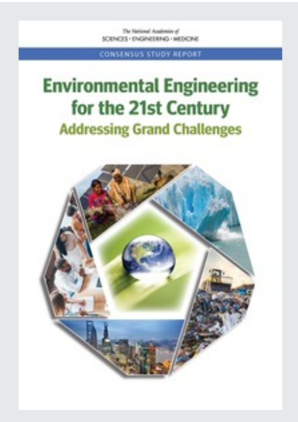

Environmental Engineering for the 21st Century: Addressing Grand Challenges (2019)

DETAILS

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farmers to protect the watershed and compensating them for their efforts, along with more modest treatment, would be the most cost-effective approach to meet the water quality objectives while providing additional watershed benefits. Developing and implementing this approach required effective engagement of all stakeholders and ultimately reduced costs.

Solving global challenges cannot be done by environmental engineers alone. Today's environmental engineers work within complex, interconnected systems, often in the context of competing demands from agriculture, industry, people, and ecosystems. Environmental engineers need to work collaboratively with interdisciplinary partners and engage the public in the development of solutions. In most cases, there is no single answer that works for all communities, and solutions may need to be adapted over time. Environmental engineers need to examine the challenges and the alternative solutions using community input and considering short- and long-term consequences across local, regional, and global scales. In this role, the profession can provide a broad systems perspective for the disciplines and communities that are building the future so that they can more effectively achieve success. An engineering profession that represents the diversity of society at large will ensure that varied perspectives are understood and that the field draws upon the full potential of talent available.

> To effectively address the changes ahead, environmental engineering practitioners should work collaboratively with stakeholders and other disciplines to analyze, design, and implement practical, systems-based solutions. To support these efforts, the environmental engineering field should cultivate a more diverse workforce, focusing especially on increasing the racial and ethnic diversity of the pipeline.

Examples of steps that environmental engineers can take to transition to more collaborative and systems-based practices include the following:

1. Enhance stakeholder engagement by seeking diverse sources of information and community input.
2. Make use of available tools to incorporate full-cost life-cycle analysis and other sustainability tools to help stakeholders and decision makers understand the potential consequences of decision alternatives.
3. Build new tools to understand and predict adaptive and emergent behaviors of complex systems.
4. Implement evidence-based tools to recruit underrepresented minorities and women into the field beginning at the K-12 level and extending through graduate training.

Environmental Engineering Education

Although there are multiple models for educating and training environmental engineers, the 4-year undergraduate engineering program has traditionally served as the foundation for environmental engineering and is typically the minimum education required for practice. Most undergraduate environmental engineering programs today initially emphasize fundamental knowledge in the basic and applied sciences, mathematics, and engineering. This foundation is usually followed by more advanced courses focused on fate, transport, and treatment of contaminants in air, land, or water, and additional topics such as environmental health or the impacts of pollutants on ecosystems. Finally, through advanced courses or capstone projects, students explore subspecialties of the field and hone the skills that they will ultimately use in professional practice.[291] Many of these undergraduate students continue their environmental engineering education in graduate school to receive additional training and specialization. Because of the complex multidisciplinary nature of the field, environmental engineering has among the highest percentage of engineering practitioners with graduate degrees (50 percent based on 2014 data).[292]

Meeting tomorrow's more complex, integrated, global, and nuanced challenges will call for additional knowledge and skills beyond what today's environmental engineering curriculum provides. Educational institutions need to work with thought leaders from academic and practitioner communities and beyond to strengthen the education of tomorrow's environmental engineers, enhancing the curriculum and building essential skills.

Enhancing the Curriculum

To address society's environmental challenges, environmental engineers will need to have strength in their area of expertise but also have sufficient breadth to appreciate the broader societal context and devise effective solutions (Figure 6-2). For example, they will need to appreciate the social and behavioral components of the challenges they are trying to solve; even an efficient and effective technological

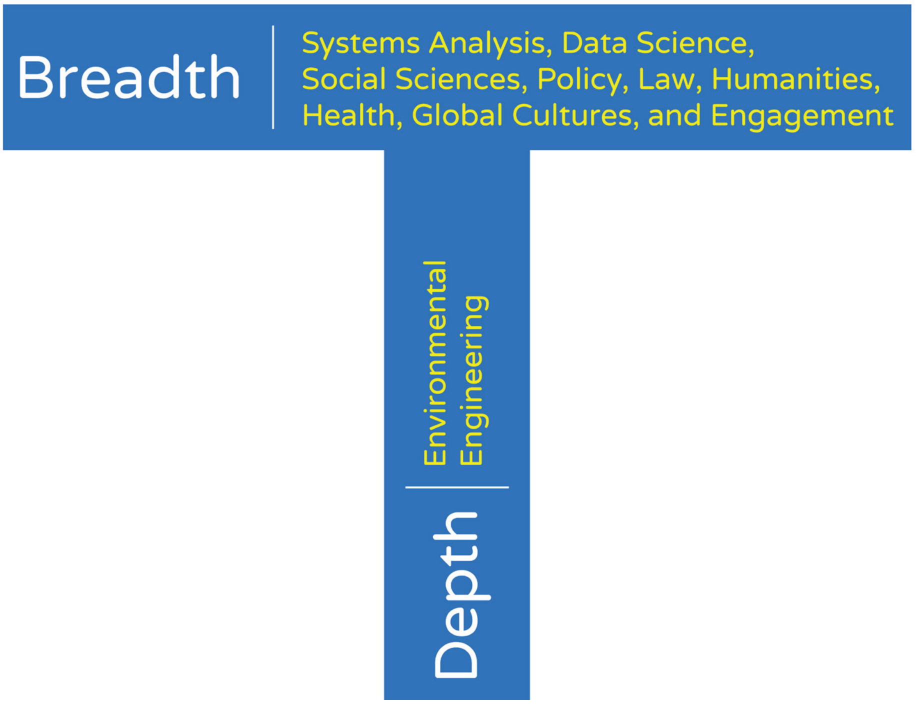

FIGURE 6-2. A T-shaped environmental engineer brings engineering depth with breadth in topics such as social science and policy that are essential to understanding and developing effective solutions for today's complex challenges.

solution cannot realize its full potential without consideration of societal, cultural, economic, legal, and political issues (see Challenge 5). To anticipate potential outcomes and avoid unintended consequences, environmental engineers will also need to understand the nonlinear and dynamic forces in many natural and human systems and the feedbacks that these forces can create.

Students also need opportunities for in-depth education in the scientific subspecialties that are most relevant to the future challenges. While environmental engineering programs provide a robust foundation in water and contaminants (in keeping with the historic focus of the field), topics such as climate, air pollution, and energy are sparsely covered in most current university curricula, leading to knowledge gaps between what our education system provides and the challenges future environmental engineers will face. Furthermore, most current environmental engineering curricula lack sufficient training in data science, which is emerging as a key strategy in 21st century solutions.

> To complement and build on the traditional emphasis on applied science, mathematics, and engineering, environmental engineering education programs should strengthen foundational knowledge in two areas: complex system dynamics and the social and behavioral dimensions of environmental challenges. In addition, programs should ensure that the scientific content of their curricula keeps pace with current and anticipated global challenges and the most promising tools for developing solutions.

Examples of steps that can be taken to enhance the foundational content of environmental engineering programs include the following:

- Cultivate rigorous systems thinking by integrating training in complex systems, data science, and decision analysis into the environmental engineering curriculum.
- Engage with colleagues in the social sciences to develop learning opportunities relevant to understanding the social, cultural, economic, legal, policy, and political contexts of environmental engineering challenges.

- Strengthen scientific curricula and subspecialty offerings for topics relevant to the full spectrum of current and anticipated challenges, such as climate, energy, and air pollution, in addition to more traditional areas of focus.

Building Essential Skills

In addition to these new areas of foundational knowledge, tomorrow's environmental engineers will require new types of skills, capabilities, and perspectives. Finding solutions that are feasible within the broader context also requires engaging decision makers and the public, and working collaboratively with experts in other disciplines. To complement the traditional focus on problem-solving skills, environmental engineering programs should educate students to communicate well and work collaboratively in interdisciplinary multicultural teams. In practice, it is rare for a single engineering solution to engender unanimous support. Environmental engineers must therefore learn to think creatively and critically, balance competing needs and priorities, forge compromises, and communicate persuasively. These capabilities are enhanced by an understanding of how people and communities make decisions, especially in the context of uncertainty, as well as a sense of empathy and social conscience.

> Environmental engineering education should equip graduates with the skills to communicate effectively, work collaboratively, think critically, and forge compromises.

Examples of steps educators can take to equip trainees with these skills include the following:

- Teach communication skills such as analyzing a communication situation, assessing the communication capacity and needs of target audiences, establishing goals and objectives, and formulating strategies.
- Develop partnerships with practitioners and community leaders to develop student learning experiences that involve real-world projects that are solved with creativity, stakeholder engagement, consensus building, and compromise.
- Provide opportunities for aspiring environmental engineers to directly experience community decision-making processes.
- Incorporate culturally relevant and diverse approaches to educational experiences, including activities that challenge students to develop solutions specific to socioeconomically disadvantaged and underserved communities.
- Create opportunities to explore the ethical and social dimensions of environmental engineering challenges.
- Offer educational experiences in negotiation, compromise, and conflict resolution.

Approaches to Engineering Education Reform

Solving the grand challenges in environmental engineering demands a broader approach to education. Interdisciplinary, experiential learning equips students to consider how myriad factors such as budget constraints, historical context, public acceptance, and regulatory frameworks affect the design and implementation of technological solutions to societal challenges. A new model for environmental engineering education is needed to support the development of more innovative, creative, and effective problem solvers.

There is already movement in this direction. Several universities have instituted engineering leadership initiatives and developed educational models that broaden the undergraduate engineering experience.[293] The National Academy of Engineering also has led several efforts to advance undergraduate engineering education through its work with the Engineer of 2020 Project[294] and the Grand Challenge Scholars Program.[295] These initiatives illustrate how existing engineering programs can be enhanced without necessarily adding new coursework. For example, the Grand Challenges Scholars program involves training on five basic components—research/creative, multidisciplinary, business/entrepreneurship, multicultural, and social consciousness—that can be layered upon or crafted within existing degree requirements. By encouraging universities to adopt project- or service-based learning models to provide students with experience designing solutions in the context of real-world complexities, the Grand Challenge Scholars Program engenders a broader educational experience without fundamentally disrupting existing programs. This type of program could extend to significant global experiences with the goal of creating more effective and engaged environmental engineers.

There are limits to how much can be included in a 4-year undergraduate program. New subspecialties related to the grand challenges may need to be introduced at the undergraduate level but fully delivered through graduate programs. Engineering education can also be enhanced through other opportunities for formal and informal education. Continuing education that develops specialized knowledge and skills for practicing engineers is particularly important. Extracurricular activities involving experiential learning, such as student projects, study abroad, internships, independent research, student professional societies, and community involvement programs would benefit undergraduate and graduate programs.

Engineering programs are outliers in professional education in that they conflate the necessary preparation for practice with a general college education. Other

professions have abandoned this approach, transitioning their degree requirements to graduate programs to accommodate the needs of an increasingly demanding and specialized profession while enabling a comprehensive pre-professional college education. Physical therapy, pharmacy, and nursing are examples.[296] To cultivate a professional workforce with the breadth and depth necessary to address grand challenges, greater emphasis on graduate education in environmental engineering may be needed. By shifting specialization out of the undergraduate experience, this approach would also open opportunities for those with an undergraduate degree in engineering to pursue further education in other fields, such as law, policy, education, and economics, thus bringing a rich engineering background to those fields and enhancing opportunities for interdisciplinary collaboration. However, such an approach could have an undesired result of further reducing the percentage of underrepresented minorities in the field. If greater emphasis is placed on graduate programs to educate the environmental engineers of the future, targeted programs may be needed to recruit underrepresented groups into environmental engineering graduate programs.

> College and university programs should evaluate their undergraduate and graduate degree requirements and other educational opportunities to ensure that environmental engineers can receive sufficient training to address the grand challenges. Several approaches are available to broaden and strengthen the undergraduate environmental engineering education, but these changes may necessitate a greater reliance on graduate education for specialization.

Among the engineering disciplines, environmental engineering is well positioned to lead the charge toward a broader, more holistic approach to education. Examples of steps that educational institutions can take include:

- Restructure programs with greater reliance on graduate school for specialized training to allow undergraduates more room to explore topics such as the social and behavioral dimensions of environmental challenges, complex systems dynamics, data science, and real-world problem solving and to build the skills needed to develop solutions to complex interdisciplinary challenges. Such a change would likely require concurrent efforts to recruit and retain underrepresented minorities.
- Use practice- or service-based learning models to encourage experiential learning and enhance the undergraduate experience.
- Incorporate the Grand Challenge Scholars Program into undergraduate education.

Environmental Engineering Research

Research will continue to play a central role in propelling the technological innovations and the approaches needed to address society's grand challenges. Environmental engineering research is carried out in a variety of settings. Universities are perhaps the most visible contributors (and the primary backdrop for the analysis and vision outlined in this section), but national laboratories, government agencies, private corporations, nonprofit organizations, and international organizations and collaborations are also vital hubs for research and innovation.

The purpose of research in engineering is to increase the body of knowledge and discover better ways to solve problems. Underlying these overarching goals, there are two key factors that influence what types of research questions are pursued,

how research is carried out, and how the results are translated into practice. The first driver relates to employment structures for researchers. The second relates to research funding. While employment and funding structures vary across sectors, generally speaking, most researchers start by acquiring specialized foundational knowledge and research experience through formal education, obtain a research position within their subdiscipline, and then advance their career by independently spearheading projects, securing research funding, and publishing findings. In the United States, research funding, by and large, flows from the federal government into universities and other research organizations; however, many private companies also perform research.

Although these structures have produced significant gains, there is a growing awareness of ways in which the research enterprise falls short,[297] thus limiting engineering research—and consequently, engineering practice—from reaching its full potential. One of the most significant and pressing challenges in both research and practice is the need for effective interdisciplinary collaboration. Solving the grand challenges of the future will require advances within traditional environmental engineering disciplines but also engagement across the engineering disciplines, natural sciences, social sciences, and humanities. Environmental engineers today routinely collaborate with other engineering and science disciplines, but genuine collaboration with the social sciences is essential to developing effective solutions to 21st century challenges (see Challenge 5). Interdisciplinary research integrates information, perspectives, and techniques from multiple disciplines to address problems that cannot be fully addressed within a single discipline.[298]

Incentivizing Interdisciplinary Research

Successful interdisciplinary collaboration requires a cultural transition to embrace new areas of expertise and new ways of thinking, reinforced by incentives that provide tangible rewards for interdisciplinary work from the scale of the individual to the scale of the institution. This transition has been under way for approximately two decades,[299] but barriers remain.[300] Many university early career scholars are counseled to avoid interdisciplinary and team-based research based on the rationale that researchers should demonstrate strength within their discipline before engaging outside their discipline. This is reinforced by employment structures (particularly in universities) in which research positions are allocated to departments organized around a traditional discipline; researchers earn recognition and promotions by prioritizing independent scholarship in that discipline. Winning sole-investigator research grants and publishing with their students (rather than colleagues) in disciplinary journals is a far surer way to earn tenure and promotions than participating in large collaborations, for which papers take a long time to publish and have author lists comprising numerous investigators. These factors combine to make interdisciplinary research a liability for some early career scholars, despite the recent growth in funding, job opportunities, and, most importantly, the potential for substantial impact from such collaborations.

> Despite recent progress, when evaluating accomplishments many universities continue to prioritize disciplinary endeavors at the expense of interdisciplinary collaboration. To facilitate the collaboration necessary to meet future challenges, research employment structures should evolve to value and incentivize interdisciplinary work.

Examples of actions that research institutions can take to incentivize interdisciplinary collaboration include the following:

- Develop recruiting, promotion, and reward processes that reflect the interdisciplinary nature of environmental engineering, including valuing impact associated with coauthorship and publication in nontraditional interdisciplinary journals.[301]
- Enhance interdisciplinary mentoring to support the development and impact of early career scholars in nontraditional academic units and careers.

Interdisciplinary Research Support

Research support is a key factor for building and sustaining research programs and developing the next generation of scholars. Some of the primary agencies supporting research in the United States, including the National Science Foundation (NSF), still rely on disciplinary structures to organize their research agendas. However, crosscutting funding support for interdisciplinary scholarship has improved in recent years, stimulating a new generation of innovative research. Examples include NSF programs in Smart and Connected Communities, Innovations in Food, Energy and Water Systems, Dynamics of Coupled Natural and Human Systems, and Water Sustainability and Climate—programs that overlap substantially with the challenges presented in this report. Research support for early career scholars, such as the NSF Faculty Early Career Development Program (CAREER) and the Graduate Research Fellowship Program, remain primarily discipline based. Opportunities such as these can dramatically shape the long-term trajectory of a scholar.

Research teams supported by interdisciplinary initiatives often include engineers, social scientists, economists, and other experts. Success of these teams is contingent on genuine integration across disciplines. This requires more than placing experts from different disciplines into a room and adding interdisciplinary

verbiage to a proposal. Addressing today's interdisciplinary challenges requires investigators to invest time to build connections with others outside of their discipline, and universities need to value and reward this investment of time and effort. Although seed funding can incentivize new collaborations and reduce the barriers to launching new interdisciplinary projects, some of the most successful interdisciplinary collaborations are those that develop organically from groups of researchers inspired to address a common problem. For example, forums that bring interdisciplinary scholars together to discuss and present research can catalyze discussion and launch new collaborations. Though effective, these types of interactions are not yet commonplace. Interdisciplinary institutes can be well-suited for engaging diverse scholars around a common theme, provided that the institute itself does not become a silo.

> Interdisciplinary collaborations require meaningful interactions and genuine integration across disciplines. Funding organizations and research institutions can facilitate effective collaboration through well-designed grant programs and by fostering environments where relationships and collaborations can develop organically.

Examples of steps that research agencies, organizations, and corporations can take to foster interdisciplinary collaboration include the following:

- Craft opportunities for research support for early career scholars geared toward crosscutting and interdisciplinary themes.
- Prioritize expansion of interdisciplinary research support, even at the expense of disciplinary support, and incorporate proposal evaluation techniques that reward research teams and proposals that ensure genuine collaboration among scholars.[302]
- Develop NSF Engineering Research Centers focused around grand challenges, as recommended in the 2017 National Academies report, *A New Vision for Center-Based Engineering Research*.[303]

- Support workshops and other forums that stimulate interdisciplinary engagement and discussion around the grand challenges in environmental engineering.
- Embrace interdisciplinary research structures and programs that bring together researchers with different disciplinary expertise but common interests around specific challenges or themes.[304]

Industry and Community Engagement

The impact of interdisciplinary research is realized when new knowledge created by interdisciplinary teams is put into practice in industry and communities. Prototype applications at field scale provide opportunities to validate and refine new knowledge gained through scholarly research, and they provide a gateway for translation for societal benefit. These interactions also provide faculty with opportunities to understand the practical and fundamental issues that challenge engineering practice. Many university scholars have limited experience in translating research knowledge to applications at field scale. University promotion and reward programs often do not acknowledge the significance of these efforts, despite their importance. Several programs provide opportunities for both basic and translational research engaging academics and industrial partners in teams that solve real-world problems, including the Clinical and Translational Science Awards Program at the National Institutes of Health and NSF's Grant Opportunities for Academic Liaisons with Industry and Partnerships for Innovation programs. Examples of steps that research agencies, organizations, and corporations can take to enhance the translation of research to practice include the following:

- Develop additional opportunities for translating interdisciplinary research into practice through collaborative partnerships between industry, academia, and communities.
- Develop promotion and reward systems at universities to incentivize faculty engagement in translating environmental engineering research findings into practice, with emphasis on research products and technologies that have a demonstrated positive impact on society.

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