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Early Engagement and Vertically-Integrated Learning: Developing Whole-Person and Entrepreneurially-Minded Engineers

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Early Engagement and Vertically-Integrated Learning: Developing Holistic and Entrepreneurially-Minded Engineers

Abstract

Nationwide, 40-60% of engineering students leave their engineering major, with women and underrepresented minorities doing so at higher rates. In the School of Civil and Environmental Engineering (CEE) at Georgia Institute of Technology in recent years, 50% of students have changed to a new major in their first two years, while roughly the same numbers have entered the program simultaneously from other engineering majors. Similar departure rates are seen in programs across the country. Reversing attrition from civil and environmental engineering is a critical need for addressing society's grand challenges effectively. This attrition is due in part to limited discipline-focused engagement until students' junior year. To address this, the School of CEE is providing early engagement in authentic engineering experiences and giving students the opportunity to reflect on these experiences to solidify their CEE identity. We are creating opportunities early and across the curriculum for our students to engage in interactive problem-based learning centered on the global grand challenges, while developing their technical and computational knowledge, skills, and mindset. We are also equipping our students to work effectively in teams and to apply story-driven learning to become more reflective learners. This takes the form of a "spine" of vertically-integrated courses. These innovations in the curriculum contribute to the development of holistic engineers with an enhanced sense of belonging to the discipline and a strengthened self-concept as a civil or environmental engineer. The initiative also supports the development of entrepreneurially minded engineers, that is, engineers who know how to create value for society and do so habitually. We outline these innovations in each of the four vertically-integrated courses, while emphasizing the techniques applied and how they connect to create a cohesive curriculum that engages students as engineers from the first year.

Introduction and Objectives

Statistics indicate that 40-60% of engineering students in the U.S. eventually drop out or change majors (Desai & Stefanek, n.d.), with women and minorities doing so at higher rates (Geisinger & Raman, 2013; Ohland et al., 2011; White & Massiha, 2016). In the School of Civil and Environmental Engineering (CEE) at Georgia Institute of Technology in recent years, 50% of students have left the program in their first two years, while roughly the same numbers have entered the program simultaneously from other engineering majors (Haas 2017-2019). These retention rates stem from at least one issue our outreach has discovered applies to a number of CEE programs across the nation. Discipline-focused student engagement begins later in the curriculum, generally late in the second year or early in the third year, to accommodate for general engineering and non-engineering core courses. This delay comes with the risk of students changing their majors as they may feel little sense of belonging within the program, have little understanding of the CEE profession, and make little progress in constructing their identity as a civil or environmental engineer in these early crucial years.

To address this need, we have embarked on a journey to engage our students in CEE from the first year and keep them engaged in vertically-integrated learning throughout the program. We are creating innovations to develop *holistic* and *entrepreneurially-minded* engineers. Improving human and societal conditions is at the heart of what CEEs do. Holistic education embraces the development of cognitive, interpersonal and intrapersonal skills, and has been identified as an essential approach to educating students to be successful in the 21st Century workplace (Georgia Institute of Technology, 2018; The National Academies of Sciences Engineering and Medicine, 2017). Graduates with an entrepreneurial mindset know how to create societal, economic and personal value, and have the culture of creating value wherever they go (*Entrepreneurial Mindset | Engineering Unleashed*, 2022).

Several authoritative initiatives on CEE education have identified the need to graduate more well-rounded CEEs to tackle society's grand challenges and improve the human condition. The American Society of Civil Engineers' (ASCE) 2019 Civil Engineering (CE) Education Summit in Dallas, for example, summarized key elements of the future of CE education as providing students with the following: (1) the *power skills* necessary to succeed in the CE profession; (2) *authentic experiences* to promote learning and excitement; (3) a *mindset* toward innovation, societal focus, sustainability and systems-thinking in their design solutions, (4) a *commitment to diversity, inclusion and equity*, and, (5) the *flexibility* to pursue their *passion(s)* (Hall et al., 2019).

Along similar lines, the National Academies 2019 report: Environmental Engineering for the 21st Century urges environmental engineers to respond to the grand challenges and provide the leadership required to address them, noting that this vision will require a new model for environmental engineering (EnvE) practice, education and research. The report calls for EnvEs to: (1) move away from a focus on addressing single problems toward *systems-based solutions* that address a broad set of issues; (2) become proactive in *anticipating problems* rather than reacting to them; and (3) *cultivate diversity and engage collaboratively* with stakeholders and other disciplines (National Academies of Sciences Engineering and Medicine, 2019).

This call to educate and graduate more holistic engineers is not new. Other authoritative efforts such as The Vision for Civil Engineering in 2025 (American Society of Civil Engineers, 2006), the National Academy's Call to Action to address Societal Grand Challenges (National Academy of Engineering, 2008), and the National Association of Colleges and Employers Annual Job Skills Survey (National Association of Colleges and Employers, 2019) all point to a demand for more holistic engineers to address society's grand challenges. In addition, there is growing acknowledgement that CEE programs will benefit from modernization to stay abreast with technological evolution, including retaining students who actively seek computational thinking and skills development (Haddad & Kalaani, 2015).

We aim to develop holistic and entrepreneurially-minded engineers through a vertically-integrated spine of interactive courses in the first, second, third and fourth years. Below we discuss our approach to early engagement and vertically-integrated teaching and learning in the School.

Method: Integrating Pedagogies

In order to develop holistic engineers, many teaching pedagogies are incorporated into the curriculum. These pedagogies are integrated into a "spine" of courses offered in the School of

Civil and Environmental Engineering to varying degrees and intensities, with the expectation that there will be broader adoption over time. Before discussing the spine course model, we briefly discuss each of the pedagogies and methodologies we applied.

Problem-Based Learning (PBL) is an approach to problem solving that is primarily student-driven and is rooted in real world scenarios (Hmelo-Silver & Barrows, 2006; Hughes et al., 2013; Newstetter, 2006). A problem statement is posed to student groups mirroring a relevant issue in their field of study. Students are given little supporting information; instead it is up to them to brainstorm and determine what relevant information they already know and develop lines of inquiry towards what they will need to learn to address the problem. Throughout this process, the instructor acts as a facilitator, asking probing questions that challenge the students. The goal of problem-based learning is not to arrive at a specific or predefined "right answer," but rather to require the students to use problem-solving skills to identify a "good" or perhaps "the best" design, evaluation or other solution to the problem.

While *teaming* on its own is not a distinct pedagogy, the ability to work effectively in teams is a crucial skill for all engineers (Borrego et al., 2013). Within the spine courses, we give a particular focus to team development that advances with the students as they move through the curriculum. Concepts like psychological safety and diversity of thoughts and experiences are introduced early. Students in the first-year course engage in team reflection activities focused on team performances, authenticity, and core values. In later courses, our teaming methodology expands to include team structuring, project phasing, conflict types, conflict management and resolution, feedback, and evaluation. A more in-depth description of the elements of team effectiveness in each course is included in the results section.

One of the outcomes we are working toward through this curriculum initiative is to develop engineers with an Entrepreneurial Mindset (EM). Developing EM is not about start-ups or business strategies necessarily; rather EM empowers engineering students to recognize and identify opportunities, focus on their impact, and create value in any context (Bosman & Fernhaber, 2018; *Entrepreneurial Mindset | Engineering Unleashed*, 2022). EM is comprised of three elements: curiosity, connections, and creating value (the 3Cs). To encourage the 3Cs, we use two methodologies: s*tory-driven learning,* and v*alue sensitive design.* Story-driven learning (SDL) encourages students to be reflective of their learning experience. As an affective-focused pedagogy, SDL provides students with opportunities to create and share stories of their experiences through an EM lens, as well as hear others' stories, helping them to see themselves as being entrepreneurially-minded and coming to know what it means to be an entrepreneurially-minded engineer. Value sensitive design (VSD) brings a focus on including human values throughout a design process (Friedman & Hendry, 2019, 2012; Miller et al., 2007). VSD includes theories and methods that encourage the engineer to consider values and norms, direct and indirect stakeholders, and long-lasting impacts early in the design process to craft more equitable solutions and reduce or eliminate unintended consequences. Implemented in the classroom, this supports the 3Cs by asking students to curiously explore multiple perspectives, make connections between their technical knowledge and their moral imagination, and seek to create value for a range of stakeholders.

A successful model linking courses across the undergraduate curriculum through a cohesive teaching methodology already exists in CEE: the in-house engineering communications program established in 1998. This program, which addresses written, visual, and oral communication, pioneered the embedded model of teaching engineering communication—that is, teaching engineering communication skills within an engineering context. This model has a Principal Academic Professional educated in English embedded within the School. Her responsibilities include co-teaching the core courses, a role that allows her to introduce new communication skills as they are relevant to the course content. In a vertically-integrated program, students are first taught fundamental principles of written, visual, and oral communication in the Engineering Systems course; they then learn more specific skills in their laboratory courses, and finally learn professional practice skills in the capstone course. Because integrating instruction in communication into engineering course content has been shown to encourage a deeper understanding of the technical content, as opposed to a stand-alone course (Riemer, 2007; Troy et al., 2016), the introduction of the first-year and second-year spine courses provides the opportunity to expand the vertically-integrated communications program and its impact on student learning.

This curriculum innovation initiative introduces early engagement and extends vertical integration in a spine of courses that are to be required for all students in the program.

The Spine Courses

The spine refers to a set of four vertically-integrated courses designed to create a cohesive learning experience connected across each year of the civil and environmental engineering undergraduate curriculum. While the engineering content of the courses is not fully and directly connected, the methods and approaches to learning are consistent between the courses, each employing the above pedagogies and methodologies in ways that are relevant to the particular course. Figure 1 is an outline of how each course aims to apply problem-based learning, team development, story-driven learning, and values sensitive design to ultimately create holistic and entrepreneurially-minded engineers.

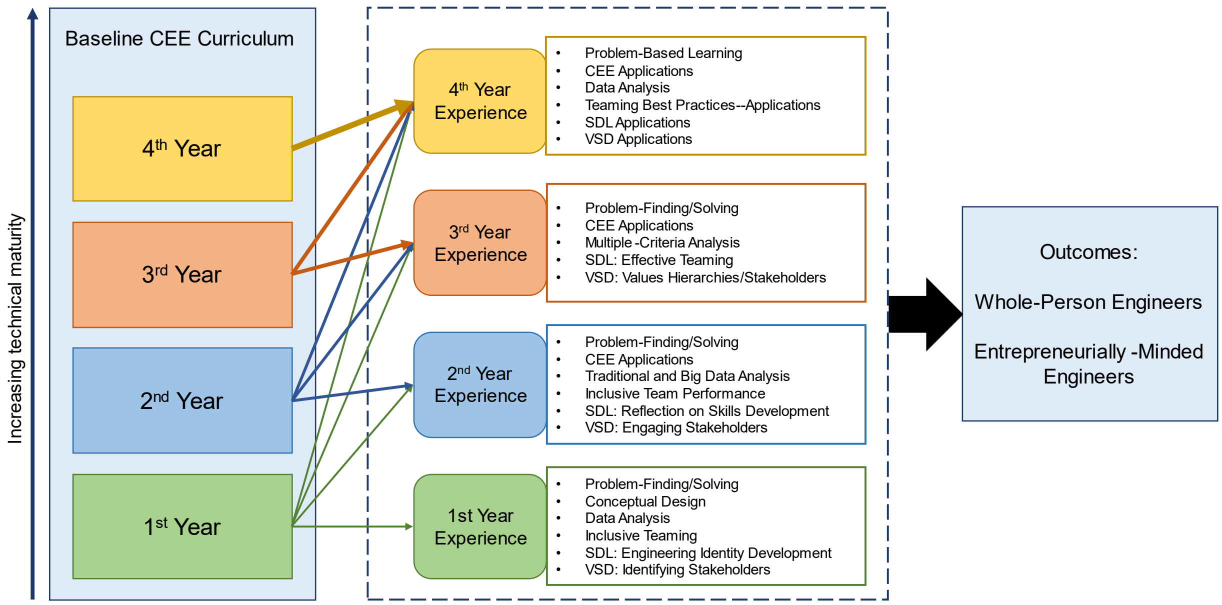

Figure 1: The model of vertically-integrated courses designed to use various methodologies to create holistic and entrepreneurially-minded engineers.

At the start of this curriculum innovation process, the courses were in various stages of development. The third-, and fourth-year courses were already established courses that were being taught regularly, and the first-year course had been offered twice in two years. The first-year course was originally an optional special topics class but is slated to become part of the set of required courses as part of the spine. The second-year course did not exist prior to the initiation of the spine courses. It was designed to address the need for engineers to have evolving data analysis skills. Including this new course in the set of vertically-integrated courses presented a unique opportunity to incorporate these data methodologies early in the curriculum. The faculty involved in transforming these courses met regularly to discuss potential implementations and to give and receive feedback. They worked together and iteratively as a collaborative unit to ensure that the courses would become truly vertically-integrated, making changes to individual courses with the vertical integration of the courses in mind. Individual faculty also worked with various pedagogy mentors within and beyond the Institute to determine and refine implementations within their respective courses.

Results: Vertically-Integrated Courses

In the following section, we present highlights of how each spine course is incorporating problem-based learning, team development, story-driven learning, and value sensitive design. We include the names and short descriptions of the courses to provide context, but the focus of this paper is to describe *how* we are integrating these pedagogies rather than what we are teaching specifically.

First-year course: Exploring Civil and Environmental Engineering

This course is designed to be an introduction to CEE, focusing on four big ideas that cross traditional boundaries. The School of CEE addresses societal grand challenges by focusing our contributions in four broad, cross-cutting research areas: resilient infrastructure, healthy communities, sustainable systems, and smart cities. These are introduced in the first-year course through a series of modules and built upon in each of the successive courses in the spine. Each module is presented in three sections: learn (introduction and discussion), do (small group assignment), and reflect (individual writing reflection). The "do" portion of each module is the students' first encounter with problem-based learning. The students are placed into groups to work on a project related to topics within the relevant module. In prior offerings, these projects have been designed to be open-ended, allowing students to pursue topics of their interest within the framework of the specified guidelines within the module. This has allowed the students to have the freedom to explore topics, but also demonstrated the challenges that they will face seeking out information and data to solve engineering problems. Another of the objectives for these projects is to introduce students to "wicked problems," associated with the four CEE cross-cutting research areas, where there are no unique solutions. For the Resilient Infrastructure focus area, for example, they tackled the following design problem:

"Coastal infrastructure, including buildings, is particularly susceptible to risks from high water levels associated with storms and sea level rise. In this project, you will take on the role of a consulting engineer making recommendations to developers who have proposed a coastal project in light of what you know about storm surge from historical storms and what you anticipate regarding future sea level rise for a specific location."

The students discovered that for this project the design requirements would depend on many different factors including the acceptable level of risk, which depends on the type of infrastructure being designed. They also learned that there was no simple answer for what the required design water level should be as there is much uncertainty in projected sea level and storm events.

This group project also serves as the start of the students' experience with team development. One faculty member, an Academic Professional with leadership development education and experience, is the team development instructor in all of the spine courses as well as other courses within the school. His first session with the students occurs after their first of four group projects. In this session, he introduces the basics of inclusive teaming. He encourages the students to reflect on what did and did not work in their first team project and gives them tools to improve their experiences in subsequent group projects. At this stage of the spine, team development focused on team formation, the value of diverse members, psychological safety, and structuring. Forty-four out of 64 students surveyed after the second group project said they directly tried to incorporate a number of the strategies that were discussed in the team effectiveness session, with the top strategies being: clearly dividing tasks by individual strengths, developing open communications from the beginning, and validating others' opinions.

The "reflect" portion of each module is an exercise in story-driven learning. Students are asked to reflect not only on what they learned in that module, but also how they see it being relevant to them and their future as an engineer. These initial reflection activities kick start the student's development of self-concept as a civil or environment engineer and encourages them to imagine how they can possibly contribute to that space in the future.

Second-year course: Data and Computation for Civil and Environmental Engineers

This course was created to enhance data management and analysis in the CEE curriculum, including the analysis of datasets ranging from the small to the very large, while also addressing a grand challenge issue: e.g., climate change. It is made up of three sections: introduction to data science, artificial intelligence and machine learning, and a final project. The final project is one instance of problem-based learning in this course. The project tasks students to analyze some aspect of a large data set from local sources related to grand challenge problems (for example, as related to our Smart Cities focal cross-cutting research challenge: traffic sensors, temperature records, air quality information, storm events, etc.). The local context of the data roots the students' work in a relevant context that they connect with. The complexity of these types of datasets also forces the students to ask questions and figure out what exactly they need to focus on in order to come to a reasonable answer. Problem-based learning also is present at the beginning of the course. The first assignment is an open-ended question pushing the students to dig into learning about the types of data sets that exist before they have had much chance to work with them. This includes more traditionally collected data as well as emerging big data sets. The expectation is that the students will then discover on their own the depth and breadth of data that they may need to work with to arrive at defensible solutions. The design calls for the team development instructor to work with students to build on what they learned in the first course. In terms of team building and team processes, the sophomore course is designed to introduce students to interdependency and the different types of conflicts within teams, the importance of building trust, and how to create shared mental models. The sophomore course builds upon work done in the first-year course on stakeholders. The design also calls for students to apply VSD tools to identify the stakeholders of the problem they are studying to characterize the different stakes they have in the solution, and how data can be used to address these challenges.

Third-year course: Civil Engineering Systems

In this class, students learn about civil and environmental engineering systems, with a particular focus on our Sustainable Systems focal cross-cutting research focus, encouraging students to contemplate what makes CEE systems more sustainable, and how to apply an integrated systems/sustainable engineering framework to plan, design, implement, operate and renew these systems. As with the other spine courses, this class has incorporated problem-based learning. PBL in the course encourages the students to become comfortable with uncertainty. There are also team development sessions focusing on roles and responsibilities, conflict states, feedback and evaluation, and assessing team health. This course also presents examples of story-driven learning and value sensitive design being used to develop EM engineers. The instructor leads by example in the first class and shares her story of becoming a civil engineer. By starting with this story, the students connect how their experiences have led them to this point and how they identify as civil or environmental engineers. The students then share their stories with each other and connect with their classmates. In a panel assessing the sustainability of a large-scale urban redevelopment, civil engineering and other professionals are also prompted to share related elements of their professional development stories. Third, a reflection activity has been implemented that applies story-driven learning (i.e., reflecting and journaling) to consolidate learning on what it takes to develop effective teams that create value. In this activity, the students reflect weekly on their experiences working in their teams and how curiosity, connections, and creating value (the 3Cs of EM) feature in their development of effective teams. At the end of the course, students have entries that tell the story of their growth as a team via the lens of the 3Cs through the semester.

We engage value sensitive design by adapting the "Values Hierarchy" method (van de Poel, 2013) as a classroom reflection tool. With this model, during the project presentations module students reflect as a class on the values of sustainable systems design, and norms that encourage or obstruct the development of sustainable systems. In their teams, they also reflect on the design requirements that would enhance the sustainability of their projects of study. Connections are drawn between how values shape norms that contribute to design requirements and how certain design requirements reflect certain norms and assume specific values. From this exercise, students are expected to have a stronger appreciation for the power of values to shape the built environment and a knowledge of values that foster the development of more sustainable systems. They are also expected to come away with a stronger appreciation for the importance yet difficulty of including representative stakeholder views in built environment decision making.

Fourth-year course: Senior Capstone Design

The senior capstone design class completes the set of spine courses. This implementation of capstone design has been a completely problem-based course for more than 20 years where student groups execute a real-world project unique to their team mentored by an industry sponsor through the entire semester. It is also the time for students to apply all that they have learned from the team development sessions in the other spine courses. Here, in particular, highly interdisciplinary design projects emerge that address Healthy Communities, the fourth core cross-cutting focal research area of CEE. The instructors fulfill the role as facilitator in problem-based learning as they do not have a "right" answer to the design problem offered by their sponsor. Instead the instructors push the students to discover it on their own. Story-driven learning is also on display in this course as the instructors all have substantial experience in industry and can share their own stories of tackling challenging engineering problems such as proposal deadlines, ethics issues, and team interactions. By interacting with local engineers through the sponsored projects, students can see how their experience in capstone strengthens their identity as an engineer. Value sensitive design's intense focus on the values of stakeholders (both direct and indirect) —including aspects of public health— is especially useful in this course as well. While engaging with stakeholders directly is generally not permitted by the sponsors, students are still asked to brainstorm and reflect on applicable stakeholder groups, their alternate perspectives, and design accordingly.

Discussion

The purpose of linking four courses across the undergraduate curriculum is to provide a cohesive teaching methodology across the four years that engages students from the first year and keeps them engaged throughout the four years. Consistent, maturing and vertically-integrated instruction on team development that compounds each year aims to create effective team members who can manage conflicts in their capstone design teams and into their careers. A consistent emphasis on human values aims to create engineers who are more aware of other perspectives, conscious of potential impacts, and habitually work to create value. While each course may implement the pedagogies to different degrees, the underlying design of a vertically-integrated set of courses reinforces threads that are critical to becoming a holistic engineer. Reflection is one such thread. In each course there is an emphasis on students reflecting on their experiences, whether that be from their past, in teams, or while learning a new subject. Reflection is a valuable element in story-driven learning. It internalizes experiences and makes the students evaluate how a situation made them feel, engaging the affective side of learning. By reflecting on instances of acting like an engineer in the classroom, the students begin to believe that they can be an engineer, increasing self-concept and solidifying their identity as an engineer (Brubaker et al., 2019; Drewery et al., 2016; Gutierrez et al., 2016). Engaging in reflection early often encourages students to be aware of their goals and adjust accordingly if their goals and experiences are ever misaligned.

Teamwork is key to becoming a successful engineer. All the spine courses have group projects, with capstone being the closest adjacent to a real-world engineering team. Because team effectiveness is taught in a consistent and compounding way throughout the set of courses, students use those skills immediately in their classes and they are reinforced and built upon each year. Teams and group work are certainly present in other classes in the curriculum, and these skills are just as easily applied in those courses as they are in capstone design. The team effectiveness training considers the students' experience levels in engineering teams as well as how teams are being used in the course. For example, psychological safety is introduced in the first-year course. It is a foundational aspect of teams that enables the team members to feel like they are welcome and encouraged to contribute. For many students in the first-year course, working in groups may be one of their first experiences on an engineering team so it is important to establish psychological safety from the beginning. From psychological safety, teams can develop trust, which is an aspect to be further explored in the second-year course. It is important for students to be able to trust their teammates to contribute effectively, such as when handling separate aspects of a complex data analysis. In the third-year course, techniques for providing productive feedback and evaluations are presented. This is an important part of improving as a team but cannot be done without understanding how to build trust. We expect these experiences will lead to more inclusive teaming.

Problem-based learning is one of the dominant pedagogies implemented in the spine. Because of this, students see a strong emphasis on real-world problems relating to the School of CEE's four strategic cross-cutting research areas addressing the grand challenges of society, our environment, and our infrastructure. Their classes are less about testing abstract concepts and more about solving or tackling problems that they see as relevant. Beyond just being rooted in the real-world, many of the projects posed in the spine courses are "locally sourced." These are problem statements that students can step outside and interact with using their senses. Creating problems statements related to parks or public transportation is a great way to make those projects relatable, and this connects well for our students when constructed as a local project around the Atlanta Beltline or MARTA (the Metropolitan Atlanta Regional Transportation Authority).

One of the main outcomes of the curriculum innovation is creating holistic engineers, that is engineers who have developed cognitive (e.g., problem solving), interpersonal (e.g., teaming), and intrapersonal (e.g., reflection) skills (Georgia Institute of Technology, 2018). Through the spine of interactive courses, we expect CEE graduates to have honed their problem-solving/discovery and computational skills and developed their communication, teaming and reflection skills. The spine curriculum is aimed at developing students with a stronger self-concept as a civil engineer or an environmental engineer, which we expect will lead to enhanced sense of belonging to the profession and their majors. With team development comes more vulnerability, leading to the development of trust. We expect to observe CEE students coming to recognize the value of effective teams, appreciate their knowledge of how to build effective teams and leverage these in their classes and in the real world.

The other overarching outcome of this curriculum innovation is creating entrepreneurially-minded engineers, and we are using story-driven learning and value sensitive design to achieve this. In order to produce engineers that create value habitually, they first need to see themselves as value-creators (encouraged through story driven learning) and know what kind of value they want to create (assessed with value sensitive design). Curiosity is encouraged in the first-year course with the SDL reflections on how the students potentially see themselves engaging civil and environmental engineering challenges in the future. VSD and team effectiveness development encourage the students to explore multiple perspectives whether that be perspective within the team or different perspectives when approaching a project. The students make connections and gain insights while reflecting on their own teaming and learning experiences. Last, they are value creators when they actively strive to understand the values of stakeholders and design to optimize or enhance value and have a lasting impact while minimizing unintended consequences.

A current limitation is the gradual build-up of momentum that accompanies curricular change. Change cannot happen overnight or between semesters. At time of publication, only three of the four courses have been taught, with the second-year course is in development for fall 2022. Assessment across the entirety of the spine is not yet possible. For the time being, assessment of students is dependent on the specific changes that have been implemented. We anticipate doing an evaluation across the set of vertically-integrated courses after all four are established in the curriculum. Even still, we have seen some early signs of improved retention with a much smaller proportion of students changing majors in their first year – based on data from the first-year course (around 14% in 2020 and 2021 down from 25% in 2019).

Conclusion

Driven by the need to enhance a sense of belonging to the profession and the major, and opportunities to develop more holistic and value-adding engineers, the School of Civil and Environmental Engineering at the Georgia Institute of Technology embarked on a journey to introduce early engagement and expand vertically-integrated learning and teaching in the undergraduate curriculum. Through a spine of vertically-integrated interactive courses, CEE students are introduced to real-world experiences and problems addressed by CEEs in the areas of smart cities, sustainable systems, resilient infrastructure, and healthy communities starting in the first-year. In the first year, they engage in conceptual problem solving and preliminary data analysis, develop their team skills and apply story-driven learning to develop their self-concept as CEEs. Subsequent courses build upon these skills through story-driven learning, problem-based learning, value sensitive design and team development. Coupled with a mature embedded communications instruction within the curriculum, CEEs mature in their application of engineering and computational knowledge as well as skills to address real-world problems - as they develop their reflection and teaming skills and a nuanced understanding of stakeholder values. When they graduate, we expect them to begin their careers as holistic engineers and entrepreneurially-minded engineers – equipped to approach projects holistically and create value wherever they go.

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