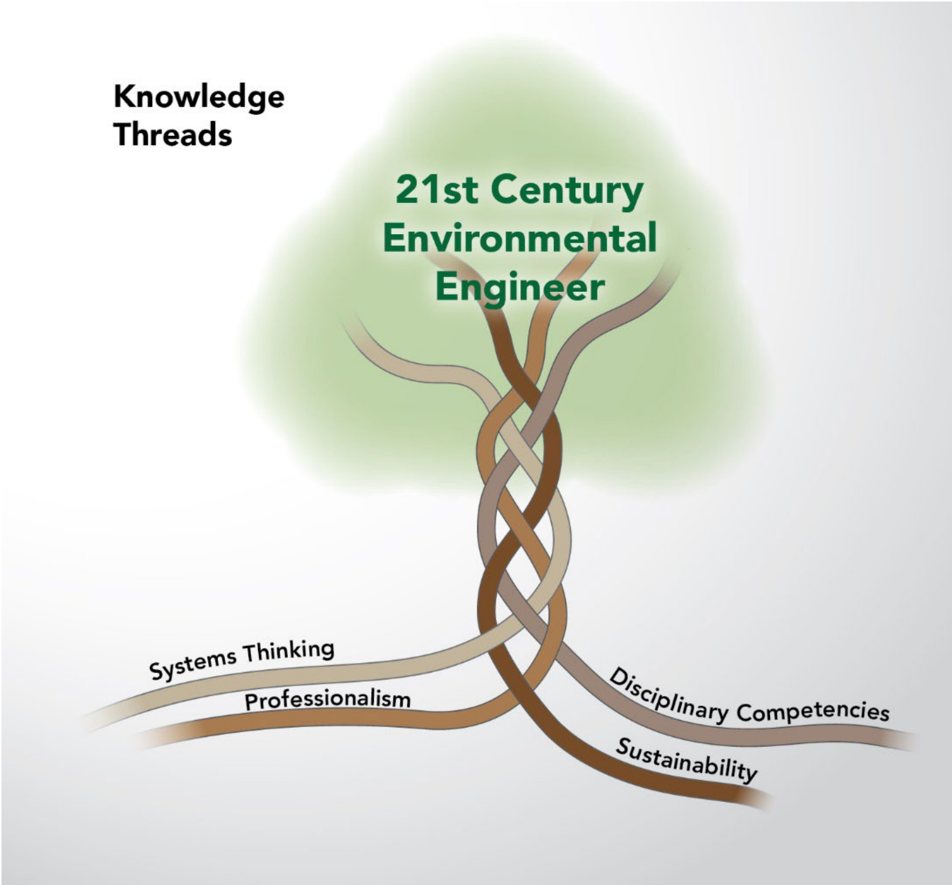

Figure 2. Knowledge Threads

Each knowledge thread contains a variety of *competency strands*. For example, the professionalism thread encompasses teamwork, communications, social justice, and ethics (Figure 3).

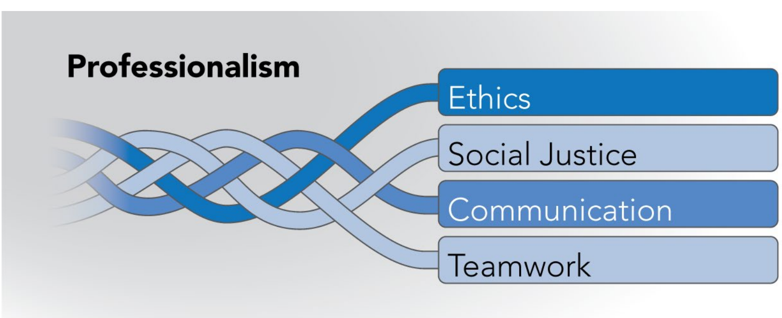

Figure 3. Professionalism Thread Competency Strands

The disciplinary knowledge thread reflects multi-disciplinary competency strands, to include science and engineering fundamentals, project management, public policy, and environmental engineering specific topic areas, such as surface water resources and hydrology, air quality and control, solid and hazardous waste, etc. Within each strand, competency domains were identified to provide additional detail as shown in Figure 4. For each domain, specific learning outcomes were identified.

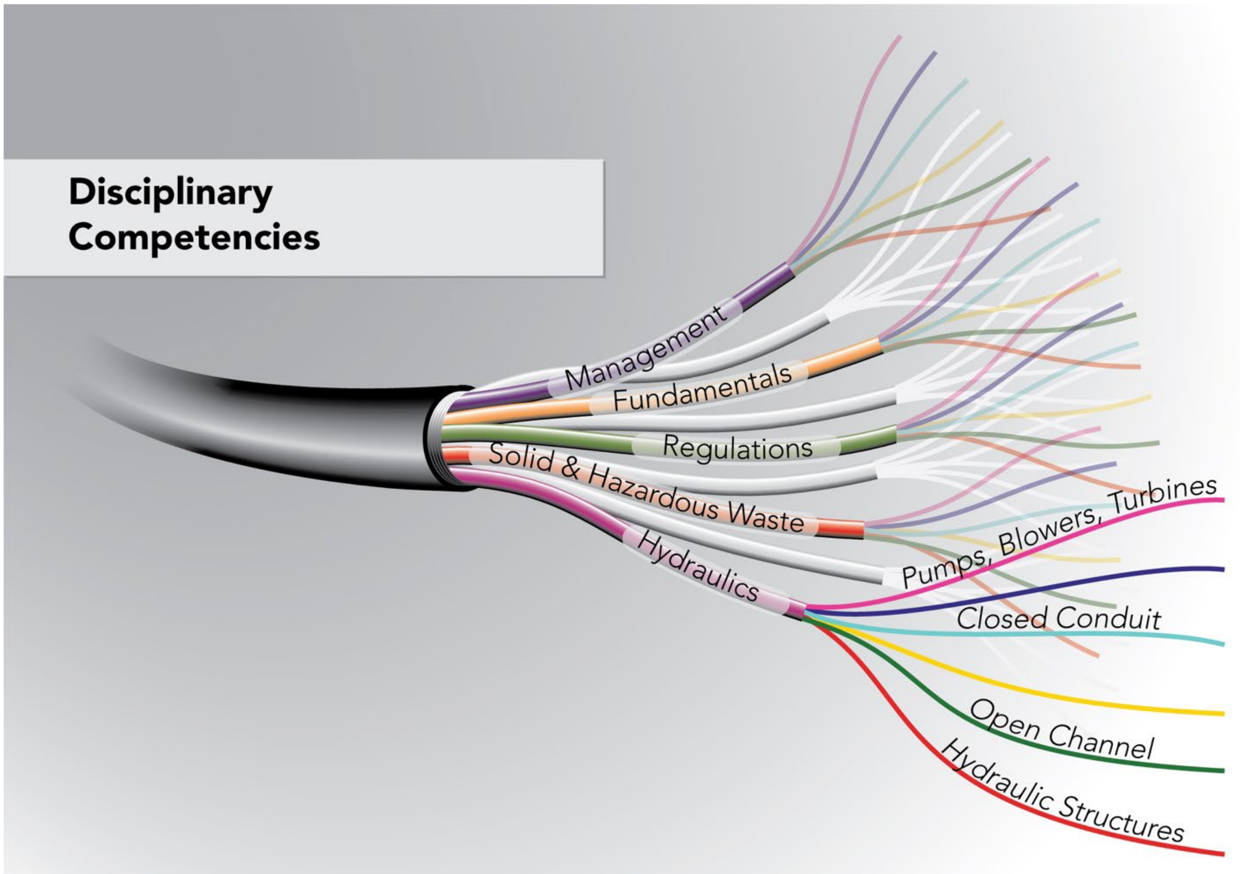

Figure 4. Disciplinary Competency Thread – Example Strands and Domains

Purpose

The purpose of this paper is to examine the redesign of the environmental engineering curriculum as essentially a collaborative engineering design process. We conceptualize the curriculum as the implementation of a faculty consensus on desired student learning outcomes; as such, faculty collaboration represents a key component for systems change. We explore lessons learned during the two-year design process and examine take-aways that can be applied to course development as we transition into the implementation phase of the project. In particular, we consider how faculty can seamlessly integrate systems thinking, professionalism, multidisciplinary content, and sustainability into new project-based learning courses without overwhelming both faculty and students.

Systems Change Process

<u>Understanding the existing system</u>
The STREEM project benefits immensely from the active engagement and involvement of *all* tenure-track faculty in the environmental engineering program, as well as from the incorporation of perspectives and insights gleaned from multidisciplinary team members outside the

department. To effect change, the project team first needed to gain insight into existing conditions. The first step in the curriculum re-design process, therefore, involved clarification of what content was being delivered to students in required courses, both within and outside the department, as well as what content students may or may not receive based on their selection of electives. In addition to reviewing multidisciplinary course syllabi and stated learning objectives, the team explored student perspectives through the involvement of a student advisory group. Students were helpful in identifying courses where no, or only minimal, content appeared applicable to environmental engineering coursework or professional practice. These insights were beneficial to the team in identifying where curriculum coherence was lacking, either due to lack of alignment between required courses and intended program outcomes, or due to students being unable to independently make the necessary connections between various topic-focused courses.

Describing the desired system

The project team undertook a bottom-up outcomes-based approach to define the competencies and attributes a successful undergraduate engineering student would ideally attain by the completion of their program of study (as detailed in [6]). Discussion of curricular level learning outcomes was undertaken without reference to existing courses or program of study. This approach helped to liberate the team from working within the confines of the existing system. Another important innovation in this process was the involvement of non-departmental faculty to offer their diverse perspectives on what they considered critical student learning outcomes related to professionalism (communications, ethics, social justice, and teamwork), public policy, engineering management, sustainability and systems thinking. Multidisciplinary discussions helped to clarify how "integration" might be implemented in individual courses and how integrated competencies could be scaffolded to achieve higher level skill attainment by students as they progress through the program. The conversations also aided with the prioritization of multidisciplinary competencies for integration into new and existing environmental engineering coursework.

Clarifying system boundaries and constraints

Prioritization implies that not all learning outcomes can be incorporated into the redesigned curriculum due to system constraints. The team outlined a variety of system limitations, such as student credit hour requirements, faculty workload constraints, and the ability to influence course content outside of the department. Using the current curriculum flow chart as a starting point, the team then identified leverage points where sustainable changes could effectively be made. The resulting program structure utilizes existing courses that already meet desired program outcomes, identifies core environmental engineering courses that can be modified to better integrate desired learning outcomes, and adds new project-based learning courses that focus on the application and practice of integrated learning outcomes. The revised curriculum flow chart establishes where intended changes will be made. As can be seen in Figure 5., the revised model upends the traditional hierarchical course model by introducing project-based learning into each year of the program. The PBL course series will provide students with progressively challenging opportunities to apply technical knowledge and to build professional practice skills and experience throughout their program of study.

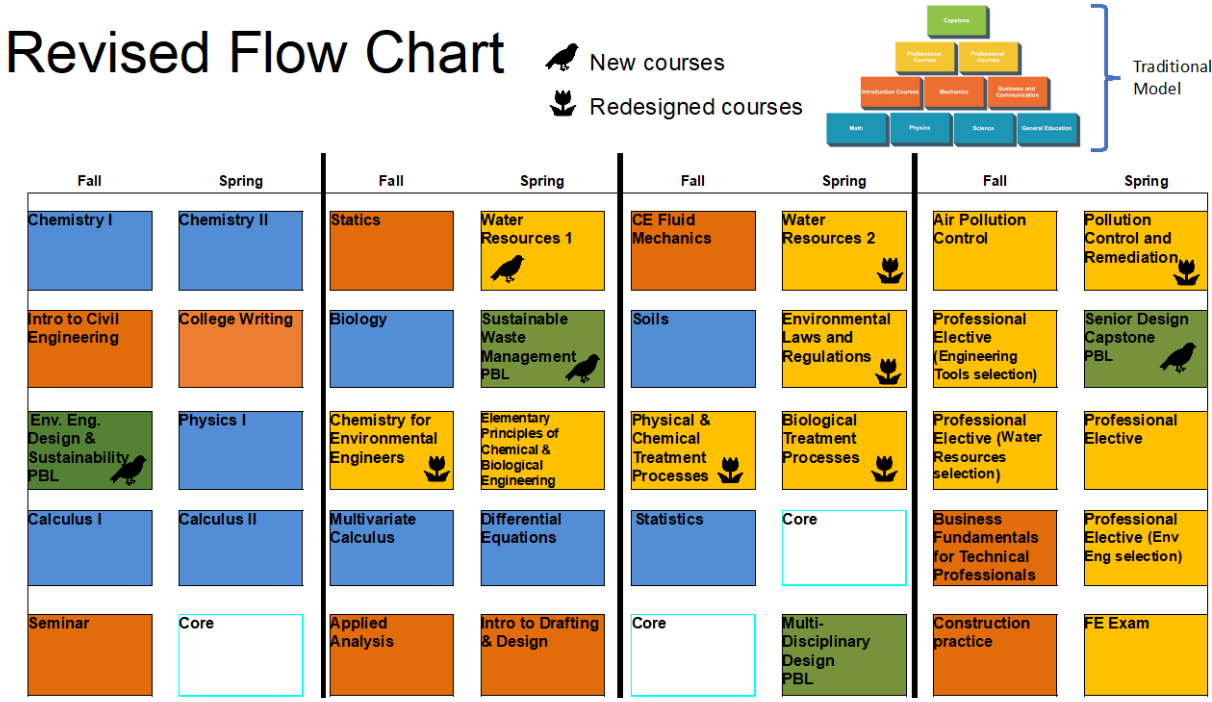

Figure 5. Revised Curriculum Flow Chart

<u>Shared Understanding</u>

The establishment of a shared understanding of the existing program as well as the development of a shared vision and overarching goals for the new program embodied an essential starting point before the team could move into the implementation phase. Achieving consensus on desired student learning outcomes and the overall curricular structure was attained through weekly discussions among the core team, specialized meetings and coordination with multidisciplinary team members, and consultation with a student advisory group and external industry advisory board. While the process has been time-consuming and not always straightforward, it has aided the team in developing a collaborative faculty culture, which is one of the STREEM project's main objectives. Development of a shared understanding is inherently a collaborative process and forms the basis for collective action and systems change [11]. Faculty are invested in the project as they see the new curriculum and team-teaching approach as enhancing both student and faculty experiences which is a core value of the team. The team's efforts are also fully supported within the College for tenure and tenure-track faculty.

Next Steps - Implementation

Details on exactly how intended integrated learning outcomes can be mapped onto the new curricular structure (i.e., matched to specific courses) as well as the pedagogical methods that will be employed to teach integrated competencies are currently being worked out by the team. The database the team collectively created of desired program learning outcomes has proved useful for matching outcomes to specific courses and, especially, for helping faculty to understand the program holistically. The initial mapping process highlighted major gaps in coverage and helped faculty to make connections or to identify potential linkages between multiple classes and topics (beyond the courses they individually teach). However, the outcomes database contains over 400 outcomes that do not neatly equate with course-level learning objectives. The sheer number of intended outcomes also hints at a future task; faculty will need to prioritize and make trade-offs in the implementation stage.

The team is currently shifting its attention from high-level program conceptualization to the question of how courses will be taught to achieve intended learning outcomes and how outcomes will be assessed as we move into the implementation stage. To underline the core faculty's commitment to faculty coordination, knowledge sharing and continuous learning, the first two project-based learning courses are intended to be team-taught. The team established guidelines for ensuring that collective decision-making remained part of the course development process for new integrated PBL classes, while ensuring that lead instructors have the necessary autonomy to move forward with course design and delivery. The intention is that at least three months prior to the start of the semester, lead instructors will present their course syllabus to the full group for discussion and approval. The syllabus will include course outcomes, an outline of course content, a breakdown of assessment plans, and their intended approach to project-based learning, including expected student deliverables. Once approved, the lead instructors are free to move forward with course development and delivery as they see fit. The guidelines are meant to balance faculty autonomy with collective decision-making in a manner agreeable to the team.

The first freshman-level integrated project-based learning course, *Introduction to Environmental Engineering Design and Sustainability,* will be offered in fall 2023. The second year PBL course, *Sustainable Waste Management*, will be offered in spring semester 2024. Two different teams, each made up of two faculty members, are currently developing integrated PBL content for the first offerings of the new courses. Both courses aim to introduce and provide students with opportunities to develop and apply systems thinking, sustainability, multidisciplinary and professionalism competencies through project and design work. How to accomplish this ambitious objective appears to be an overwhelmingly daunting question at first glance. We propose that the collaborative curriculum redesign process the team has undertaken over the past two years provides a helpful guide for faculty as they begin developing an approach to integrated learning in new PBL courses.

Application of Systems Thinking to Integrated PBL Course Development

The systems change process detailed above is essentially an application of systems thinking to a design problem, in this case, one of curriculum design. Here we adopt Arnold and Wade's goal-oriented definition of systems thinking as "a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviors, and devising modifications to them in order to produce desired effects" [12, p 676]. In developing the project's systems change approach, the team practiced specific systems thinking skillsets: characterizing past system behavior, considering the system holistically, recognizing interconnections and boundaries, developing concept models, and exploring multiple stakeholders and perspectives [13].

The proposed modifications to the department's approach to undergraduate education are undertaken with the objective of graduating environmental engineers capable of solving complex, 21st century global environmental challenges. In our formulation, improved capability is defined in terms of ABET's student outcomes criteria with a focus on improving teaching and learning in areas that have been traditionally underemphasized, specifically, 1) interdisciplinarity and contextual competence; and 2) teamwork, social justice and ethical leadership. We find that systems thinking as a framework for understanding interrelationships represents an anchor point within the curriculum for fostering students' ability to draw connections between disciplines, as well as to situate engineering practice within larger social, economic, and environmental contexts.

Integration of sustainability into engineering education is a case in point. The Engineering for One Planet Framework calls out "systems thinking *from an environmental perspective* as the most fundamental concept and approach that students must learn" [14]. Wiek and Redman also identify systems thinking as a key competence in sustainability, noting that development of successful strategies toward sustainability requires systems analysis "across different domains (society, environment, economy, etc.) and across different scales (local to global)" as well as an "understanding of cascading harmful effects and dynamics" in complex coupled human-environment systems [15, p. 207]. As students work through design problems, instructors can foster a sustainability mindset through a systems approach to problem-solving, which amplifies students' awareness of system boundaries, tradeoffs and tipping points, and contextualizes engineering solutions within larger interconnected systems [14].

An important part of describing a system is identifying stakeholders and their needs. From a sustainability perspective, stakeholders encompass both humans and the natural environment. A consideration of multiple perspectives must be anchored "in a core belief in the dignity and worth of people and the natural environment" [16, p. 138]. Beliefs about the value of the environment, social justice, and ethics are critically important in the development of professionalism competencies, but they are difficult to assess in the classroom. One reason for this difficulty is the fact that they are highly situationally dependent; what a student knows is not directly linked to what they will do in a given situation [2]. The professionalism competencies identified in the STREEM project can be conceptualized as both teachable skillsets and the development of a practice orientation. Practice orientation is described as "a range of habits of mind and predispositions that orient practitioners to think, make decisions, and act in particular ways in professional settings" [16, p. 139].

Integration of a systems thinking approach to project-based activities can foster students' development of a professional practice orientation. For example, to gain insight into a system under study, identification of stakeholders and exploration of multiple perspectives can be incorporated as a critical step that students implement in every project-based activity as a key component of the design process. This approach is in line with recommendations made by participants at the National Academy of Sciences workshop on ethics education [17]. In outlining skills and knowledge that should be developed in ethics education, workshop participants utilized language very similar to that used to describe a systems thinking process more broadly. Participants identified required ethics skills to include:

- Identifying relevant stakeholders and socio-technical systems.
- Collecting relevant data about the stakeholders and systems.
- Understanding relevant stakeholder perspectives.
- Identifying value conflicts.

- Constructing viable alternative courses of action or solutions and identify constraints.
- Assessing alternatives in terms of consequences, public defensibility, institutional barriers, etc.
- Engaging in reasoned dialogue or negotiations.
- Revising options, plans, or actions [17, p. 12).

Implementation of this approach in teaching ethics shifts the focus from an abstract consideration of individual decision points in presented case studies to the repetitive enactment of critical and necessary components of engineering design practice. Utilization of a systems approach in PBL activities thus leads to the repeated application of a related set of desirable ethical skills.

This natural compatibility between systems thinking, sustainability and ethics can be extended to other knowledge threads and domains, such as teamwork and leadership. The traditional preoccupation with leaders as individuals with specific skills or attributes is no longer adequate in developing the type of leadership required by 21st century challenges [18], [19]. In sustainability fields among others, leadership is increasingly conceived as a collaborative process in which the various actors do not have positional power over one another [18], [11]. In this formulation, leadership is demonstrated through the practice of social interaction, in which shared understanding is developed among multiple stakeholders, providing the foundation for collective action [19], [11]. Leadership, therefore, can be developed in undertakings pursued by teams of peers, such as in project-based design activities, in which team members collectively formulate and apply their understanding of entire systems to design appropriate interventions.

Discussion

Evidence on project-based learning demonstrates that PBL activities are an effective way to foster students' ability to connect and apply knowledge from different disciplines, contextualize their learning in broader social, economic, and environmental contexts, and to practice professional skills. Our curriculum design experience at the program level has highlighted the ways in which having students utilize a systems approach in PBL courses can further reinforce integrated learning and serve as a unifying thread for faculty as they develop and implement integrated project-based courses.

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