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# Developing Engineering Formation Systems for Sustainability

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# DEVELOPING ENGINEERING FORMATION SYSTEMS FOR SUSTAINABILITY


**Abstract**

Engineering challenges are increasingly complex, mired in characteristics Horn and Weber have described as the "social mess" – little agreement on problem definition, multiple interconnected problems, consequences difficult to imagine, let alone characterize, and riddled with ideological, political, and cultural conflict. Climate change looms large as an example of a social mess that engineers will need new capacities to effectively confront.

The capacities engineers need include many attributes long discussed within the Liberal Education/Engineering and Society Division of ASEE and echoed in the NAE Engineer of 2020 report at the turn of this century: creativity, leadership, communication, lifelong learning, ethics, resiliency, and flexibility. There is increasing recognition that we additionally need to grow our capacity for holistic systems (or systems-of-systems) thinking, data-informed decision-making, transdisciplinarity and epistemic humility, critical understandings of power relations in organizations and society, and affective components of ethics, leadership and change agency, community-building, communications, and lifelong learning – all in addition to specific technological breakthroughs and enabling technologies to reconfigure essential sociotechnical systems.

As we seek to instill these capacities, we are also confronting an engineering education ecosystem mired with obstacles and inequities. We need to build infrastructure that equitably resources learning, cultivates interest, and ensures flexible access across lines of race, class, gender, ability, and other categories, smoothing transition points from two-year colleges, military service, work in the trades, and life events that too often prevent individuals from pursuing engineering.

In the specific context of a project focused on preparing an engineering workforce that can realize vehicle and roadway electrification and grid decarbonization for a sustainable transportation infrastructure, we developed a strategic agenda for instilling cross-disciplinary capacities and creating a smooth interconnected system of pathways through engineering.

This paper discusses the structural changes needed in our educational infrastructure and the curricular and pedagogical changes required for engineering formation to address sustainability challenges in the future. We identify areas for growth and a set of strategic actions in pre-college, undergraduate, graduate, and professional education to realize our vision for educating holistic and diverse engineers who are prepared to confront sustainability challenges.

## Introduction

At ASEE's 125th Anniversary Distinguished Panel in 2018, incoming ASEE President Stephanie Adams spoke to us of the "social mess" problems engineers and society face now and in the future[1]. Horn and Weber characterize social mess problems as complex, poorly defined and highly uncertain, riddled with ideology, disagreements about facts, and values conflicts.[2] Examples include global pandemics, Industry 4.0, climate change, and smart infrastructure. As a LEES reviewer helpfully pointed out, these messes are not purely "social" but rather co-constructed with technology. We offer here the revised term "sociotechnical messes," resisting false technology-society dualisms and recognizing the mutual shaping of messes that are simultaneously and complexly social, political, and technical.

Given this reality, what should engineering educators do to prepare the workforce of the future? How do we prepare engineers for a future in which their own jobs can be automated? How do engineers enter into values-laden conversations able to recognize, represent, uphold, and sustain core public and professional values including but not limited to health, safety, well-being, trust, quality, and integrity?

In order to prepare engineers (and other members of the future workforce), we need to foster not only systems thinking but also systems-of-systems thinking, where transdisciplinarity is central and where engineers are thinking critically about data, putting it all in the broader context of systems of power and how organizations play that power out in societal and global context. Engineers need to develop strategic understandings to be better able to navigate social and political environments in organizations. P.B. Shelley noted that "the great instrument of moral good is the imagination" (17); preparing engineers requires developing moral imagination so that engineers not only learn what engineering ethics principles are in the profession, but also develop the ability to think critically about those principles, and exercise empathy in proposing new ones.[3] When much of engineering technical analysis can be automated, this is the value added that engineers will need to be able to offer – thinking in sophisticated and deeply contextualized ways about technology.

One of the settings in which sophisticated and deeply contextualizing thinking about sociotechnical systems is sorely needed is the climate crisis. The authors of this paper are engaged in a daunting endeavor over the next decade: rising to meet global climate challenges by developing electrified infrastructure for US transportation, facilitating decarbonization of our interconnected electric power and transportation systems.[4] This effort, which is the work of the Advancing Sustainability through Powered Infrastructure for Roadway Electrification (ASPIRE) Engineering Research Center (ERC), requires convergence in engineering research[5] and transformation of multiple sectors and disciplines, including the nexus of systems that facilitate formation and development of a diverse engineering workforce.

Framing engineering workforce development as its own "sociotechnical mess" of highly interconnected systems provides new insights and a renewed urgency to broaden, work around, or get entirely outside of the existing narrow paths into and through engineering, in order to build a more diverse network of roadways and pathways to prepare people to contribute to the sustainable transformation of our education, economic, social, industrial, electric, and transportation systems.

## What Capacities do Engineers Need?

Our goal is to develop engineers with capacities in three overarching areas: transdisciplinarity; systems thinking; and professional skills. Transdisciplinarity is fundamental to addressing social (or sociotechnical) messes. Narrowly-trained engineers will not have the necessary expertise to tackle real problems that pay no heed to disciplinary boundaries. Engineers need exposure to a range of specialties within engineering, and as importantly, need social science knowledge that it not only complementary to, but also deeply integrated with, traditional engineering knowledge. Take climate change for example. Addressing climate change requires an understanding of technical issues *as well as* public policy and politics.[6] Today climate change is considered a highly partisan issue, but this simplistic take masks two important facts: one, that political elites were not always so polarized on the issue of climate change in particular and the environment generally, and two, despite the polarization at the elite level, there is substantial agreement among the mass public that global warming is due to human activity and that adaptation and mitigation measures should be taken to address global warming.[7] For example, 94% of Democrats, 72% of Independents, and 69% of Republicans believe that "human action has been at least partly causing global warming." Similarly, large majorities of Democrats (98%), Independents (79%) and Republicans (63%) agree that the government should do "at least a moderate amount to deal with global warming." Engineers armed with this type of social science knowledge will be better prepared to face the social mess of sustainable transportation.

A key component in forming transdisciplinary engineers is instilling epistemic humility[8] early on - the recognition that others may have different ways of knowing that are valid and valuable. This disposition needs to be supported early through formal and informal precollege learning and sustained in undergraduate curricula and beyond. Opportunities for boundary crossing - through a liberal education undergraduate structure with room for exploration of different ways of knowing, enhanced through working in cross-disciplinary teams, can scaffold the development of this ability.

We seek to instill a system of systems approach so that engineers are able to address not just complex or wicked problems, but the kinds of "sociotechnical messes" we will see increasingly as we move toward mid-century and beyond. A system of systems can be defined as a collection of systems where resources and capabilities are combined to obtain a more complex system that offers more functionality and performance that the sum of the constituent systems.[9] For example, transportation system, and electric power grid system easily qualify as systems of systems by this definition. Electrified transportation has to consider these two extremely complex systems of systems together, so engineering systems of systems is in the ASPIRE core.

We want to see engineers take responsibility for problem formulation in a flexible and adaptive way.[10] We know our future will be increasingly data-intensive and AI-integrated, where critical thinking, creativity, and design thinking will be needed more than ever. Sustainability and ecosystems thinking are essential for the particular transformations ASPIRE seeks for electrified transportation.

A decade ago, NSF and other communities made significant investments in research to define educational needs for sustainability generally and climate specifically – relying on expertise from members of the LEES division.[11] We seek to build on these innovations and drive forward with urgency to scale up these ideas to prepare a greater number of engineers for our common future.

Professional competencies are also foundational for engineers in the 21st century. From innovation and entrepreneurship to participatory leadership and mentoring, to ethics and empathy, to communication, intercultural competencies, and the ability to work in diverse teams, these skills form the backbone that supports engineering as a profession. Engineering education research has given us tools to measure and grow these capacities in students.[12]

Our approach embeds attention to diversity and culture of inclusion (DCI) into all these professional competencies. DCI is not treated as a separate endeavor; rather, it is woven into the very essence of professional training and engineering workforce development. One cannot develop capacities for leadership, communication, ethics, or teaming, for example, without being able to analyze difference, power, and privilege in organizations and interpersonal interactions, as well as take positive action to foster inclusion and interrupt unjust or inequitable dynamics.[13]

DCI considerations are also interwoven in the fabric of the technical research for ASPIRE; we cannot build accessible transportation infrastructure if we do not consider issues like equity and justice in access along multiple axes of diversity;[14] assessing benefits and risks for environmental health;[15] and enactment of inclusive and just participatory processes for infrastructure planning.[16]

## How do we develop an engineering workforce with these needed capacities?

We realize we are not the first, and surely will not be the last group of engineering educators to propose an ambitious integrative and holistic vision for engineering education and practice. We understand there are complex and enormous challenges involved in implementing our vision in perpetually inert and compacted engineering curricula. Developing an engineering workforce capable of addressing sustainability and myriad sociotechnical mess challenges requires changes not only to engineering curricula at all levels, but also to engineering pedagogy and, crucially, to the structure of engineering education itself. Each will be discussed below, beginning with structural changes to engineering education systems.

### *Structural Changes*

We view the engineering workforce development (EWD) space as a system of systems – or an ecosystem, if you will[17] –including K-12, informal learning spaces like museums, makerspaces, and libraries, 2-year and 4-year colleges, experiences in the military and the trades, and learning in the workforce. Too frequently these have been treated as isolated systems, held separate from one another and their broader socio-political contexts, so that the efforts in one area don't connect well to efforts in another.[18] With a unifying vision and a focus on leveling structural barriers between systems we hope to offer a new model for EWD efforts in ERCs, with greater potential for impact at scale. Engineering education research expertise from our four institutions undergirds our work as we implement the latest promising practices, and develop new ones. Further, we see ERCs as an under-utilized opportunity for longitudinal research in both EWD and DCI. This ability to trace individuals and patterns over time is an invaluable knowledge resource, especially as we seek to develop an infrastructure of roadways and pathways for EWD.

Figure 1 shows an impressionistic schematic of what we envision: an interconnected system of systems where the same individual who participates in an informal summer camp or other outreach activity has access to further learning through formal K-12 experiences, 2 and/or 4-year undergraduate degrees, Trades, graduate degrees and professional workforce learning opportunities... with seamless transitions among them. These are pathways - not pipelines, which may leak with no recovery[19]... and we hope that through our efforts some pathways become roadways, smoothly traversed with multiple lanes for changing emphasis and destination. Despite decades of investments and activity in this space, there remains much more to do in order to create smoother transitions.[20] We are hoping that our 10-year project provides a unique opportunity to work across levels and modes of education. By taking the big picture into account over a longer time scale, we hope to transform not just the pathways themselves, but also how we as a nation think about and value engineering workforce development.

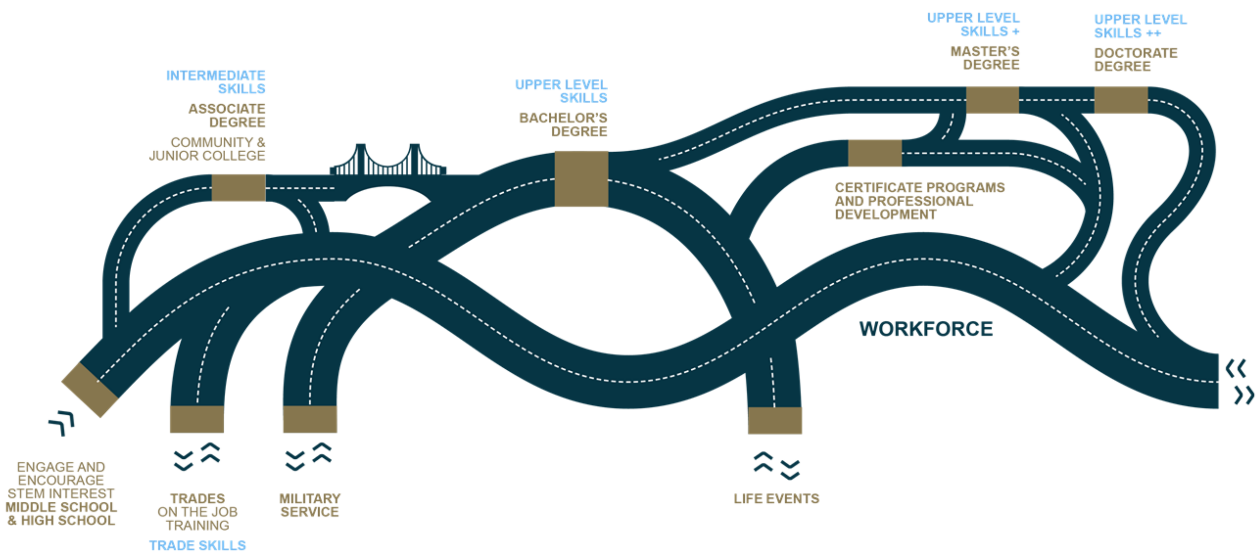


**Figure 1:** Pathways and Roadways. We envision a connected system of systems with robust access to learning through formal and informal pre-college experiences, 2 and 4-year undergraduate degrees, trades, graduate degrees and professional workforce learning opportunities… with seamless transitions among them. (Image Credit: Jeremy Nixon, Graphic Designer, Utah State University)

As precollege education has grown more unequal, our undergraduate institutions have persisted in using biased and exclusionary measures of merit for admission; despite our pretense toward a “level playing field” the emphasis on standardized tests and Advanced Placement have imposed gateways that disadvantage or exclude outright students in under-resourced settings, who are more frequently Black, Indigenous, or other People of Color (BIPOC), more frequently poor, and more frequently first in their families to attend college.[21] Students seeking to enter four-year institutions through a two-year college pathway or through military service find additional barriers in how previous work is credited or recognized, and how the transition to the new campus is facilitated and supported.[22]

To broaden participation and engage underrepresented groups in EWD, our pre-college strategy focuses on developing curriculum, competency and inclusive pathways that leverage teacher networks, school guaranteed admission agreements, and informal education partnerships along with creating high-quality curricula, scalable teacher professional development models, and viable access pathways for students to engineering.

Our professional development centers on empowering K-12 teachers as partners in EWD by increasing opportunities for building teacher capacity in engineering education.[23] Each teacher reaches hundreds if not thousands of students over the course of their career. However, very few are trained to teach engineering content, design or habits of mind, creating a large need for access to high-quality, Next Generation Science Standards (NGSS)-aligned engineering curriculum and the accompanying professional development (PD) coaching. Most K-12 teachers have no experience teaching engineering concepts or design. Getting comfortable with design and computational thinking takes practice, and our goal is to increase educators' confidence and ability, and in turn grow students' interest and identity in engineering. To offer teachers affordable and accessible training, we propose to develop a scalable blended model for teacher professional development that can be implemented at any regional college or school district. Starting with ASPIRE-themed local in-person/virtual professional development (PD) workshops, we will then scale up via a blended PD model in partnership with professional educator networks to increase teacher capacity nationally and globally.

In order to meet the challenges posed by changing climate over the next decade, it is also imperative that we reach current engineering practitioners in the workforce, and work with trades organizations to transition employment to the data-rich context of smart infrastructure, constructing new pathways to and through engineering, and broadening the space of what engineering disciplines and careers can be and do in the world. This structural change can reinvigorate higher education and forge new connections and collaborations among high school technology programs or vocational high schools, two-year colleges, and four-year institutions.

### *Curricular and Pedagogical Changes*

These structural changes establishing inclusive infrastructure pathways for EWD and DCI undergird an integrated plan to develop and deploy inclusive engineering curricula and participatory learning pedagogies over the next decade (Figure 2).

Pre-college curriculum development is at the start of EWD and our pedagogical approach will integrate the engineering design process,[24] design thinking skills,[25] and engineering habits of mind,[26] which have proven effective as engineering is taught as an integrated part of math, science, and literacy in K-12. With the adoption of NGSS, or adapted state standards, 1.9 million elementary and 600,000 secondary STEM teachers are faced with the challenge of integrating engineering and design thinking into their curriculum. We will develop hands-on module lessons integrating ASPIRE topics, including sustainability, transportation systems, and electric infrastructure, that incorporate NGSS[27] and DCI content to ensure diversity and inclusivity. These modules will be co-designed with K-12 educators and ASPIRE researchers, expert reviewed, classroom tested, revised, then curated and broadly disseminated via the TeachEngineering Digital Library, which has 3.5M unique educator users/year.

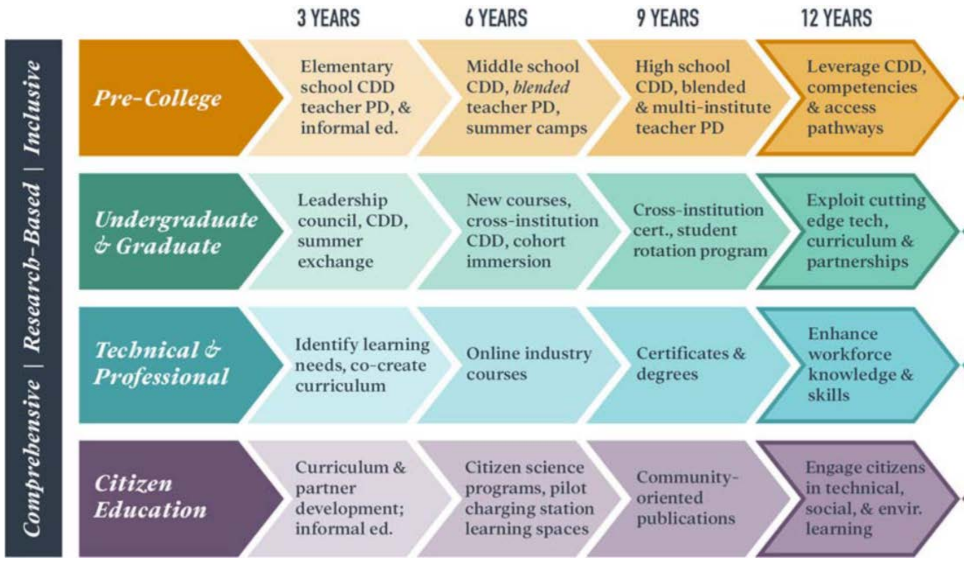


**Figure 2:** Our integrated EWD and DCI plan builds inclusive infrastructure pathways through curricula development and participatory learning strategies; CDD = curriculum development and dissemination, PD = professional development. (Image Credit: Jeremy Nixon, Graphic Designer, Utah State University)

Informal instructional activities in partnership with local makerspaces and science museums, for example, will also be developed from formal lesson modules. Viewing this through our lens of pathways and roadways, we will ensure that our pre-college after-school, weekend workshop, and summer camp programming is informed by ASPIRE expertise and in age-appropriate engineering learning; and strategically placed in order to connect students with pathways into engineering. We will leverage or improve structural mechanisms like guaranteed admission agreements and state support for access to higher education. Students targeting trades in high school will be connected to the university and remain in contact through our trade and industry partners, for potential use of pathways to college later.

We have taken an inventory of our undergraduate and graduate curriculum through instructor self-reports. Reviewing 53 courses from 7 institutions involved in our ERC, most courses focusing on center-related topics were upper-division or graduate level courses. 28 focused on materials in one research area alone, indicating a need to develop more cross-cutting or convergent courses. 9 courses were reported by their instructors to address capacities in transdisicplinarity, systems-of-systems approaches, and professional skills, while 10 courses cover two of those three areas, and 8 covered one. None indicated that they include diversity and culture of inclusion as part of the curriculum, which is clearly a curricular gap.

All institutions have strong course sharing capabilities, suggesting that developing an offering at one institution can potentially benefit others. We have begun by developing a course that introduces cross-cutting center themes in a convergent fashion, where all three capacities and DCI components are addressed.

Our undergraduate and graduate curriculum development will include smaller scale micro-enhancements and modules, as well as new courses in ASPIRE research areas: power, transportation, data, and adoption. Curriculum enhancements will be rolled out to our partners and at disciplinary and engineering education conferences via faculty development workshops. At the same time, we will focus on relationships at the heart of engineering formation. With structured near-peer mentoring, cohort immersion experiences across role and position, leadership training, and student rotation across campuses. Through these experiences and their day-to-day learning and research in the ERC, we believe students will be embodied conduits of the convergence we seek to create, moving between campuses and disciplines, noting systems interdependencies and busting silos where they see them. They are key accountability partners in this effort.

When we consider our pathways infrastructure, we see a need to enhance accessibility at transition points. Our institutions all have articulation agreements with community colleges, but further enhancements are needed to make these transitions smoother from a student success perspective. We need a holistic look at both the academic logistics and the cultural experience of the transition to the new campus. Transitions to graduate school and to career are smoothed by REUs, internships, and other ASPIRE activities, again with attention to how we can improve these experiences for students.

We are engaging novel opportunities develop porous boundaries between the trades and engineering degree programs, including developing a system for granting credit for experiential learning in the workforce. We are working now to engage stakeholder in defining needs and goals with the hope of developing partnerships in both electric power and transportation construction trades, using the trusted infrastructure provided through existing trades organizations, unions, community colleges, and vocational high school programs. Building infrastructure for electrified transportation can revitalize these trades as cutting-edge enterprises and ignite interest in engineering careers.

Instilling diversity and culture of inclusion in students at all levels will rely on psychological research on reducing prejudice that shows that intergroup contact is the most effective way to transform bias into positive relationship,[28] and sociological research that reminds us to take power into account in shaping organizations that support a culture of inclusivity.[29] We will draw on the learning sciences in designing effective, student-centered experiences for students of all ages, and use families of culturally relevant[30] and critical pedagogies[31] to cultivate success for students from a range of backgrounds. As we approach longitudinal research opportunities, we will employ multi-method approaches that blend qualitative studies of culture through ethnographic observation, interviews, and focus groups with quantitative measures of paths traveled and student development of core competencies.

**What does success look like and how can we measure it?**

Success for us would be: a seamless educational infrastructure where everyone finds a pathway where the assets they bring and the experience they hold are valued and integrated into the engineering education landscape. Engineers see professional skills and transdisciplinarity AS engineering. It's just what they do, who they are, how they see the world. Diversity and a culture of inclusion are not separate from this but part and parcel of it. Engineers are literally saving people and the planet because of unique abilities in problem formulation –they see the whole picture and know how and where to act effectively.

We have developed a logic model envisioning key impacts we wish to see after a decade, and mapping these in a reverse design fashion to identify key resources needed as inputs; specific activities that generate desired outputs leading to a set of short-term and long-term outcomes that ultimately achieve our overarching impacts. The outputs and outcomes are all required to be SMART (Specific, Measurable, Achievable, Realistic and Time-based). Performance indicators or metrics are mapped to these outputs and outcomes to define what and how it will be measured. This logic model serves as our guide in designing action plans from year to year and is an important artifact in our continuous improvement cycle for assessing and evaluating progress toward impact.

The overarching impacts we seek to achieve are:
1) A diverse workforce ready to face electrified transportation challenges, aligned with industry needs (competencies as described above) and a self-sustaining culture of diversity and inclusion.
2) A diverse workforce prepared for societal impact, with abilities in social justice, public policy, leadership, and ethics.
3) Widespread adoption of curriculum and pedagogy for sustainability, and a broadly STEM-literate, climate-literate, and energy-literate populace starting at a young age.

A description of one branch of the EWD and DCI logic model is included as an example. A defined input are the human resources of students, faculty and project directors. This input is linked to many activities, one in particular is establishing pathways that can recruit and retain diverse students. The activity of establishing pathways is connected to multiple outputs, one such output is the establishment of peer-mentoring programs among the partner institutions. This output is linked to the short-term outcome of improved retention and support for underrepresented minorities within educational institutions and workplaces which influences the broad impact of creating a diverse workforce ready to face electrified transportation challenges, aligned with industry needs and a self-sustaining culture of diversity and inclusion. While this is just one of dozens of branches through our logic model, this shows how inputs, activities, outputs, outcomes and impacts can be linked.

Our continuous improvement process is still at its inception, but we are brainstorming possible metrics. First, there are things we can count -The number of people impacted by activities like teacher development or DCI training. We can use google analytics to learn more about who uses our curriculum. We can count the number of ASPIRE students involved in K-12, informal education, and community engagement. We are familiar with a number of validated scales we might use to measure the competencies we are hoping to instill, like intercultural competencies, critical thinking, innovation, or technological literacy. Some items might be better measured in a more open-ended, qualitative way, for example transdisciplinarity, or impacts of community interaction.

We will need some indicators of smoothness for EWD pathways and roadways. All of our campuses participate in the MIDFIELD database, which is a powerful quantitative tool to explore the movement of our students, times to degree, retention, and other key variables. We can examine the impact of our articulation agreements, guaranteed admission, and state support mechanisms, and the effects of changes in those over time. These measures will guide formative adjustments, and help to strategically propagate successful approaches in the wider EWD ecosystem.

## Conclusion

By attending equally to (1) the structural issues in engineering formation that impede the development of a diverse workforce, (2) the curricular issues that silo disciplines, over-focus on specific and narrow technical aspects of engineering, and inhibit convergent research, transdisciplinarity, understanding power relations, and systems perspectives necessary to advance sustainability and climate justice, and (3) the pedagogical strategies that resist injustice, inspire lifelong learners, and foster empathy and reflexivity, we will develop an engineering workforce prepared to respond to the climate crisis with sustainable systems to meet our energy and transportation needs. We intend to build an engineering education infrastructure that equitably resources learning, cultivates interest, and ensures flexible access across lines of race, ethnicity class, gender, ability, and other categories, smoothing transition points from two-year colleges, military service, work in the trades, and life events that too often prevent individuals from pursuing engineering.

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