Winter 2021

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The Bridge (ISSN 0737-6278) is published quarterly by the National Academy of Engineering, 500 Fifth Street NW, Washington, DC 20001. Periodicals postage paid at Washington, DC.

Vol. 51, No. 4, Winter 2021

Postmaster: Send address changes to *The Bridge*, 500 Fifth Street NW, Washington, DC 20001.

Changes of address or requests to unsubscribe should be sent to PGibbs@nae.edu.

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The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

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The BRIDGE

Volume 51, Number 4 • Winter 2021

LINKING ENGINEERING AND SOCIETY

News and Notes

President's Perspective

Climate Change: A Defining Challenge for Science, Engineering, and Medicine

Amanda C. Staudt and John L. Anderson

Amanda Staudt is senior director of the Board on Atmospheric Sciences and Climate (BASC) and Polar Research Board (PRB), National Academies of Sciences, Engineering, and Medicine. John Anderson (NAE) is president of the National Academy of Engineering.

Nations gathered at the COP26 meeting in Glasgow (https://ukcop26.org) last month to grapple with the devastating global impacts of climate change. How we minimize the impacts going forward and how we adapt to the changes in ways equitable to all humans and other living things that share this planet are the defining questions of our time.

Tackling climate change requires leveraging the science and engineering enterprises broadly—in academia, government, private industry, and civil society—to identify and develop solutions that draw from diverse expertise and address needs across all sectors. This requires a convergence of knowledge across the breadth of physical and social sciences, engineering and technology, and health and medicine. The National Academies of Sciences, Engineering, and Medicine are taking steps to launch a new climate center in order to draw on leaders from all these areas to address the climate crisis.

The National Academies have a rich history of studies on climate change, dating back to the 1970s. The 1979 report *Carbon Dioxide and Climate: A Scientific Assessment*[1] includes some of the first estimates of how much warming could be expected from a doubling of carbon dioxide in the atmosphere. This short document served as a touchstone for early research and political action to address climate change.

In the decades since, other National Academies reports have helped to establish climate change as a national issue, resolved long-standing questions about the science, defined the urgency of understanding the short- and long-term impacts of climate change, and charted ways to prepare for and respond to climate change. This work has been requested and used by elected leaders across the political spectrum, has shaped US and international investments in research, and is increasingly being used by industry to make difficult business decisions and guide research and development to innovate solutions.

Most recently, the 2021 National Academies report *Accelerating Decarbonization of the US Energy System*[2] is an example of the interdisciplinary expertise that can and must be brought to bear on climate change issues. The report identifies both technology goals, such as carbon-free electricity and new transmission infrastructure, and socioeconomic goals related to jobs, equity, and inclusion, as well as potential impacts on communities and businesses—all of which must be considered in tandem to make needed progress. A summary of relevant National Academies studies and other activities is available online (https://nationalacademies.org/climate).

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1 https://www.nap.edu/catalog/12181/carbon-dioxide-and-climate-a-scientific-assessment

2 https://www.nap.edu/catalog/25932/accelerating-decarbonization-of-the-us-energy-system

The unprecedented global challenges now posed by climate change require new approaches commensurate with the scale, scope, and complexity of the problems. To meet these challenges, the National Academies' new climate center will convene the best minds from all technical sectors to explore numerous relevant dimensions of climate change and provide independent, evidence-based guidance to all levels of society. The center will encourage and enable transdisciplinary studies and activities, quickly marshal the energy and intellect of critical thinkers as needs arise, and support sustained engagement with decision makers from local to international scales. It will also create a platform to move our advice into action by all sectors of society.

As the consequences of climate change continue to become more apparent, the nation and the world will face new challenges that require innovative responses on a more rapid time scale. Because climate and our planet with all its living things are very complex systems of systems, responding to climate change will require weighing trade-offs, some with significant social and political implications. Trusted technical analysis will be essential input to these decisions. The new climate center will enable the National Academies to continue to be the go-to place for trusted technical assessments and recommendations for action to mitigate and adapt to climate change. You will hear more about the center as plans develop.

Guest Editors' Note

The US Frontiers of Engineering Symposia Forge Ahead

Jennifer L. West and Timothy C. Lieuwen

Jennifer West (NAE) is dean of engineering and applied sciences at the University of Virginia. Timothy Lieuwen (NAE) is Regents' Professor and David S. Lewis Jr. Chair in the School of Aerospace Engineering at the Georgia Institute of Technology.

The NAE typically dedicates the winter issue of *The Bridge* to papers from the annual US Frontiers of Engineering symposium, held in September each year (because of the covid-19 pandemic, the 2020 US FOE was rescheduled to February 25–26, 2021). We are delighted to be part of this issue, which presents a selection of papers from the 2020 and 2021 US FOE meetings that we chaired—Jennifer in 2020 and Tim in 2021.

The Frontiers of Engineering symposia bring together a diverse group of highly accomplished, early-career engineers who represent the best and brightest from academia, industry, government, and nonprofit sectors across all engineering disciplines. In addition to the US FOE, the series includes bilateral programs with Germany, Japan, China, and the European Union. The events provide an opportunity for competitively selected participants to learn about cutting-edge and impactful developments and to network and engage in intellectual discussions crossing traditional boundaries in engineering.

When the decision was made in fall 2020 to postpone that year's US FOE, we thought that surely we would be back to in-person meetings by early 2021. As we know now, that was not to be, so rather than postpone again, we held the meeting as a virtual event.

Frontiers of Engineering is a program where much of the magic happens beyond the technical sessions, during breaks, meals, and other times for informal exchange. This cannot be replicated easily in a virtual format, but the platform that was used allowed for people to move their avatars in "rooms," which facilitated conversations, meet-ups, and the casual exchange that so often leads to new connections and collaboration.

The technical sessions at the 2020 US FOE covered the following topics:

- *Food for Thought: The AgRevolution Shaping What We (Will) Eat*, cochaired by Lily Cheung (Georgia Tech) and Andrew Coughlin (Syngenta); talks covered plant genomics, bioinsecticides created from peptides, food safety, and automation in precision agriculture
- *Next-Generation Energy Systems Integration*, organized by Jennifer Kurtz (National Renewable Energy Lab) and Javad Lavaei (UC Berkeley), with presentations on operating future grids with new AI tools, the water-energy-food nexus, and energy systems for Native communities
- *Engineering Innovation in Women's Health*, cochaired by Kristin Myers (Columbia University) and Melissa Skala (Morgridge Institute); speakers described an approach for cervical cancer prevention, computational models to predict changes in the female reproductive system, biomimetics for reproductive tissue engineering, and an innovative method for early diagnosis of reproductive disorders[1]

[1] One of the papers from this section will appear in the spring 2022 issue of *The Bridge*, on Engineering for Women's Health.

- *Plastics: Pollution Challenges and Innovations*, organized by Anela Choy (Scripps Oceanographic Institute) and Jenna Jambeck (University of Georgia), with talks about mitigation of microplastic pollution on the Gulf Coast, environmental degradability as a design metric, and the world's first plastic credit platform.

Three papers by 2020 speakers are included in this issue. The virtual meeting also included two poster and three breakout sessions. One breakout asked attendees to develop lists of the next Grand Challenges for Engineering (the NAE's original list was announced in 2008), and others focused on disciplinary and session topic discussions. Each day concluded with a virtual happy hour. A list of the talks and speakers, abstracts of the presentations, and (where permission was granted) links to the videos of the presentations are all available at the US FOE website (naefrontiers.org).

The 2021 US FOE, September 22–24, was a hybrid event at the National Academies' Beckman Center, where the technical talks and discussions were livestreamed, and virtual poster sessions were held in lieu of breakout groups to facilitate interactions between the in-person and virtual attendees. Full vaccination and indoor masking were required for those attending in person. Thanks to the beautiful southern California weather, we were able to have breaks and meals outdoors.

The 2021 symposium featured presentations in the following areas:

- *Investigating the Final Frontier: Engineering the Future of Space Exploration*, cochaired by Allison Anderson (CU Boulder) and Jessica Samuels (Jet Propulsion Lab), with talks on the James Webb Space Telescope, in-orbit assembly and servicing technologies, the Osiris-REx asteroid sample mission, and technologies for ensuring crew health and performance during extravehicular activities

- *Resilience in Pandemics: Data and Digital Infrastructure for Informed Decision Making*, organized by Jessilyn Dunn (Duke University) and Jennifer Pazour (Rensselaer Polytechnic Institute), with a case study at Cornell University on reopening during the covid pandemic, application of process engineering's continuous improvement perspective to pandemic-related decision making for schools, digitalization of biomedical manufacturing, and use of mathematical modeling to evaluate critical care protocols

- *Transforming the Climate Change Discussion: The Role of Direct Air Capture*, cochaired by Ryan Lively (Georgia Tech) and Mica Taborga Claure (ExxonMobil), focused on this modality for reducing CO_2, with talks ranging from DAC's unique chemistry and engineering challenges from scale-up to who pays for it

- *Cybersecurity of Critical Infrastructure*, organized by Kate Davis (Texas A&M) and Roman Danyliw (Carnegie Mellon), with a Department of Homeland Security perspective on this threat and talks on protecting industrial control systems and defense strategies for wind farms.

Five papers from the September 2021 meeting are included in this issue.[2]

We thank the sponsors of the 2020 and 2021 US FOE meetings: The Grainger Foundation, National Science Foundation, Air Force Office of Scientific Research, DDR&E(R&T)-Laboratories and Personnel Office, Amazon, Cummins Inc., and individual donors. In addition, DARPA and Microsoft provided support for the 2020 US FOE.

The next US Frontiers of Engineering Symposium will be held September 21–23, 2022, hosted by Amazon in Seattle and chaired by Tim. We encourage you to nominate outstanding young engineers to participate in this program so that we can continue to facilitate cross-disciplinary exchange and promote the transfer of new techniques and approaches across fields in order to sustain and build US innovative capacity.

[2] All the papers are presented alphabetically by lead author.

Capability gaps must be addressed to ensure astronauts' safety and performance during extravehicular activity on missions to Mars.

Mars Walking: Enabling Crew Health and Performance during Extravehicular Activity

Andrew F.J. Abercromby

Andrew Abercromby is lead of the Human Physiology, Performance, Protection, & Operations (H-3PO) Laboratory at NASA Johnson Space Center in Houston.

The benefits, the opportunities, the challenges, and the risks of space exploration increase by orders of magnitude when sending humans beyond Earth's orbit and out into the solar system. Keeping a healthy human alive and well in the most extreme of environments requires spacecraft with life support systems that provide a bubble of Earth-like atmosphere far out in the void of space. Even if that delicate bubble is successfully preserved all the way from the launchpad to the surface of Mars (at least 34 million miles from Earth—a voyage of 6–9 months) and back again, the astronauts living inside it are confronted with an array of challenges and stressors, some of which are immediately apparent while others may take weeks, months, or even years to manifest.

Physiological Challenges of Spaceflight

The transition from the strong pull of Earth's gravitational field to the sudden experience of weightlessness of orbit can cause an array of symptoms, including disorientation, headaches, nausea, vomiting, and gastrointestinal discomfort (Barratt and Pool 2008; Buckey 2006). While these symptoms typically subside within 1–3 days as the central nervous system adapts, other long-term adaptations continue.

In response to weightlessness, altered sleep cycles, isolation, radiation, fluctuating carbon dioxide levels, and other environmental stressors, the body's muscles and bones lose strength, and the ability to perform maximal (or prolonged submaximal) aerobic exercise decreases (Shen and Frishman 2019). Cephalad fluid shifts can cause congestion, affect taste and smell, and may contribute to structural changes in the eyes, causing loss of visual acuity (Lee et al. 2020). Radiation exposure in low Earth orbit is significantly greater than that experienced on Earth, causing cellular damage that contributes to lowered immune function during spaceflight and increased lifetime cancer risk (Benton and Benton 2001). When astronauts leave the protection of Earth's magnetosphere, the radiation exposure and associated risks become greater still.

The myriad physiological stressors compound the psychological challenges associated with living in an isolated, confined, and extreme environment (Palinkas 2001). Astronauts typically work as members of international crews of up to seven people, with current missions lasting as long as a year; Mars missions lasting 2–3 years or more will far exceed previous human experience.

Long-duration human missions to the moon and Mars will require advanced technological capabilities, some of which do not yet exist. NASA refers to these as capability gaps (Burg et al. 2021).

Long-duration human missions to the moon and Mars will require advanced technological capabilities, some of which do not yet exist.

In this paper I describe challenges, progress, and opportunities associated with four capability gaps relating to the maintenance of human health and performance during extravehicular activity (EVA). Often referred to as spacewalking, EVA will be among the most frequent, highest-workload, and highest-risk activities during human missions to the moon and Mars. It is also perhaps the most important element, both functionally and symbolically, that distinguishes human space exploration from robotic missions.

Capability Gap: Space Suit Fit and Injury

Injury prediction, monitoring, and mitigation technologies are needed to enable planning, training, operations, and system design for all suited mission phases and for all anticipated crewmember anthropometries.

Multiple injuries to astronauts have occurred while working in spacesuits, even with a relatively low frequency of EVAs (Chappell et al. 2017; Stirling et al. 2019). Reported injuries range in severity from blisters to fingernail delamination to shoulder injuries requiring surgery. In some cases, poor suit fit is believed to have been a contributing factor, and data have also shown that reduced recovery between successive EVAs also increases injury risk.

Future spacesuits must ensure that male and female astronauts of all shapes and sizes are not only accommodated by the suit but can perform all necessary mission tasks without discomfort or increased injury risk. Changes in anthropometry that occur during spaceflight must also be identified and accommodated (Young et al. 2021).

In addition, suits must protect astronauts expected to perform far more EVAs, with far less recovery time than ever before. Apollo surface stays on the Moon were up to 3 days in duration, with astronauts wearing custom-fit spacesuits for up to three EVAs; current mission designs considered by NASA call for as much as 24 hours of EVA per person per week throughout surface stays that may be months in duration.

EVA injury incidence during Apollo as well as in the current spacesuit used on the International Space Station (ISS) suggests that musculoskeletal injuries that affect mission objectives, and potentially long-term health, are not only possible but likely during these types of long-duration surface missions unless capabilities are developed and implemented to improve fit and mitigate injury risk. Computational anthropometric and injury modeling (examples of which are shown in figure 1) will be an important part of this capability development.

Capability Gap: EVA Crew Capabilities and Constraints

Crewmember physical and cognitive state monitoring and prediction technologies will be essential to enable EVA planning, operations, system design, and decision support systems based on crewmember capabilities and constraints.

When returning to Earth after long-duration stays in microgravity, crewmembers are nauseated and have sometimes extremely reduced ability to perform even simple tasks such as walking, until their vestibular system has readapted to Earth's gravity (Mulavara et al. 2018). Unlike landing on Earth where a support team can lift astronauts out of their capsule, Mars astronauts must adapt to the transition from the microgravity of the voyage to Mars to the partial gravity of Mars (about 3/8 of Earth's gravity), get into their EVA suits, and perform any necessary postlanding tasks themselves.

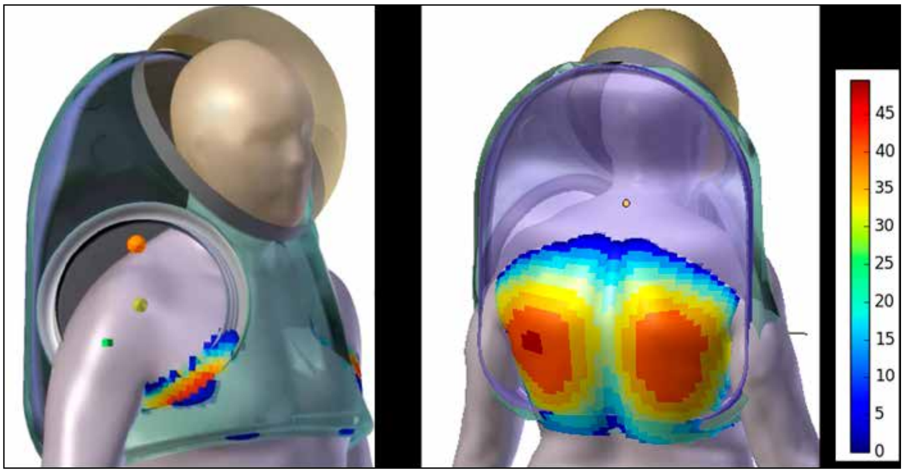

FIGURE 1 Computational anthropometric and injury modeling capabilities are needed to help ensure health and performance for crewmembers of all shapes and sizes. Images show examples of model-predicted volumetric overlap (i.e., locations and degree to which suit may be too small for an astronaut).

FIGURE 2 Testing to characterize crewmember capabilities and constraints in spacesuits often uses test environments such as the Active Response Gravity Offload System (ARGOS) shown here, which allows for simulation of reduced-gravity EVA conditions using a system similar to an overhead bridge crane.

Uncertainty and variability in what functions each astronaut will be capable of performing at any given point in a mission present many challenges, compounded by uncertainty in the exact physical and cognitive demands and cost associated with many of those functions when performed in the lunar or Mars environment.

As another example, the full-body physical workload associated with planetary EVA, especially in Mars gravity, is expected to be higher than for EVAs in microgravity (Norcross et al. 2010), where instances of fatigue-related performance decrements are already anecdotally apparent. In addition to potential performance implications, this increased workload may impact consumables usage, caloric expenditure, heat storage, CO_2 exposure, decompression sickness risk, and hydration. Human testing using prototype spacesuits in reduced-gravity simulations (e.g., figure 2) is essential to understanding these effects and developing the capabilities to accommodate them.

Capabilities to predict and monitor physical and cognitive state before and during EVA are currently very limited but will be essential to the safe planning and execution of EVA during Mars missions.

Capability Gap: EVA Bioinformatics and Decision Support

Ground-based and in-flight EVA technologies need to be developed to maintain EVA crew health and performance monitoring and decision making during increasingly Earth-independent operations.

The unavoidable communications latency between Earth and Mars will require that many of the support, monitoring, command, and control functions currently provided by a large team of flight controllers in Mission Control Center (MCC) on Earth be performed by astronauts and their spacesuits or spacecraft. This paradigm shift will require a significant evolution of technology, training, and operations. It is also likely to increase the cognitive workload for EVA crewmembers.

Capabilities to predict and monitor astronauts' physical and cognitive state before and during extravehicular activity will be essential for safe Mars missions.

Capabilities to enhance EVA scientific exploration under communications latency have been the subject of previous studies (e.g., Abercromby et al. 2013; Beaton et al. 2019; Rader and Reagan 2013), but the critical role of EVA medical operations support to continually monitor and protect crew health and performance during EVA with communication latency is not well understood. The physical and cognitive state prediction capability described above will have to integrate with life support system models and purpose-built operational EVA planning and execution tools that protect and provide for health and performance during the planning, execution, and real-time replanning of EVAs.

These capabilities are enabling for inflight crewmembers on Mars to fulfill the many critical EVA support functions currently performed by humans and systems in MCC, but they are also enhancing and possibly even enabling for high frequency EVA during lunar surface missions. Hundreds and sometimes thousands of person-hours go into planning and preparing for a single EVA on the ISS; significantly improved planning capabilities are required to enable high frequency exploration EVA.

Capability Gap: Decompression Sickness Mitigation

The fourth capability gap is the decompression stress prediction and mitigation technologies that will be needed to enable EVA planning, training, operations, and system design for planetary surface missions where existing microgravity decompression sickness countermeasures are not applicable.

Apollo missions used a 100 percent O_2 cabin atmosphere, which effectively eliminated the risk of decompression sickness (DCS) during EVA on the moon. NASA's future missions to the moon and Mars are expected to use nitrox gas mixtures of up to 34 percent O_2, 66 percent N_2; this will reduce flammability risk compared with Apollo, but will necessitate oxygen prebreathe prior to EVA to reduce DCS risk to acceptable levels (Abercromby et al. 2015). Prebreathe protocols used on the space shuttle and ISS are validated for microgravity EVAs, but the significantly increased risk of DCS during equivalent ambulatory EVAs makes these protocols inapplicable to planetary EVA (Conkin et al. 2017).

An "exploration atmosphere" of 56.5 kilopascals (kPa) (8.2 psia), 34 percent O_2, 66 percent N_2 has been recommended by NASA as a compromise that balances prebreathe duration, hypoxia, and flammability risk, assuming a 29.6 kPa (4.3 psi) spacesuit. However, this atmosphere may not be used for vehicles that do not support frequent EVA; and with commercial and international providers expected to deliver landers, pressurized rovers, habitats, and spacesuits, different combinations of vehicle and spacesuit atmospheres are possible and will each require validated prebreathe protocols.

A validated DCS risk prediction tool, encompassing the range of potential spacecraft and spacesuit pressures and atmospheres, will enable risk-informed development and operation of all future spacecraft and spacesuit operations, including contingency scenarios such as cabin depressurizations.

Conclusion

The specific research, development, and testing necessary to close each of these capability gaps is captured in the Crew Health and Performance (CHP) EVA Roadmap, a multiyear strategic planning document that is updated on an ongoing basis. The most recently published version is organized around seven gaps, which have since been consolidated to the four gaps identified here (Abercromby et al. 2020). The updated roadmap is expected to be published in 2022.

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Unique scale-up approaches are needed to accelerate the development of cost-effective DAC technologies.

A Fundamentals-based Approach for Scale-up of DAC Technology

Rodrigo Blanco Gutierrez is a researcher at ExxonMobil Research and Engineering.

Rodrigo Blanco Gutierrez

Energy touches, directly or indirectly, every aspect of daily life. As the global population increases, so does the demand for energy. The challenge is to provide affordable, reliable, and clean energy to support sustainable development (ExxonMobil 2019).

Background

To minimize the environmental and associated social and financial impacts of climate change, the Intergovernmental Panel on Climate Change set a goal to limit the rise in global average temperature to less than 1.5°C above preindustrial levels (IPCC 2014). Meeting this goal will likely require a combination of reduced greenhouse gas emissions from point source streams and removal of CO_2 from the atmosphere. Direct air capture (DAC) technology may help with the latter, similar to natural sinks, but at much higher productivity (Sinha and Realff 2019).

Technical challenges for DAC include efficient capture of CO_2 at low concentrations and minimization of its energy consumption. In addition, large-scale deployment is required to capture up to 10 billion tons of CO_2 per year (NASEM 2019).

The large scale needed and the sense of urgency to address current climate issues necessitates unique scale-up approaches to accelerate the development of cost-effective technologies. The development strategy presented in

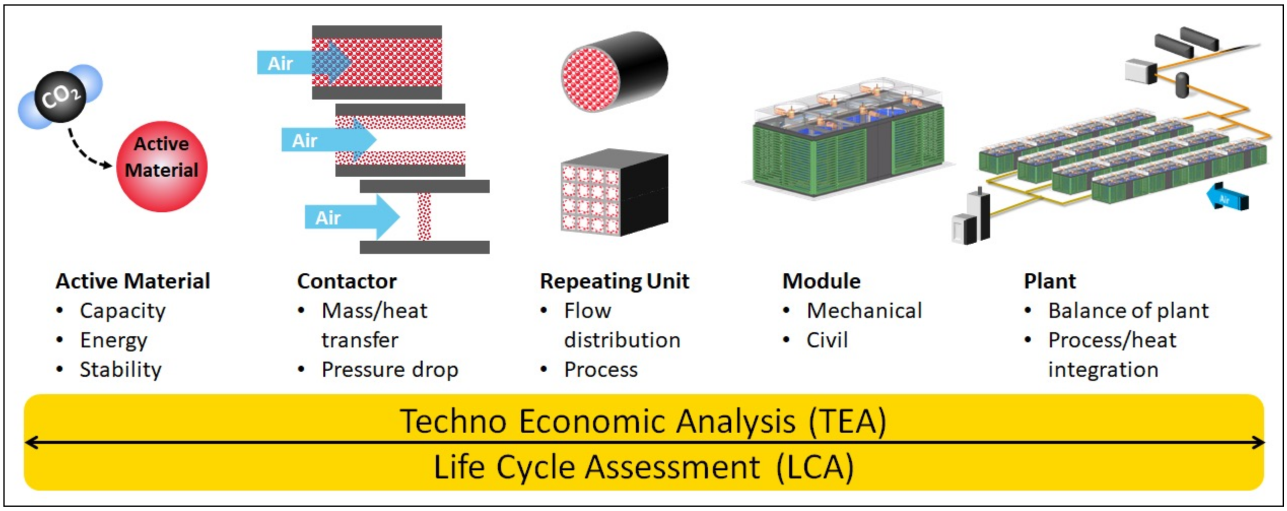

FIGURE 1 Multiscale nature of technology scale-up.

this paper relies on an understanding of process fundamentals coupled with detailed modeling, parallel work across different scale-up activities, and collaborations.

Scale-up Considerations

Technology scale-up is a multidisciplinary activity involving science and engineering across different scales (see figure 1). At one end of the scale, active materials define process characteristics that have an impact at the other end of the scale, such as plant size, mechanical and civil considerations, and potential for process integration.

To accelerate technology development, activities across different areas need to be efficiently progressed in parallel, through identification of relevant tie points across scales. For instance, the contactor geometry will have implications for larger-scale aspects such as equipment selection (to accommodate pressure drop or to provide the energy required), structural needs, and their associated implications for cost and lifecycle assessment.

The wide range of scale-up activities requires expertise across several science and engineering disciplines, such as material synthesis and characterization, and chemical, mechanical, and civil engineering. And collaborations are needed among universities, national labs, startups, and industry to accelerate scale-up and deployment.

ExxonMobil has entered a joint development agreement with Global Thermostat to advance technology that will capture and concentrate CO_2 from air. Global Thermostat brings more than 10 years' experience in the DAC space with a focus on materials and demonstration units, while ExxonMobil brings expertise in process and materials scale-up, phenomenological modeling, process development, and project execution.

Use of a Model-centric Scale-up Method

The nature of DAC involves a number of challenges across different scales. They are being addressed using a model-based method that focuses on understanding the fundamentals that drive these processes in order to identify optimal scalable solutions and potential R&D opportunities.

Process fundamentals are targeted by decoupling integrated phenomena into simpler elements that can be characterized and validated through small-scale experiments (see figure 2). This strategy improves understanding of fundamentals and increases confidence in model results when validated phenomena are integrated in larger-scale experiments and systems.

Active Materials

Another fundamental area of focus is the performance of active materials. DAC process performance using solid sorbent materials depends on the properties of active materials for capture and regeneration. During the capture step, air flows over/through the material loading it with CO_2. Once the material reaches a certain capacity, the CO_2 is desorbed, through heat and/or vacuum, to be further processed, leaving the material ready to restart the capture-regenerate cycle.

The main R&D objective is to maximize the working capacity of the active material, minimize the energy expended in regeneration through appropriate materials

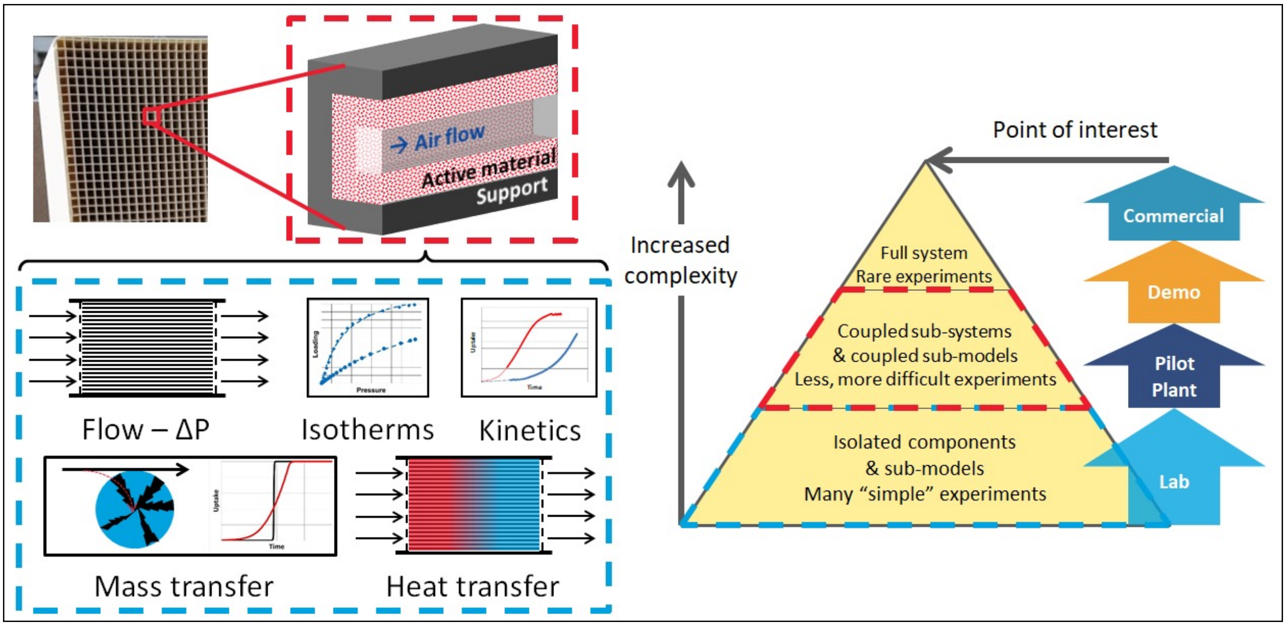

FIGURE 2 Model-based scale-up approach decouples integrated phenomena, targeting model validation through simpler experiments.

selection, and minimize energy requirements due to pressure drop to move large amounts of air by using an appropriate form factor for the process module and heat integration either between modules or with process facilities.

Two challenges for active materials in DAC technology are (1) the low concentration of CO_2 in air, which requires the use of materials that can selectively and efficiently capture CO_2 from dilute conditions, and (2) material regeneration at low temperatures. Amine-based sorbents are appropriate materials for this separation because of their CO_2 affinity at low concentrations and low regeneration temperature. Understanding of their fundamentals, such as isotherms and heat of adsorption, and the associated modeling are both critical to establish the maximum potential capacity for capture and the required regeneration conditions.

Other Performance Factors

While the fundamentals of active materials define the potential process limits, the actual performance is strongly dependent on the process conditions and the form factor in which the materials contact the CO_2 in air. These determine transport properties.

Monoliths provide a large number of parallel channels per cross-sectional area where air flows along the channels to contact the active material coated on the walls. These configurations provide a lower pressure drop than packed beds. Design parameters such as channel density, monolith length, and coating characteristics, together with process conditions such as air flow rate, determine performance metrics such as CO_2 capture rate, efficiency, and pressure drop. The regeneration energy required depends on the thermal properties of the different components of the contactor and the intrinsic heat of adsorption of the active material.

Model Validation

The use of a model-based method relies on the development and validation of models that cover detailed phenomena such as flow and pressure drop in channels, diffusion, and adsorption in porous media integrated with heat and mass transfer, including spatial variations across scales in the contactor. Furthermore, the cyclic nature of these processes necessitates the application of dynamic models to determine the performance of the process for a given design and a set of conditions by finding the cyclic steady state for the capture and regeneration cycle. Identification of these elements and validation through targeted experimentation are crucial for confidence in the results generated by the models.

Validated models allow exploration of different design contactors by varying geometry, channel density, and coating characteristics defined by a large number of variables. In addition, they make it possible to study the impact of varying process operation such as feed conditions, cycle timing, and regeneration schemes.

The large space available for design and operating decisions, coupled with the model complexity, require advanced computing techniques. The use of high-performance computing clusters can accelerate analysis through parallel processing of numerous options. The results are then further processed with technoeconomic analyses and lifecycle assessments for comparison of important scale-up considerations for DAC technology.

Conclusion

The use of model-based methods is enabling acceleration of the development and scale-up of direct air capture technologies. This approach targets validation of key phenomena to increase confidence in results for further exploration and development. It provides sensitivities of process indicators as a function of different design and operating decisions, which are useful when looking beyond the current modeling scope to assess impacts on mechanical and civil considerations, process integration, cost, and carbon footprint. And model-based methods are extremely useful for identifying improvement areas to push the boundaries of innovation in science and engineering in order to provide scalable and cost-effective solutions to address global climate change.

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Modeling showed that opening for in-person instruction would actually be safer than moving fully online.

Fighting the Pandemic with Mathematical Modeling: A Case Study at Cornell University

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Peter I. Frazier

Government response to the covid-19 pandemic has been chaotic worldwide. Past experience was no longer a reliable guide as decision makers were faced with unfamiliar trade-offs and hard-to-quantify risks. Government policies on masking, testing, distancing, and vaccination varied substantially, perhaps as much due to the cognitive biases of decision makers and their constituents as to differences in circumstances. Consequently, history may show that the human toll, in terms of both mortality and economic losses, was significantly larger than it needed to be. I argue that, collectively, we can do better and that engineers and scientists can help.

In a microcosm of the broader world, colleges and universities in the United States were challenged in the summer of 2020: Would it be safe to invite students back for the fall semester? If so, what interventions would ensure safety? Would students comply with distancing and masking restrictions? Would arriving students import and serve as hosts to a viral epidemic that would leap to faculty, staff, and the larger community?

In this article I describe how science and engineering answered these questions at Cornell University, sharing experience that may help others appreciate science's ability to guide policy.

Modeling to Determine In-Person or Online Instruction

Opinions in Ithaca, where Cornell is located, were divided on the best path forward, as they were in many communities. Many residents felt that reopening the campus would be profoundly dangerous; others felt that not reopening would harm students' educational outcomes and mental health as well as residents' ability to earn a living. These perspectives reflected similar divisions in public opinion around the country, pitting those who feared the health consequences of infection against those who feared the economic and social costs of pandemic interventions (Ferragina and Zola 2021; Vezzoni et al. 2020).

Campuswide Interdisciplinary Involvement

In the face of this division, a group of engineers, scientists, public health professionals, healthcare providers, and university administrators came together at Cornell. Among this group, I and several other faculty and students formed the Cornell COVID-19 Mathematical Modeling Team (briefly, the modeling team) to contribute mathematical modeling and data science.[1] Together, we hoped to use data and science to help the university chart a path forward.

We understood that simply asking students to wear masks and maintain social distancing might not prevent an outbreak (Yamey and Walensky 2020). Early analysis and work by other academics suggested that testing students and employees regularly and isolating positive individuals might catch asymptomatic spreaders and protect against viral spread (Frazier et al. 2020; Gollier and Gossner 2020).

Simultaneously, leaders in Cornell's College of Veterinary Medicine realized that a substantial capacity to conduct polymerase chain reaction (PCR) tests (ordinarily used to test dairy cows and other animals for virus) could be used to test for SARS-CoV-2 in people. Building on past knowledge of pooled testing and current work exploring its potential for covid-19 (Cleary et al. 2020; Gollier and Gossner 2020), university leaders hypothesized that the local testing capability could be significantly expanded through pooled testing, the application of a single PCR test on samples from multiple individuals. If the test came back negative all samples would be deemed negative; otherwise follow-up tests would be conducted on the individual samples.

Testing students and employees regularly and isolating positive individuals might catch asymptomatic spreaders and protect against viral spread.

Would the Reopening Plan Work?

Perhaps student parties would lead to overwhelming infection rates, tests would be too inaccurate, too many students would be unwilling to mask or isolate, testing apparatus would break under the large test volumes, the number of students needing quarantine or isolation would exceed the rooms available to safely house them, or the virus would simply be too infectious. We also worried that personnel wouldn't be able to keep up with large lab test volumes and surges in positive students needing isolation and contact tracing (extremely long workdays occurred frequently in several units on campus and in the local health department and we worried about burnout and staff quitting); that testing frequency would need to be increased because of elevated social contact but the lab would not be able to provide the increased capacity; or that delays in the time from sample collection to contacting positives and their contacts would prevent prompt isolation and quarantine. We weren't sure how many tests we could perform or positives we could isolate and trace per day reliably on a regular basis and we were depending on teams to hold up under large workloads.

As the modeling team contemplated this question in the summer of 2020, we found that the accuracy of

[1] The modeling team was just one of many Cornell groups responding to the pandemic at the university. Others included a newly formed Committee for Teaching Reactivation Options, the Animal Health Diagnostic Center (from which the Cornell COVID-19 Testing Laboratory was created), Cornell Health, Student and Campus Life, Human Resources, Cornell Information Technologies, the Office of General Counsel, University Relations, Institutional Research and Planning, the Cornell Center for Data Science, and the Master of Public Health program, as well as several other groups and many other individuals. Cornell also forged strong partnerships with the local hospital system, Cayuga Health System, and the Tompkins County Health Department.

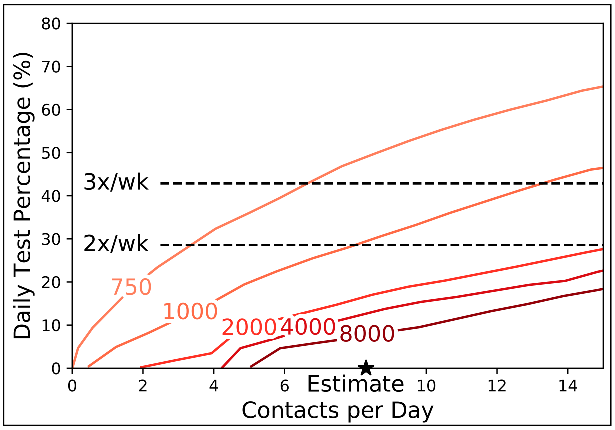

FIGURE 1 Contour plot showing the predicted cumulative number of infections in the Cornell University population vs. two key parameters: the fraction of the population that would be tested per day (y-axis) and the number of contacts that students would have per day once instruction started (x-axis). Contours (colored lines) indicate predicted infections at some parameter combinations. Predicted infections rise as daily test percentage falls or contacts per day rise. We estimated that students would have roughly 8 contacts per day (black star) and that we would see roughly 1000 cases when testing 2x/week. If students were more social than estimated, increased testing frequency (to 3x/week or more) was predicted to keep cases low: the "3x/wk" line stays above the "1000" line up until 13 contacts per day, indicating that predicted infections are below 1000 with testing 3x/week as long as students have fewer than 13 contacts per day.

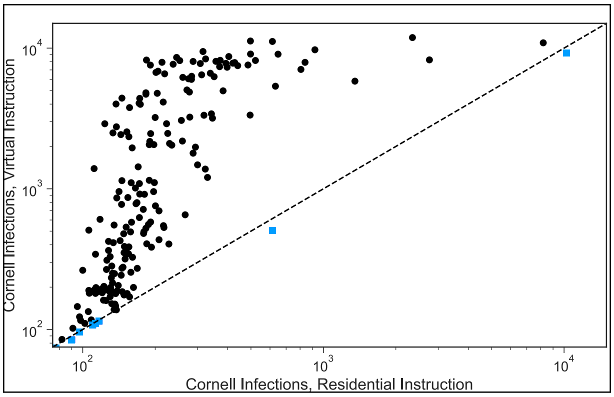

FIGURE 2 For each of 200 likely parameter sets, the number of simulated infections in the Cornell University population under a return to in-person instruction (x-axis) and fully virtual instruction (y-axis). Black dots (blue squares) show parameter sets where virtual instruction results in more (fewer) infections. The proliferation of black dots shows that there are many parameter sets where infections are much higher under virtual instruction.

modeling predictions was fundamentally limited by significant uncertainty about parameters. Nevertheless, modeling showed that, even under pessimistic assumptions about parameters, regular testing could protect the population against a large outbreak (figure 1).

Moreover, surveys indicated that, even if instruction were all online, several thousand students were likely to return to the area. Regular covid testing, social distancing, and masking would have been difficult to mandate for these students if instruction were fully online (Modeling Team 2020a). Analysis showed that the students would thus be at significant risk of an outbreak and that opening for in-person instruction would actually be safer than moving fully online (figure 2; Modeling Team 2020a, 2020b).

The Decision to Reopen

Supported by this analysis the university decided to reopen for residential instruction with a behavioral compact for returning students, as articulated by the university's president and provost in an editorial in the *Wall Street Journal* (Kotlikoff and Pollack 2020). Modeling and data supported additional decisions, such as the testing frequencies for student and employee groups and the amount of quarantine and isolation housing to reserve (Modeling Team 2020c).

Reopening was successful. Fewer than 300 cases in a population of 30,000 were reported over the 2020 fall semester, significantly fewer than many other open universities of comparable size, and similar to or fewer than several comparably sized universities that moved fully online.[2] Illustrating the danger of fully online instruction for a college town, Michigan State University in East Lansing experienced an outbreak in fall 2020 among undergraduate students living locally: although their classes were fully online, 640 cases were reported in a single week (Nadworny 2020; Stanley 2020).[3]

Cornell's success is broadly consistent with the success of regular asymptomatic screening, also deployed at a handful of other universities in the fall 2020 semester (Candanosa 2020; Denny et al. 2020), as well as concurrent academic research (Chang et al. 2021; Paltiel et al. 2020). The favorable outcome led to the broader

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[2] College Crisis Initiative, COVID-19 Data Dashboard (https://collegecrisis.shinyapps.io/dashboard/); and New York Times Survey of US Colleges and Universities, GitHub repository (https://github.com/nytimes/covid-19-data/tree/master/colleges).

[3] Michigan State University Testing and Reporting (https://msu.edu/together-we-will/testing-reporting/, accessed Oct 2020).

adoption of this strategy through the spring and fall 2021 semesters at other universities.

Four Elements of Cornell's Successful Mathematical Modeling Effort

Four key aspects of our mathematical modeling effort were critical for success: stakeholder engagement, respect for uncertainty, interpretable models, and observable systems. I share these with the hope that they may be useful for others in similar modeling efforts.

Stakeholder Engagement and Communication

First, we prioritized engagement and communication with the university administration and the public. Engagement with those in the administration who were ultimately responsible for the reopening decision started with our listening to their questions and concerns, with an ear toward understanding their approach to making trade-offs and their operational constraints. This understanding informed our analysis. We also prioritized responsiveness, providing analysis quickly in response to questions.

Engagement with the public included releasing the details of our analysis (Modeling Team 2020a, 2020b, 2020c, 2021), town hall and faculty senate meetings, interviews with media, a website where we solicited and responded to questions from the community (Modeling Team 2020e), and reports to our representative in the state legislature (Modeling Team 2020d).

We heard most prominently from stakeholders who were afraid or angry; they were the most motivated to be heard. Patience was a virtue that supported us: when fearful stakeholders lashed out, sometimes with personal accusations, we stayed calm, acknowledged their concerns, and rearticulated the scientific basis for our analysis. We were buoyed by the insight that such attacks arise naturally from fear and are not accurate comments on the person attacked.

While some people remained skeptical, transparency helped many understand that the administration's decisions came from good intentions and a basis in evidence. This eased fears while moving conversations toward civility.

Respect for Uncertainty

Our analysis acknowledged that uncertainty was substantial and identified decisions that were robust to this uncertainty. Whether an infection creates a large cluster depends critically on input parameters, several of which were unknown at the time when a reopening decision needed to be made, even after we "mined" the most up-to-date data and literature. Thus, we prioritized decisions that would work well across a broad range of the most likely parameter values.

Our analysis acknowledged that uncertainty was substantial and identified decisions that were robust to this uncertainty.

Later analysis also leveraged Bayesian methods, quantifying the effect of uncertainty by sampling from prior probability distributions over uncertain parameters.

Interpretable Models

We strived for interpretability. Alongside a detailed compartmental simulation implemented in Python, we used simpler mathematical models like the classical susceptible-infected-recovered model (Allen et al. 2008). We implemented them in spreadsheets and even on calculators and napkins. They were fast enough to run during meetings with stakeholders, gave intuition and prompted confidence in our results, and helped us understand which aspects of reality were most important to build into our more complex simulation models.

Observable Systems

We collected data from asymptomatic screening and other sources in a HIPAA-compliant database. This enabled fast analysis of the evolving situation and supported decisions that significantly enhanced safety: testing of higher-transmission student groups more often (Modeling Team 2021), planning to ensure staffing for contact tracing and housing capacity for quarantine and isolation, and interventions to improve test compliance.

Conclusion

I hope that this experience inspires others. Engineers and scientists are uniquely capable of bringing science to bear on complex policy challenges.

The benefits we observed from pursuing close stakeholder engagement, respecting uncertainty, using interpretable models, and building observable systems may be useful to other engineers who tackle policy questions. I encourage others contemplating such an effort: while advocating for a meaningful policy change is challenging, the world needs your help. You are up to this challenge.

Acknowledgments

I am deeply grateful to the Cornell COVID-19 Modeling Team and to everyone at Cornell University who fought the pandemic.

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A knowledge base of known adversarial behaviors can help organizations prepare for, mitigate, and prevent threats to industrial control systems.

Threat-Informed Defenses for Industrial Control Systems

Adam Hahn, Otis Alexander, and Marie Collins

Adam Hahn

Otis Alexander

Marie Collins

Industrial control systems (ICS), the foundation of the nation's critical infrastructure, are increasingly the target of sophisticated cyber threats. Recent US intelligence reports have claimed that multiple state actors maintain the ability to "launch cyber attacks that cause localized, temporary disruptive effects on critical infrastructure" (e.g., Coats 2019, p. 5).

While cyber threats to more traditional information technology (IT) environments have been observed for many years, only in the past decade or so have sophisticated attacks been identified targeting the critical ICS environments. For example, in 2010 the Stuxnet malware was discovered targeting programmable logic controllers (PLCs) used to operate an Iranian uranium

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enrichment facility (Falliere et al. 2010); attacks targeting Ukraine's electric grid were identified in 2015 and 2016 (Cherepanov 2017; E-ISAC 2016); and in 2017 the Triton malware was identified manipulating the safety instrumented systems used to protect critical processes at an oil refinery (Johnson et al. 2017).

These scenarios highlight risks to ICS, but there remains a lack of systematized knowledge of how these threats could impact the spectrum of critical ICS facilities and technologies. Better understanding of these threats is paramount to the development of effective ICS defenses.

Threat-Informed Defenses Using ATT&CK for ICS

To address these challenges, MITRE has developed the *ATT&CK for ICS* knowledge base, which maps adversarial tactics and techniques observed across many real-world attacks to help better understand how cyber adversaries target critical infrastructure and to identify defenses that are tailored to these techniques.

Mitigations must be designed to work within each environment's unique requirements, including long device lifecycles, resource-constrained hardware, real-time performance expectations, and communication protocols.

The knowledge base systematizes the different technical *procedures* adversaries have used across the observed ICS attacks. These procedures are grouped into common *techniques* if they use similar methods across different technologies or environments. Techniques are then categorized into *tactics* that represent the adversary's technical goal, such as how the adversary gains initial access, how they maintain persistence on systems, how they achieve lateral movement to access their target, and how they evade detection mechanisms.

Most importantly for ICS, the tactics also highlight how attackers can (i) impair process control to manipulate the underlying physical infrastructure and (ii) inhibit response functions to prevent normal operator responses from detecting and responding to the manipulation.

Table 1 provides an overview of ATT&CK for ICS, showing tactics (top row) and associated techniques (cells). Shading designates techniques observed in different attacks: yellow for Stuxnet (2010), green for Industroyer (2016), blue for Triton (2017), and orange for techniques observed across multiple attacks.

Known Adversary Techniques

The knowledge base highlights the multidisciplinary elements of ICS security. Some adversary techniques heavily overlap with those long observed in typical IT environments, such as the reuse of valid credentials to gain access to systems or the use of network sniffing to obtain data from existing communications.

Most of the identified adversary techniques are highly tailored to ICS processes and technologies. For example, techniques like program upload are needed for adversaries to extract the plant-specific application logic deployed on the PLC, while brute force input/output (I/O) can be used to directly trigger a control function through the PLC. Understanding how adversaries could perform such actions requires a strong technical understanding of various PLC architectures and the operational processes they support.

Detection, Mitigation, and Prevention

In addition to categorization of the technical methods needed to execute an attack, ATT&CK for ICS defines mitigations and data sources that can be used to detect and prevent adversarial behavior. These mitigations span broad sets of technologies and procedures that can both prevent adversary access and minimize the impact of a successful attack.

While traditional cybersecurity mitigations, like network segmentation and multifactor authentication, can help prevent many adversary techniques, they can also negatively impact the performance of ICS environments. Therefore, mitigations need to be designed and verified to work within the unique requirements of these environments, including long device lifecycles, resource-constrained hardware, real-time performance expectations, and communication protocols.

Mitigations can also include mechanical protections and safety instrumented systems that both mini-

TABLE 1 MITRE's ATT&CK for industrial control systems (ICS) matrix documenting known adversarial tactics (top row) and techniques (cells). Shading designates techniques observed in different attacks: yellow = Stuxnet (2010), green = Industroyer (2016), blue = Triton (2017), orange = techniques observed across multiple attacks. API = application program interface; COM = communication ports; I/O = input/output.

Initial access	Execution	Persistence	Privilege escalation	Evasion	Discovery	Lateral movement	Collection	Command and control	Inhibit response function	Impair process control	Impact
Drive-by compromise	Change operating mode	Modify program	Exploitation for privilege escalation	Change operating mode	Network connection enumeration	Default credentials	Automated collection	Commonly used port	Activate firmware update mode	Brute force I/O	Damage to property
Exploit public-facing application	Command-line interface	Module firmware	Hooking	Exploitation for evasion	Network sniffing	Exploitation of remote services	Data from information repositories	Connection proxy	Alarm suppression	Modify parameter	Denial of Control
Exploitation of remote services	Execution through API	Project file infection		Indicator removal on host	Remote system discovery	Lateral tool transfer	Detect operating mode	Standard application layer protocol	Block command message	Module firmware	Denial of view
External remote services	Graphical user interface	System firmware		Masquerading	Remote system information discovery	Program download	I/O image		Block reporting message	Spoof reporting message	Loss of availability
Internet accessible device	Hooking	Valid accounts		Rootkit	Wireless sniffing	Remote services	Man in the middle		Block serial COM	Unauthorized command message	Loss of control
Remote services	Modify controller tasking			Spoof reporting message		Valid accounts	Monitor process state		Data destruction		Loss of productivity and revenue
Replication through removable media	Native API						Point & tag identification		Denial of service		Loss of protection
Rogue master	Scripting						Program upload		Device restart/ shutdown		Loss of safety
Spearphishing attachment	User execution						Screen capture		Manipulate I/O image		Loss of view
Supply chain compromise							Wireless sniffing		Modify alarm settings		Manipulation of control
Transient cyber asset									Rootkit		Manipulation of view
Wireless compromise									Service stop		Theft of operational information
									System firmware		

mize dependencies on vulnerable cyber infrastructure and ensure redundancies in core devices and systems. For example, Triton was the first malware developed to intentionally compromise critical safety controllers used to protect hazardous processes. Organizations must assume similar compromises are feasible and ensure that the industrial plant remains safe if they occur.

ICS organizations can use ATT&CK for ICS to improve their cyber preparedness. By identifying adversary techniques most relevant to the operational technologies and processes in their environment, organizations can develop feasible attack scenarios and use them to structure their security programs. They can then use the associated mitigations and data sources from the relevant adversary techniques to prioritize future investments in new defensive technologies. Further, by better understanding relevant adversary techniques, organizations can improve their preparedness by developing both incident response plans tailored to these threats and tabletop exercises to assess their maturity.

ATT&CK for ICS also helps vendors better align the security features of their devices. Many devices are considered "insecure by design" as they fail to implement basic security protections against known adversary techniques (Peterson 2018), raising serious questions about what security protections are adequate. A recent review of ICS vulnerability advisories found that 64 percent of ICS patches don't properly mitigate a risk because of a lack of device security protections (Dragos 2018). The same report also found that such advisories typically lack effective mitigation recommendations for environments where patches cannot be immediately deployed.

Organizations that take a leadership role in sharing information and helping others improve their security should be applauded.

This problem has spurred the development of multiple standards (e.g., IEC 62443, IEEE 1686) to define the security capabilities needed for ICS devices. While there's a strong need for improved security capabilities in ICS devices, these can also increase long-term device management costs, especially when scaled to the potentially thousands of devices deployed in an ICS (Dolezilek 2020). The challenges with ICS security mitigations won't be easily overcome, though ATT&CK for ICS strives to help device vendors develop ICS products with greater security capabilities and produce more effective vulnerability advisories when problems are discovered.

Challenges of Limited Information

While ATT&CK for ICS improves knowledge of threats to and defenses for critical infrastructure, obtaining accurate information about recent events is a continual challenge. Accurately mapping adversarial tactics and techniques depends heavily on open-source threat intelligence from each observed incident. It is difficult to maintain up-to-date resources as this information is often unavailable or considered too confidential to share publicly.

One problem is that many organizations lack sufficient security monitoring capabilities to even detect these attacks. For example, in February 2021 an attacker gained access to a water treatment facility in Oldsmar, FL, and attempted to manipulate the level of sodium hydroxide used in the treatment process. But few forensic data are available, likely because of the organization's limited ability to detect the activities.

Furthermore, private organizations may choose not to share incident details out of concern that it reflects negatively on their organization or may warrant additional industry regulation. The May 2021 Colonial Pipeline ransomware event provides an example, as very little public information was released from the incident although it was heavily investigated (Reeves 2021).

Unfortunately, the victims in these attacks are often heavily criticized in the media for their lax security practices or poor responses, which further incentivizes organizations to minimize the information they share. The problem of ICS threats and attacks is too serious, especially in matters of critical infrastructure, to play the blame game. Instead, organizations that take a leadership role in sharing information and helping others improve their security should be applauded.

Future Directions

The security of US critical infrastructure is directly tied to a better understanding among ICS operators, vendors, and policymakers of adversarial capabilities and motivations. Well-informed ICS organizations can better communicate these risks to executives and advocate for needed funding to support new technologies and programs. Such knowledge can help security engineers identify products that meet their security requirements and help vendors address deficiencies when products lack key protections.

In addition, organizations need better incentives to share incident details to support collaboration toward both improving understanding of threats and ensuring that defensive efforts are appropriately aligned.

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New tools in control theory, optimization theory, AI, and machine learning are being developed to enhance grid reliability.

Enabling the Operation of Future Grids Using New Tools in Control Theory and AI

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The shift toward a more sustainable energy future has led to a number of critical challenges in how to reliably and efficiently operate the electric power grid. Supply and demand must be balanced at all times, but renewable energy resources such as wind and solar produce power only when the wind blows and the sun shines, not necessarily when it's needed, and there is very little grid storage. And while some proposed pathways to sustainable energy systems call for electrification of resources that directly consume fossil fuels (e.g., vehicles, heating systems, and some industrial processes) along with decarbonization of the electricity grid, electrification greatly increases the load on the grid, which in many parts of the country and world is already operating at its limit.

Distributed Energy Resources

To accommodate more wind, solar, and load, power systems researchers are developing approaches to exploit the flexibility of distributed energy resources (DERs). DERs can help the grid by responding to electricity prices or local measurements of voltage or frequency. However, they can provide even more value if aggregated to provide a large grid resource, sometimes referred to as a virtual power plant (Pudjianto et al. 2007).

DERs include small-scale storage mainly from batteries; electric loads with flexible consumption patterns (e.g., electric vehicles, air conditioners, and water heaters); and renewables such as residential solar photovoltaic (PV) systems with control functionalities enabling curtailment and/or reactive power control.

Choosing an Architecture to Coordinate DERs

A key research question is, What is the most effective architecture for coordinating DERs? Specifically, how should the power system operator, utilities, electricity consumers, and, possibly, third-party companies like DER aggregators interact?

A market mechanism, like transactive energy (Kok and Widergren 2016), would have each of them participate in a market to buy or sell electricity. In contrast, a control-based approach might have them all sign contracts with aggregators specifying a prenegotiated amount of flexibility that the aggregators would control in real time to participate in electricity markets by buying/selling energy and/or offering ancillary services.

The best choice of architecture depends on the product or services the resources are providing, the timescale of participation, and consumers' willingness to participate and engage in real-time decision making.

Ensuring Supply/Demand Balance through DER Control

Wind and solar necessitate more balancing services to ensure supply/demand balance (Makarov et al. 2009). Existing balancing services operate on timescales of seconds to minutes. For these fast timescales, I would argue that a control approach makes the most sense as it can achieve a reliable response and does not require frequent consumer engagement. In contrast, eliciting consumer responses through changes in electricity prices or direct participation in markets can result in inconsistent responses and may even synchronize demand, leading to oscillations that could be destabilizing to the power system (Nazir and Hiskens 2018).

A common objection to control approaches is that they leave consumers without sufficient autonomy over their own DERs. But consumer preferences can be accommodated during contract negotiation in which consumers and aggregators agree on the type/amount of flexibility offered, compensation, rules for control, and opt-out possibilities.

Challenges Associated with DER Control

There are a number of significant challenges in aggregating and coordinating DERs through control approaches. Consumers may be hesitant to give control of their DERs to an aggregator because of concerns about privacy and, in the case of flexible loads, worries about potential impacts on their life (e.g., uncomfortable home temperatures, uncharged electric vehicles). Further, coordinating large numbers of DERs can require transmitting large amounts of data (potentially very fast/often) and solving very large and complex control problems.

Aggregations of distributed energy resources can help the grid accommodate more wind, solar, and load.

Additionally, the flexibility of most DERs is inherently uncertain. For example, solar PV curtailment and reactive power control potential are a function of uncertain solar power production and load flexibility is a function of uncertain load usage.

Finally, coordinating DERs to provide a particular service can exacerbate other grid issues. For example, providing balancing services can induce over- or undervoltages in the distribution network if network power flows are not explicitly considered by the controller (Ross et al. 2019).

Principles for Coordinating DERs

What principles should be followed when coordinating DERs to provide fast-timescale grid services?

1. Don't annoy the consumers. Minimize the need for private information and keep the control as nondisruptive as possible (Callaway and Hiskens 2011). For example, cycle air conditioners only within each home's normal temperature range (usually around 1° plus/minus the temperature setpoint).
2. Keep things inexpensive. Minimize measurement and communication requirements and use scalable and computationally tractable approaches that enable coordination of large numbers (hundreds to tens of thousands) of DERs.
3. Plan for uncertainty. Ensure that the approach works (or, at least, does not fail catastrophically) when renewables and/or load do not match their forecasts and when the communication network is slow or goes down.

4. Do no harm. Ensure that the control approach does not induce new grid problems or negatively impact the DERs themselves.

Promising New Approaches

New tools in control theory, optimization theory, artificial intelligence, and machine learning are being leveraged and further developed by grid researchers to address the challenges of DER coordination. There are innumerable recent papers in this space and rather than give a broad summary, I highlight some specific promising approaches that tackle these challenges and align with some of the principles above.

Time-Varying Optimal Control

Researchers at the National Renewable Energy Laboratory (NREL) have developed an approach to coordinate an aggregation of DERs connected to the same feeder (i.e., a portion of the distribution grid served by the same substation) to provide fast balancing services while managing distribution network constraints (Dall'Anese et al. 2018).

When coordinating DERs, don't annoy the customers, keep things inexpensive, plan for uncertainty, and do no harm.

Power system measurements are gathered by an aggregator and used to solve a time-varying optimization problem; the resulting control actions are sent to DERs, which change their power consumption/production. The feeder's total power consumption/production then tracks a signal (e.g., a frequency regulation signal) that varies on timescales of seconds.

NREL has demonstrated this approach in practice with Holy Cross Energy in a net zero affordable housing community in Basalt, Colorado (O'Neil 2019). Importantly, this approach directly addresses the fourth principle—do no harm—by explicitly considering the distribution network impacts of DER control.

"Packets" of Energy

Researchers at the University of Vermont (UVM) and their spin-off Packetized Energy are developing and deploying a bottom-up approach to DER coordination (Almassalkhi et al. 2018). In contrast to the NREL approach, which is top-down in the sense that the aggregator sends control commands to the DERs, the UVM approach requires DERs like flexible loads to request "packets" of energy (i.e., to turn on for a fixed duration) and the aggregator approves or denies those packets. The aggregator's choice of how many packets to approve enables it to shape demand to provide a grid service.

Packets are anonymous and therefore consumer privacy is preserved, addressing the first principle: don't annoy the consumers. Packetized Energy has deployed its technology for residential water heaters and energy storage.

Nondisruptive Load Coordination

In my research group, we are developing approaches that are computationally tractable, are completely nondisruptive to electricity consumers, and minimize real-time communication needs.

For example, we have developed a method to coordinate thermostatically controlled loads like air conditioners and water heaters to track balancing signals (Ledva et al. 2018a; Mathieu et al. 2013). These types of loads switch on and off to maintain a temperature within a narrow band; our approach switches on and off the loads at slightly different times than normal to maintain temperatures within existing bands. It leverages Markov models to compactly represent the dynamics of a large aggregation of loads, a simple predictive controller, and Kalman filters to estimate states that we do not want to measure and transmit in real time, thus both reducing costs and preserving consumer privacy.

We also use online learning to estimate the real-time power consumption of the controlled loads, which is needed as feedback to our control algorithm, based on whatever measurements are already available from the network and loads (Ledva et al. 2018b; Ledva and Mathieu 2020). The online learning approach is data driven but uses dynamical system models to give some structure to the problem.

With funding from ARPA-E we are testing our load coordination ideas in practice, to identify possible technical issues when load coordination is implemented at scale and develop control approaches to address them, with an overarching goal of establishing credibility for load coordination at scale. Specifically, we are exploring distribution network impacts, unwanted dynamical behaviors like synchronization/oscillations, and problems that may arise due to imperfect communication networks.

We are doing physical experiments at Los Alamos National Laboratory and field tests on 100 households in Austin, Texas, with our partner Pecan Street Inc. The University of California, Berkeley is also a partner.

Conclusion

DER coordination is a critical tool to address some key challenges posed by the integration of high penetrations of intermittent and uncertain renewable energy resources like wind and solar. Innovations from control, optimization, artificial intelligence, and machine learning are being used by grid researchers to develop DER coordination approaches that address the four principles identified above to make DER coordination effective, reliable, and practical. Beyond leveraging existing theory and algorithmic tools, grid researchers are developing new theory and tools as we identify problems that existing approaches do not address.

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The technological promise of DAC will be largely irrelevant to the climate crisis if the question "who pays?" cannot be resolved.

Who Pays for DAC? The Market and Policy Landscape for Advancing Direct Air Capture

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Direct air capture (DAC) is a key climate technology with the potential to make major contributions to stabilizing atmospheric CO_2 levels (McQueen et al. 2021). It is location-flexible, uses relatively little land area, and produces a verifiable, high-purity stream of CO_2 that can be permanently sequestered or utilized for a variety of purposes. These features have led to a great deal of interest in the technology, and aspirations to deploy it at large scale as part of the response to the climate crisis (Hanna et al. 2021).

However, as with all technologies, DAC cannot reach large-scale deployment without a profitable business model, in which the cost of building and operating DAC facilities is offset by revenue from one or more sources. This is particularly challenging for DAC because it does not directly displace a technology or product with an existing market.

Also, the current cost of the technology, roughly $500 per ton of carbon dioxide (tCO_2), is high compared to most other options for removing CO_2 from the atmosphere (NASEM 2018). Investments in research, development, and demonstration (RD&D) and learning by doing will bring this cost down over time, but the challenge of finding revenues will persist (Baker et al. 2020; Lackner and Azarabadi 2021). Therefore, realization of the technology's climate potential requires an answer to the question "Who pays for DAC?"

Options to Pay for Direct Air Capture

Companies that build and operate DAC facilities have three basic options for securing revenue: sell CO_2, participate in voluntary offset markets, and receive policy subsidies. These options have significantly different values, market sizes, and reliability. Some combinations of them can be jointly claimed by DAC facilities, while others are mutually exclusive. Currently, none are valuable or reliable enough on their own for a DAC company to depend on exclusively, which means that complex revenue "stacks" are necessary to make projects economically viable.

Sale of DAC-Sourced CO_2 for Utilization

Although CO_2 is an unwanted pollutant in the atmosphere, it has economic value in uses such as enhanced oil recovery (EOR), air to fuels, cement and concrete, commodity chemicals, and food and beverage. The sale of CO_2 removed from the atmosphere to these markets is known as CO_2 *utilization*. There is considerable ongoing research effort to expand such uses, and small amounts of early revenue for the DAC industry already come from niche utilization markets (Sandalow et al. 2017).

But the existing commercial market that provides CO_2 relies on sources that are much cheaper than DAC, including capture from bioethanol and ammonia production plants (largely for the merchant market) and natural/geological sources (largely for the EOR market) (Lorch 2021; Nichols et al. 2014). While some small applications in the US merchant market pay well over \$100/ton for high-purity CO_2, the average price for CO_2 used in EOR (by far the largest market) is approximately \$40/ton, reflecting low production costs (Núñez-López and Moskal 2019).

Without major DAC technology cost reductions and/or policy intervention, it is hard to see how DAC-sourced CO_2 could be economically competitive in CO_2 markets at scale.[1] DAC companies are therefore unlikely to rely on utilization by itself as a revenue source, even though they may seek to secure some part of the revenue stack from EOR and/or merchant market sales.

In addition to these price and cost considerations, it is worth noting that the total market for CO_2 utilization is well below the volume that must be removed to meet global climate targets (IEA 2019; NASEM 2019). Further, while some forms of utilization have a direct climate benefit by displacing the use of fossil fuel as a feedstock, many of these forms are best characterized as "recycling" because CO_2 is returned to the atmosphere on timescales of days to months (Bhardwaj et al. 2021).

Thus while utilization has important climate benefits, they are less than those of DAC paired with geological sequestration or other permanent storage. These considerations will influence policymakers as they examine options for policy support (see below).

DAC Participation in Voluntary Offset Markets

Voluntary offset markets, which are largely ad hoc for DAC, consist of companies (or even individuals) that wish to buy carbon removal services to offset their own emissions without any government requirement or incentive to do so. DAC has begun to attract attention in this realm as traditional offsets, which are heavily reliant on forestry projects, face increasing concerns about their quality (Badgley et al. 2021).

> *The total market for CO_2 utilization is well below the volume that must be removed to meet global climate targets.*

Another driver for voluntary market demand is the growing number of companies declaring net zero emissions targets (Black et al. 2021). Several have recently begun to directly procure negative-emissions services as a form of carbon offsetting and have collectively made purchases of several thousand tons of CO_2 removal and storage via DAC (Shopify 2021; Stripe 2021).[2]

Prices up to \$775/tCO_2 have been publicly announced, although this is for extremely small volumes with a clear indication that the buyer expects future prices to be lower due to technology cost reductions.

These procurements have highlighted several challenges to scaling voluntary carbon markets: (i) a lack of well-established companies with mature carbon removal

[1] Remarkably, both the United States and United Kingdom have recently faced repeated shortages of industrial CO_2 due to fragile supply chains. This may create a small competitive role for DAC as a reliable CO_2 supply for some industrial users (Lorch 2021).

[2] Also see Microsoft's FY21 Carbon Removal Portfolio (https://aka.ms/carbonremoval).

technologies that can participate in procurement processes, (ii) poor or inconsistent accounting regarding the longevity of storage of removed CO_2, and (iii) confusion in the marketplace between carbon removal from the atmosphere and the avoidance of carbon emissions (Joppa et al. 2021).

As a technology solution for providing carbon removal and storage services, DAC paired with geological sequestration addresses some of these difficulties by offering pure removal with permanent storage. If technology costs continue to fall, DAC may therefore be well positioned for the growing voluntary market.

It is likely that the voluntary market will play only a limited role in DAC revenues beyond a certain scale.

However, substantial uncertainty about future prices, market size, and reliability, together with competition from other lower-cost forms of carbon removal (such as high-quality forest offsets and biomass carbon removal and storage; Sandalow et al. 2021), make it likely that the voluntary market will play only a limited role in the DAC revenue stack beyond a certain scale.

Another complicating factor is that the emerging voluntary market may not accept DAC paired with certain forms of CO_2 utilization such as EOR and CO_2 recycling, preferring permanent storage instead. This would mean revenues from some forms of utilization and the voluntary market could not be claimed simultaneously by DAC companies, limiting the overall value of these options.

Government Policy Support for DAC

Government policy can support DAC through grants, production subsidies, tax breaks, or other mechanisms. The federal 45Q tax credit (CRS 2021) and the California Low Carbon Fuel Standard (LCFS)[3] are the primary policy support mechanisms available to DAC companies.

The 45Q tax credit is currently valued at \$50/tCO_2 for sequestered CO_2 and \$35/tCO_2 for utilized CO_2, while prices in the LCFS averaged \$200/tCO_2 in 2020. DAC projects can stack these revenues by claiming both under current policy, and this has directly influenced the economics of the first major planned DAC facility in the United States (McCulley 2020). The lower-value tier of 45Q can be claimed simultaneously with utilization, and EOR (but not other forms of utilization) is compatible with LCFS requirements.

However, both 45Q and LCFS have drawbacks as sources of revenue for DAC. In the case of 45Q, the credit is nonrefundable, meaning that a claimant cannot get more value from it than their current tax liability, which may be small in the case of newer DAC companies. Also, the facility must start construction before 2026, a challenging timeline for megaton-scale projects using novel technology. Legislation currently being debated in the US Congress would address these issues and increase the value of 45Q to as much as \$180/tCO_2, an important step toward making this policy effective.

The LCFS does not include these problematic features in its design, but it has the drawback of a relatively small market size of approximately 15 million tons of CO_2 per year (45Q is unlimited in its effective market size). A small number of megaton-scale DAC projects seeking to sell credits into the LCFS could drive down prices substantially, undermining value.

While revenue support is tremendously important, other forms of policy are also needed to enable DAC to scale. These could include

- measures to reduce the cost of capital to finance plant construction (which is generally very high for novel technologies),
- public funding for the construction of CO_2 pipeline infrastructure (enabling DAC companies to transport CO_2 for sequestration or utilization at low cost),
- government procurement of products made with DAC-sourced CO_2 or direct procurement of CO_2 removal services (creating a market for DAC operations), and/or
- a federal mandate for a subset of companies to adopt or financially support DAC (Capanna et al. 2021; Meckling and Biber 2021).

Ongoing support for RD&D will also be needed to advance new concepts in DAC toward technological

[3] Information about the LCFS is available from the California Air Resources Board, at https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

maturity and address unforeseen technical complications that may arise with DAC facilities at scale.

What's Needed to Move Forward with DAC

The technological promise of DAC will be largely irrelevant to the climate crisis if the fundamental question "who pays?" cannot be resolved. Near-term support that blends the three broad categories described above will be a key part of the answer, despite the complexity that these multiple sources of revenue create for DAC companies.

While utilization and voluntary markets can play important early roles, large and sustained policy support is needed to truly bring DAC to the vast scale required by the accelerating climate crisis.

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Biologic peptides are safe, effective alternatives to current synthetic agrochemical pesticides.

Peptides as a New Class of Biopesticide

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A stable and affordable food supply is critical to the foundation and growth of any nation's economic prosperity. In the United States, agricultural productivity has steadily increased since the Industrial Revolution, and the last 60 years have seen a threefold rise in total crop yield, all while using 25 percent less land (Wang et al. 2018). Innovations like chemical fertilizers, pesticides, plant breeding and trait development, and enhanced cultivation methods are the major drivers of this productivity improvement that affords Americans some of the lowest food prices per capita anywhere in the world.[1]

Recent analysis, however, suggests that productivity gains have slowed, threatening the nation's food security (Steensland and Thompson 2021). In particular, the crop protection industry is suffering from an innovation crisis.

Background

Pesticides become less effective over time as target pests become resistant (Hawkins et al. 2018). At the same time, the development rate of new pesticides has decreased dramatically and others have been pulled from the market because of safety concerns (Windley et al. 2012). Thus crop protection options for farmers are dwindling (figure 1), resulting in overuse of the

[1] USDA table: Percent of consumer expenditures spent on food, alcoholic beverages, and tobacco that were consumed at home, by selected countries, 2015–20; available at https://www.ers.usda.gov/media/e2pbwgyg/2015-2020-food-spending_update-july-2021.xlsx.

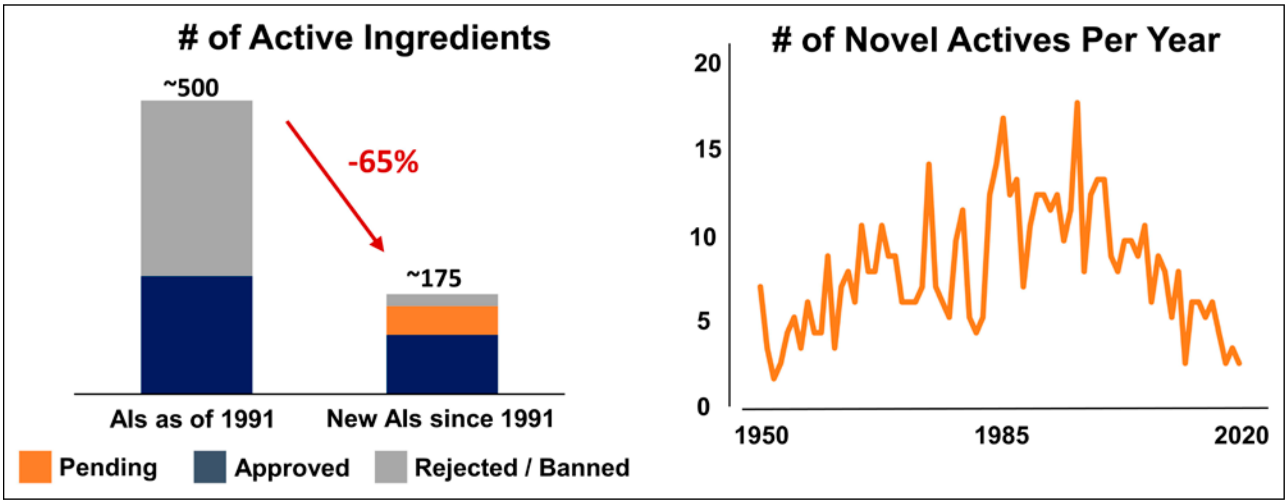

FIGURE 1 Innovation crisis in agricultural insecticides. Left: In 1991 US farmers had hundreds of crop protection options to control pests. More than half of those options have since been removed from the market because of toxicity concerns. Right: At the same time, the rate of novel active insecticide product launches has been declining, resulting in far fewer options for farmers to control insect pests.

limited available options and further reducing pesticide efficacy as pest resistance increases.

Even with the existing options for pest management, 5–20 percent of all US crops are lost to insect damage, and in parts of the world without effective pest control crop losses can exceed 50 percent (Savary et al. 2019). If the current reduced rate of crop protection development continues, staggering crop losses may be anticipated.

Innovations are urgently needed to address the coming shortfall in safe, effective pesticides and to maintain at least current levels of food security. This paper details some of the challenges facing the insecticide industry and proposes biologic peptides as safe, effective alternatives to synthetic agrochemical products

The Innovation Challenge for Crop Protection

The causes of the declining supply of effective crop protection solutions are multiple but include the higher rate of pest resistance, restrictions on current pesticides, and the increased time and cost to develop new synthetic products.

Pest Resistance

Insects evolve resistance to pesticides over time (much as bacterial pathogens can become resistant to antibiotics), putting a lifespan on the effectiveness of every insecticide. As an example, fall armyworm, an annual corn pest that can destroy entire harvests, has evolved resistance to 29 insecticides (Gutiérrez-Moreno et al. 2019). For this and other pests, the rate of resistance development is proportional to its exposure to any one insecticide.

The development of pest resistance can be mitigated with integrated pest management options such as rotation of different insecticides across seasons. In many cases, however, the lack of new insecticides has left farmers with few options. The US Environmental Protection Agency (EPA) has had to allow special use exemptions[2] for more toxic pesticides to be applied in some instances.

Regulatory Restrictions

Regulatory agencies charged with protecting consumers and the environment have been enforcing more stringent environmental and toxicity safety regulations over the last several decades. Such efforts can be credited for an industrywide shift away from pesticides that are toxic to people and other vertebrates. For example, the midcentury use of organophosphates has largely been banned or limited because of their human toxicity, especially in children. And the banning of DDT has been widely credited for the recovery of several endangered avian species (Grier 1982).

Banned pesticides have been replaced with new classes that have much better target specificity and thus much less toxicity for vertebrates. However, the toxicity

[2] See the EPA Emergency Exemption Database at https://ordspub.epa.gov/ords/pesticides/f?p=124:2:::::: (updated October 19, 2021).

burden has now shifted to beneficial insects such as pollinators like bees, with the result that these new chemicals also face restrictions or bans (Schulz et al. 2021). Regulatory agencies face a dilemma as in some instances there may be no effective alternative to current synthetic agrochemical products.

Increased Cost and Time to Develop Synthetic Pesticides

In 1958 it cost around $2–3 million (~$20–30 million in 2021 dollars) to bring an insecticide to market (Barnard 1958). Today, costs are estimated to range from $150 to $300 million to develop a similar product.

In addition, the time it takes to develop and register an insecticide continues to increase. Whereas in the early 1990s a new product could be developed and marketed within 8 years, it now takes over a decade to commercialize a synthetic insecticide (Olson 2015; Sparks 2013).

The higher costs and long development times have led to reduced productivity and fewer products in the market.

Advantages of Peptide Biologics for Crop Protection

The slowing rate of innovation threatens food supplies as pests develop resistance to existing pesticides. The dual challenge is that new products are needed to avoid a crisis *and* environmental safety and sustainability cannot be compromised. I propose the use of peptide biologics to design environmentally sustainable pesticides that work as effectively as standard synthetic agrochemicals while resetting the resistance clock through the expedient introduction of more (and safer) products.

> *Peptide pesticides have little environmental toxicity, thanks to their amino acid building blocks and lack of toxic metabolites.*

Biopesticides represent a small fraction of the $58 billion crop protection market but are growing at a rate above 15 percent per year and are expected to equal the synthetic market in the next 2 decades (Damalas and Koutroubas 2017). The potential promise of biologics as biopesticides has been known for several decades, but manufacturing and delivery challenges have prevented their widescale commercialization until recently.

Large protein biologics (e.g., antibodies or enzymes) have driven a biotechnology revolution in the pharmaceutical industry thanks to their high efficacy, predictable safety profile, and ease to develop. In crop protection, however, they have had less success as biopesticides because they typically have limited stability in the field, they require cold supply chains, and they have difficulty penetrating the insect cuticle to reach essential targets. To ensure a sustainable future and move away from synthetic agrochemicals, these challenges must be addressed.

Smaller versions of proteins called peptides can overcome these stability and delivery challenges and target the exact same receptors as synthetic agrochemicals. In nature, insect-specific peptide neurotoxins are used by many species of spiders, scorpions, and centipedes to immobilize and kill their prey, offering a model for the derivation of safe, effective pesticides (King 2019).

Further advantages include peptides' smaller size, which facilitates their penetration across outer barriers (as discussed below) and could allow for more efficient manufacturing, lowering input costs for farmers. Another manufacturing and delivery benefit is the fact that peptides can be made highly stable through crosslinking, ensuring long-lasting field performance and stability through the supply chain. Because stable peptides do not need a cold supply chain, they eliminate a problematic and costly barrier for the adoption of biologics in crop protection.

Importantly, peptide pesticides have little environmental toxicity, thanks to their amino acid building blocks and lack of toxic metabolites. They have high specificity for target pests and receptors, and so no risk of unexpected toxicity for vertebrates or beneficial insects like honeybees.

Challenges and Opportunities for a Peptide Biologic Future

Three factors play a role in the widespread commercialization of peptide biopesticides: bioavailability, manufacturing cost, and regulation.

Bioavailability

Bioavailability has been the most significant barrier to the commercialization of biologics that target insect receptors (Windley et al. 2012). This challenge can be conceptualized by thinking of the outer structures of an insect pest (exoskeleton or gut lining) as a filter that discriminates by size. Larger molecules, such as proteins or nucleic acids, are mostly prevented from entering, while small molecules like chemical synthetics can pass relatively unimpeded. Peptides are between synthetic agrochemicals and protein biologics in size, and thus have an intermediate ability to cross these barriers.

The intrinsic bioavailability of peptides can be sufficient to directly target internal receptors such as those in the nervous system. The recently approved peptide GS-ω/κ-Hxtx-Hv1a, for example, targets the same receptor as two major classes of synthetic agrochemicals and can kill insects on contact in a commercial formulation.

Manufacturing Cost

The cost to manufacture biologics can be too high for the application rate needed to ensure contact, such as outdoor applications where less of the spray reaches its destination. In these instances, bioavailability enhancers may be necessary to reduce peptide use rates. This has been successfully demonstrated for a caterpillar application of the GS-ω/κ-Hxtx-Hv1a peptide combined with microbial *Bacillus thuringiensis*, dramatically reducing necessary peptide application rates by permeabilizing the insect gut and increasing peptide access to the target. By pairing a microbial with a peptide biologic, the environmental safety profile is maintained while also providing synthetic agrochemical insect control.

Biologic manufacturing costs have fallen 100-fold since the 1990s and are expected to continue to fall as manufacturing capacity increases, raw inputs become commoditized, and cell-based manufacturing strains become engineered for greater efficiency. Declining costs will support the expansion of peptide use in a wide range of pesticide markets and applications (Farid et al. 2020).

Regulation

Existing regulatory frameworks do not apply well to new and emerging biotechnologies (e.g., gene editing, nucleic acids, peptides/proteins). New frameworks are needed, and the US EPA and European Environment Agency have begun to update them for novel biotechnology solutions, including peptides, in crop protection. But the changes may create challenges if the proper tools or expertise to evaluate a new technology are not available.

The best path forward is transparency, to give the most certainty possible to developers as they navigate the evolving regulatory process and ensure safety for growers and consumers.

Conclusion

Innovation is required to keep up with insect resistance. Synthetic agrochemicals are too expensive and slow to develop and are unsustainable for the environment. Biopesticides address these shortcomings: they are faster and cheaper to develop, and sustainable for the environment. Specifically, peptides offer the safety profile of microbial biopesticides combined with the efficacy of synthetic agrochemicals. Combined, these properties make peptides a sustainable alternative to synthetic agrochemicals.

The biotechnology revolution in agriculture is fast approaching. For crop protection, a move away from synthetic agrochemicals toward more sustainable pesticides is highly desirable but may increase risks to food security if pesticide effectiveness cannot be maintained. Peptide-based biologics offer an alternative to synthetics as they possess the dual traits of sustainability and efficacy, making them ideal candidates to form the backbone of a green future in crop protection.

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Residential photovoltaic systems can provide affordable, much-needed electricity for thousands of Native American families that lack grid-tied electricity.

Enabling Residential-Scale Energy Systems for Native American Communities

Suzanne Singer is executive director and cofounder of Native Renewables, Inc.

Suzanne L. Singer

Native American tribes have historically developed fossil fuel and mineral resources on their lands to provide electricity to major US cities. Yet many tribal members still do not have the benefit of grid-tied electricity.

In 2000 the Energy Information Administration reported that 75 percent of all Native American homes without electricity were on the Navajo reservation, which covers approximately 27,000 square miles spanning Arizona, New Mexico, and Utah (EIA 2000). An estimated 15,000 of the nearly 50,000 homes—one in three—on the reservation do not have grid-tied electricity (Gallucci 2019).[1] Many of these families rely on batteries for flashlights, kerosene or propane for lighting (figure 1), and gasoline for generators. For those that do have energy, it can be costly—some families spend up to 50 percent of their income on electricity (Begay 2018).

On-the-Ground Solutions

On-the-ground, Indigenous-led, community-based organizations are leading efforts to build sustainable programs to meet tribal community needs for energy (as well as food and water).

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[1] US Census, 2015-2019 American Community Survey 5-Year Estimates: Navajo Nation Reservation and Off-Reservation Trust Land, AZ--NM--UT – Housing (https://www.census.gov/tribal/?aianihh=2430).

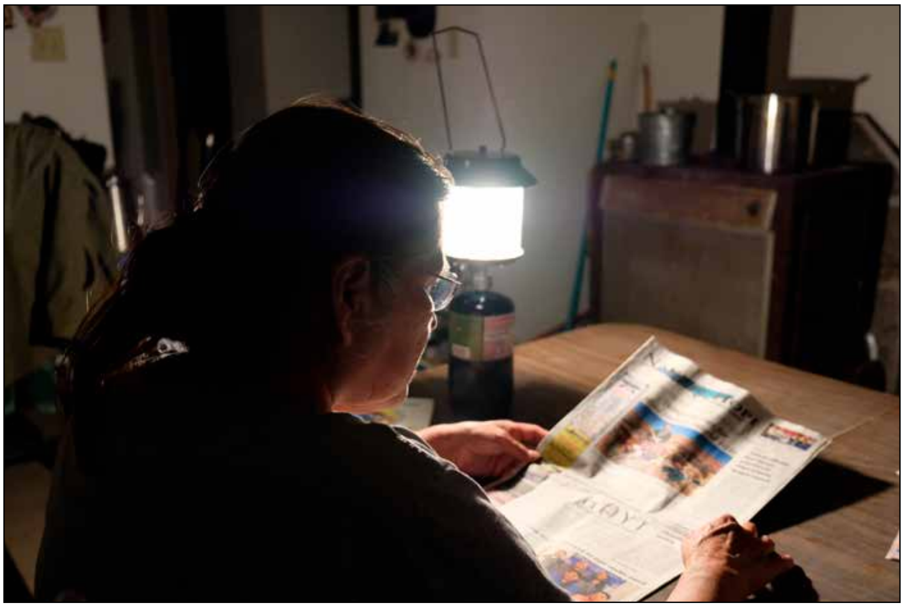

FIGURE 1 Approximately 15,000 families on the Navajo Nation live without grid-tied electricity. Many of them rely on propane lanterns for lighting, as shown here.

Indigenous-Led Services

Native Renewables Inc. (NRI) is a nonprofit organization founded by two Navajo women to empower families to own and manage their power as a path to energy independence. NRI is growing integrated programs to solve energy access issues for thousands of families of the Hopi and Navajo Nations. The NRI staff are Hopi and Navajo tribal members who live in the communities they support, speak traditional languages, have experience living the off-grid lifestyle, and understand how to navigate infrastructure challenges of unpaved roads and gaps in cell phone and internet access.

Indigenous people have traditional knowledge of the sun that guides relationships, everyday practices, and cultural stories. This knowledge includes a concept of harmony and balance that is encompassed in the word *Hozho*. NRI wants its programs to help bring Hozho to the homes of families they support.

Power from the Sun

The Southwestern region of the United States has the best solar resource potential in the country (Sengupta et al. 2018). With the decreasing cost of solar installations, particularly from modules and batteries, solar power technology is the perfect solution for families living off-grid (Feldman et al. 2021). Off-grid solar photovoltaic (PV) systems can incorporate battery storage to support electricity needs at night or on cloudy days.

NRI has designed and installed 2.4 kilowatt (kW) off-grid residential PV systems to provide electricity for refrigerators (less than 11 cubic feet in volume), lights, and the charging of phones, computers, and satellite internet (figure 2). These systems also incorporate battery storage to support 3 days of autonomy without charging. Systems are mounted on frames that sit on the ground for homes that may not have updated roofs with good structural integrity.

The most identified need for families is a PV system large enough to power a refrigerator so they can store food and medicine. Electricity is also importantly needed for children who rely on tablets and laptops for their education as well as people of all ages who need to charge cell phones for communication and to power satellite devices for remote work or education. There are many other benefits:

- Refrigeration may result in less frequent trips, which sometimes take hours, to procure food and ice.
- Solar-powered lights are used in spaces for cooking, working, or leisure, eliminating the need to buy fuel for lanterns.
- For families that use generators, solar power can drastically reduce the amount of fuel consumed. In one case, a family who used a generator a few days per week was able to reduce their use to a few times per year, reducing both their fuel expenditures and greenhouse gas emissions.

The size of the solar modules and battery storage dictate what energy loads are allowable to properly maintain the PV components for their lifetime, so educating families on the benefits and limitations of off-grid solar power is instrumental to the sustainability of their power. Before installation, NRI conducts an energy load survey with the family to tabulate the watts of loads, time(s) of use, and frequency of use. The total Watt-hours per day (W-h/d) of all loads will show whether energy consumption exceeds or falls within the threshold of allowable consumption (e.g., 3000 W-h/d). If it exceeds the threshold, the family will need to adapt their energy habits to align with the capabilities of the PV system. Education and continued communication with the families can also reduce maintenance needs.

Families with an off-grid PV system have energy independence: They have the power to manage their energy and are not affected by grid-related power outages. They also reap benefits in time and money saved and a safer, more reliable source of energy and light.


FIGURE 2 Pictured here are Native Renewables (NRI) staff—three of whom completed NRI's workforce training—with an NRI-designed 2.4 kilowatt off-grid solar plus battery storage unit. Such units are installed by an NRI-trained solar workforce.

Workforce

A critical component to sustainable programs is to invest in local tribal members. NRI works to build off-grid solar technical knowledge, creating training opportunities and paving the way to a solar energy career. Investing in a local workforce creates job opportunities and can ensure that technical support is available within tribal communities and that projects are implemented by Native-led organizations and businesses.

In 2019 NRI held its first in-person workforce training in the community of Hardrock, Arizona. The goal was to train 10 Navajo/Hopi tribal members to install and maintain a 2.1 kW off-grid battery-based solar system, hosting the training at local community centers and removing the cost burden associated with training—there was no fee to participate, and participants received meals and financial support for travel expenses (some of the participants drove more than 100 miles one way).

Coordination with the chapter leadership[2] and local nonprofit partners was instrumental to the success of the program. The chapter leaders not only streamlined the process with their approval but also invested their time by sitting in on part of the training and then launching solar projects in their communities; and a local nonprofit partner, Tó Nizhóní Ání ("Sacred Water Speaks"), provided resources such as classroom space, advertising, and meals.

The 7-week program included meeting 2–4 days/week to learn PV theory in a classroom setting and hands-on training for participants to eventually build their own 55 watt PV system. A portion of the class time was spent on professional development (e.g., resume writing, LinkedIn, mock interviews). Invited guest speakers shared their experiences working in tribal communities, empowering entrepreneurs, and leading renewable energy projects and energy policy efforts. All 10 participants completed the program and earned their OSHA 10 certification.

In 2021 NRI started hosting virtual training in response to the covid-19 pandemic and limitations on in-person gatherings. The goal was to provide an off-grid foundation before beginning hands-on training. The cost of training was heavily subsidized for the 10 invited participants, who were asked to commit to spending 30 hours over 4 weeks at their own pace to complete the training.

The six participants who fulfilled all requirements received a certificate of completion and were invited to continue their hands-on training. One unfortunate challenge for some tribal members is not having high-speed internet access to watch educational videos or take online quizzes.

[2] The Navajo Nation is divided into 110 local governance centers known as chapters.

Opportunities

Both resource and infrastructure challenges suggest opportunities to develop energy systems that integrate electricity and energy efficiency, while reducing greenhouse gas emissions.

Innovative, interdisciplinary programs are needed to solve energy access issues in an affordable and sustainable way. One potential solution is to provide financing options that incorporate financial literacy and nontraditional lending. Advances in technology, materials, and manufacturing processes can also improve the affordability of critical needs for families, including efficient appliances and internet access.

Policies can promote a clean energy economy, climate resilience, and equitable energy access for Indigenous communities. They can also enhance data privacy, support infrastructure improvements, and expand opportunities for tribal leadership and community organization input.

Increasing investment in Indigenous communities (e.g., access to capital, technical assistance, skills building) is necessary to continue building a thriving economy.

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We are working to develop systematic, comprehensive assessment instruments for our engineering innovation and entrepreneurship training program.

Are We Making a Difference? A Case Study of Assessment in Innovation Training

Lyn Denend, Paul G. Yock, Josh Makower, Dan E. Azagury, and James K. Wall

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James Wall

Over the past several decades, universities in the United States and abroad have seen exponential growth in training programs in innovation and entrepreneurship. Although substantial talent and resources have been invested in creating a variety of offerings, there is no consensus on the best means of measuring the impact of these programs on the careers of the trainees (Lyons et al. 2015). We present a case study that tracks how we developed and deployed assessment methods for a program in health technology innovation over a 20-year period.

Lyn Denend is director for academic programs at the Stanford Byers Center for Biodesign and a lecturer in the Stanford School of Medicine. Paul Yock (NAE) is the founder of Stanford Biodesign, the Martha Meier Weiland Professor of Medicine, and founding cochair of and professor in Stanford's Department of Bioengineering. Josh Makower (NAE) is cofounder and director of Stanford Biodesign. Dan Azagury is director for education and James Wall is director for program development for the Biodesign innovation fellowship program; both are also associate professors of surgery with Stanford Medicine.

Background

Stanford Biodesign was launched in 2000 as an interdisciplinary postgraduate training experience in the medical technology (medtech) space.[1] The design of the program was shaped by several major trends in industry and academia. In industry, medtech was experiencing a remarkable period of growth, with robust startup activity in California's Silicon Valley and other technology hubs. Students from engineering, medicine, and business were increasingly attracted to careers in this dynamic sector. At the same time, there was a developing awareness on university campuses that innovation could be approached as a discipline, with design thinking and entrepreneurship blended into popular new course offerings at both the undergraduate and graduate levels (Kelley and Kelley 2013).

We needed a more systematic evaluation of career outcomes and of the program elements influencing them. But determining what to measure proved difficult.

In the context of this emerging landscape, Stanford Biodesign chose an initial focus on postgraduate training. There appeared to be an educational "white space" for engineers and physicians at this level who wanted to develop careers in medtech entrepreneurship or intrapreneurship (innovation-based careers in existing companies).

At the time, courses in innovation and design at the undergrad and graduate levels did not offer sufficient depth in critically important areas such as intellectual property, regulation, reimbursement, and business planning. Engineers or physicians who directly entered industry careers were typically channeled in their early years into focused technical roles and did not gain enough breadth from their experiences to feel confident in launching entrepreneurial careers. And although business schools were increasingly offering courses on innovation and entrepreneurship, there typically were not specific offerings in the medtech domain.

The Biodesign Innovation Fellowship

The initial structure of the Biodesign Innovation Fellowship was unique in several ways. We recruited engineers and physicians who had finished their graduate training. Some of the engineers had industry experience; physicians generally had completed their residency. Fellows were assembled in teams of four, combining physicians and engineers from different backgrounds. Fellows received a stipend on a postdoctoral-level scale for this 1-year experience, which resulted in a certificate of completion.

The training curriculum (dubbed the "biodesign innovation process") was a medtech-specific version of needs-based design thinking (Yock et al. 2015).[2] The fellows learned and practiced the process through a project-based educational experience intended to equip them to

1. identify and prioritize important unmet health-related needs,
2. invent and vet new technologies to address the most compelling of these opportunities, and
3. develop detailed implementation plans to bring the concepts into further development and commercialization (see figure 1).

The fellowship drew heavily from the local medical technology ecosystem for experts, mentors, and coaches with real-world experience to help train and coach the fellows as they advanced their project through this process.

Early Program Evaluation

Participant Feedback

For the first several years, program evaluation was primarily limited to a year-end feedback session with the outgoing fellows. Program leaders did not perceive a need for significant change, since fellows completing the training were successfully launching medtech innovation careers in industry and academia. In some cases, fellows were successful in founding and leading their own startups based on technologies they originated during their training.

[1] Stanford Biodesign became the Byers Center for Biodesign in mid-2016.

[2] Over time the program evolved from roots in cardiovascular medicine to all disciplines of health care (Augustin et al. 2020; Nimgaonkar et al. 2013; Schwartz et al. 2016).

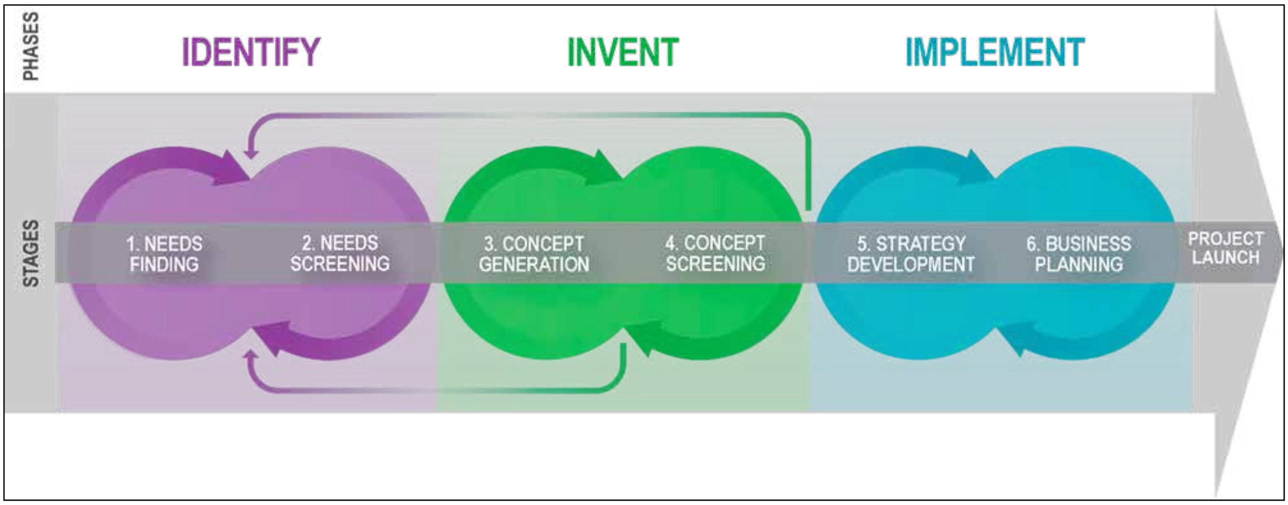

FIGURE 1 The Stanford Biodesign innovation process. Reprinted with permission from Yock et al. (2015).

After approximately 10 years of gradual program evolution, faculty and core advisors recognized the need to provide a more systematic evaluation of career outcomes, as well as an assessment of the elements of the program that could be influencing those outcomes. But determining what to measure proved difficult.

Retrospective Analysis

We did a retrospective analysis that focused primarily on the startup activity of the individuals trained in our innovation fellowship as well as a graduate course and two global partner programs[3] that offered similar curricula. The results (Brinton et al. 2013) showed a solid tally of entrepreneurial successes. By this point 26 new companies (of which 15 had been launched by participants in our innovation fellowship) had originated directly from the combined training programs, $200 million in funding had been raised, and, most importantly, the new technologies had been used to help 150,000 patients.

Beyond startup formation, alumni who chose other career paths appeared to be placing well in existing companies or in university faculty positions. A few of the academic alumni had launched and were leading similar medtech-oriented programs at other universities.

These data, though encouraging at a macro level, did not directly address the actual learning outcomes of the fellowship program. Specifically, they did not indicate to what extent the skills acquired in the program equipped our fellows to assume leadership positions as innovators in startups, medtech companies, universities, medical centers, and organizations.

Approach to More Rigorous Evaluation

In 2014 we initiated a three-pronged approach to more systematically evaluate and improve the fellowship program:

1. conduct an in-depth qualitative evaluation of our educational inputs;
2. survey program alumni with respect to learning objectives, skills acquisition, and career productivity; and
3. track and assess the career pathways of our alumni and compare them to a matched group of individuals who did not complete the fellowship.

Assessment of Educational Inputs

For this qualitative assessment, we sought to identify unmet program needs through alumni focus groups, in-depth interviews with current fellows, and interviews with program mentors from the medtech industry. We sorted, coded, and summarized the information into major themes for improvement, reported below.

Survey of Alumni Learning Objectives, Skills Acquisition, and Career Productivity

To assess how well we met learning objectives, building relevant skills, and positioning the fellows for productive medtech careers, we conducted a detailed survey to probe alumni opinions about how beneficial the fellow-

[3] In 2007 we launched a joint fellowship program with India's department of biotechnology and the All India Institute for Medical Sciences in Delhi, followed in 2010 by a joint fellowship with Singapore's Economic Development Board and Agency for Science, Technology and Research (A*STAR).

ship program had been for their careers, how well it achieved specific educational goals, and how effective it was in teaching select skills.

Additionally, we sought to capture self-reported data on important productivity metrics, such as number of issued patents, patents licensed for human testing or commercial development, peer-reviewed publications, board seats, roles as clinical investigators for health technologies, and roles teaching/training others on the biodesign innovation process.

So as not to overburden alumni, we decided to conduct the survey every 3–5 years.

In an effort not to overburden alumni, we decided to conduct this survey every 3–5 years; it was first conducted in 2016 (Wall et al. 2017), and then again in 2020.[4] With fellowship leaders' personalized outreach we achieved a response rate over 90 percent for both surveys.

Comparative Career Tracking

To obtain more specific information about alumni career pathways, we initiated an effort to track their career outcomes. For those in industry, we gathered job titles and company names from public sources such as LinkedIn and company websites. For alumni on academic paths, we captured data from university websites.

For comparison purposes, we also collected similar data from public sources for finalists who interviewed for the fellowship but were not selected (Wall et al. 2017).[5] As background: Each year we interview a finalist group that is approximately twice the size of our final cohort (e.g., 24 finalists for 12 fellows chosen). These finalists are selected from an applicant pool of approximately 150 individuals. While clearly these two groups (fellows and finalists) are not matched in any statistically significant sense, the intent of this analysis was to explore any large differences in individual career trajectories that might lead to a better understanding of candidate selection and/or impacts of the fellowship program.

In parallel, we continued collecting data on the companies launched based on technologies conceived by the fellows during the training program.[6] Company metrics are tracked by an annual survey of fellowship alumni who founded medtech startup companies based on their fellowship projects and reflect all stages of funding until acquisition or closure. The data included number of companies founded, total funding raised, number of employees hired, status/stage of the company, and total number of patients helped by the technologies as self-reported by the founder(s) (based, for example, on their records of patients enrolled in clinical trials and sales data).

Findings and Implications

Educational Inputs: Categories for Improvement

Our initial interviews and the 2016 survey indicated that the fellowship was generally equipping fellows to be successful in a variety of roles in medtech innovation. However, program alumni and external mentors sent a clear message that the curriculum was not evolving at the same pace as the rapidly changing environment we were preparing our fellows to enter. Opportunities for improvement fell into five main categories:

- Provide specific training and mentoring on *health economic and commercial value* as an increasingly important determinant of the commercial viability of a new technology.
- Reorient the needs identification experience and the innovation process we teach toward health *outside of the hospital*—in clinics, ambulatory care centers, community facilities, home care, and rehabilitation centers.
- More deeply address *engineering fundamentals*, including more advanced prototyping and technical derisking.
- Provide mentoring "beyond the pitch" to support more in-depth training around *commercial translation* (team building, business planning, fundraising).

[4] The Stanford Institutional Review Board determined that a survey for program improvement did not meet the definition of human subjects research.

[5] The names of finalists who interviewed for the fellowship but were not selected were not available for the academic years ending in 2002, 2003, 2004, or 2009.

[6] In this context, we define a company as an entity that has raised at least $250,000 in external grant and/or private capital funding, licensed intellectual property from Stanford or other relevant owner (if applicable), and completed incorporation.

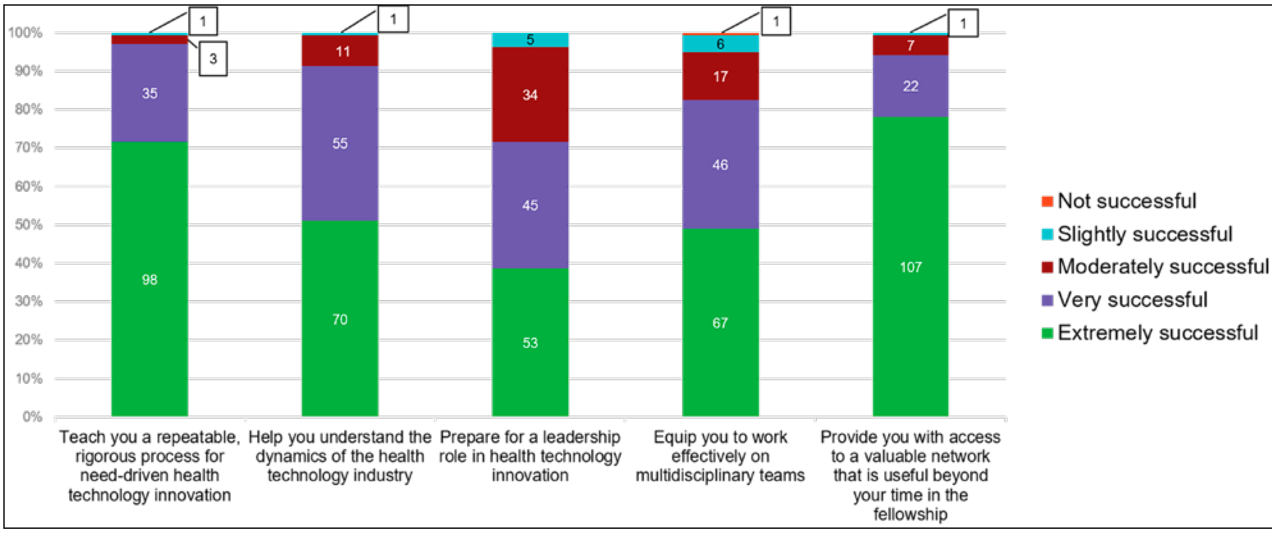

FIGURE 2 Success rate of the Stanford Biodesign Fellowship in achieving learning goals (number/percentage of 2020 survey respondents). Source: Stanford Biodesign 2020 Innovation Fellowship Alumni Survey.

- Increase the focus on individualized *career placement and mentoring* to help alumni succeed after completing the fellowship.

In response to this feedback, we created advisory teams composed of faculty and outside experts in each opportunity area to coordinate the development and implementation of relevant new content in the fellowship curriculum.

Progress against these improvement objectives was tracked as part of our qualitative survey work, allowing for further iteration. For instance, figure 2 from the 2020 survey shows that we need to do more to explicitly prepare our alumni for leadership roles. Accordingly, we recently expanded our career placement and mentoring workstream to include curriculum enhancements related to professional leadership development.

Learning Objectives and Skill Acquisition

Despite efforts to strengthen our educational input described above, the 2020 survey reinforced that we still have room to improve when it comes to the areas of engineering fundamentals, economic value, and commercial translation, as well as team building and conflict management. We identified permanent internal leads with specialized knowledge and expertise in these areas, and they further expanded the curriculum and established specific deliverables to enhance skill acquisition and the educational experience in these zones.

These workstreams were further improved through the creation of "bootcamps." During each fellowship year the fellows receive 2–3 days of intensive didactic and project-based instruction in engineering, value, and commercial translation at the respective points in the process when these skills are most needed to advance their projects.

To address team building and conflict management, we expanded our use of a psychologist specializing in team and interpersonal dynamics to meet with and guide the fellowship teams on a biweekly basis.

Career Productivity

The measures of impact we consider most important are the numbers of patients helped by technologies invented by the fellows and alumni, followed by certain business metrics. By the time of the 2020 survey, 3.35 million patients had been helped by technologies initiated by fellows during the program, and an additional 1.4 million patients were helped by technologies subsequently invented by alumni (table 1). In aggregate, companies formed by fellows either during or after the fellowship have raised nearly $1.9 billion in funding, and account for 1850 new full-time positions.

Several other measures of career productivity are worth highlighting. Among the 137 who responded to the 2020 survey of 149 alumni, they hold a total of 93 board seats in health technology companies. Among responding clinician alumni, 1 in 2 have led clinical trials of a new technology. Among all responding alumni, 2 out of 3 have at least one US patent. And 91 percent of the responding fellows have formally or informally

TABLE 1 Metrics related to technologies invented by Stanford Biodesign fellows. Source: Stanford Biodesign 2020 Innovation Fellowship Alumni Survey.

Technologies initiated...	Companies founded	Full-time employees	Funding raised	People helped
during the fellowship	29	1205	$770 M	3,350,000
after the fellowship	68	647	$1.1 B	1,400,000
Total	97	1852	$1.87 B	4,750,000

trained or coached others on aspects of the biodesign innovation process, with an average of 154 trainees per alumna/-us.

Finally, as an overall qualitative measure, 94 percent of alumni responding to the 2020 survey said they found the fellowship beneficial to their career development (2 percent said it was only slightly beneficial). And 91 percent reported that the fellowship was influential on their chosen career trajectory (5 percent indicated that it was only slightly or not influential on their choices).

Comparative Career Tracking

The comparison of alumni with the group of finalists (as described above) indicates that our alumni choose careers in the health technology field in greater numbers than candidates who interviewed for the fellowship but were not selected (figure 3). They also hold leadership positions at a higher rate than the comparison group (figure 4).

Limitations

We recognize that there are significant limitations in our approach to assessing the three domains of our program. For instance, data gathered from public sources are prone to error; self-reported input is inherently subjective; and our use of a comparison group that is not formally matched has major shortcomings. On this basis, our findings described here must be considered directional in nature.

An overriding challenge is the lack of validated assessment instruments in the area of engineering innovation and entrepreneurship training (as opposed to core engineering education).

An analysis of the wide variety of published approaches to assessment yielded a taxonomy of the instruments used (Purzer et al. 2016). Like the large majority of the 50-plus assessment approaches reviewed in that study, our analysis is primarily "summative" (designed to assess the program itself), "local" (addressing only one program), and survey-based. The authors of the 2016 analysis raise the concern that few studies provide any validation of the assessment instrument used and suggest that a group comparison is one important method where feasible. Our study at least attempted a group comparison, albeit with the significant shortcomings mentioned.

Future Opportunities

Despite the limitations outlined above, our approach to gathering more expansive data about the effectiveness of our fellowship has been useful in several respects.

We now understand that tracking only the technologies/companies founded out of our fellowship—the easiest data for us to "count"—was leading us to be complacent about the design and conduct of our training program. Through detailed surveys and focused interviews, we uncovered areas in our curriculum that needed enhanced attention. Similarly, we realized that we were missing and/or undervaluing substantial alumni career activities other than startup formation.

This work also has motivated us to explore a different category of skills assessment. As explained, our fellows learn and practice an innovation process that begins with identifying important unmet health needs. We teach the use of specific tools for needs characterization, including the creation of a need statement and development of need criteria that specify (in advance) the features that a successful invention will require. In conjunction with providing training on how to use these tools, we teach how to perform observations and conduct stakeholder interviews to augment secondary research and provide the background for needs characterization.

Although we have evolved our teaching approaches in these areas, we have not yet developed objective assessment techniques for evaluating the quality of observations and interviews or the resulting need statements and criteria. To date, this type of evaluation has been subjective and dependent on the perspective of the instructor or coach who is providing feedback. We

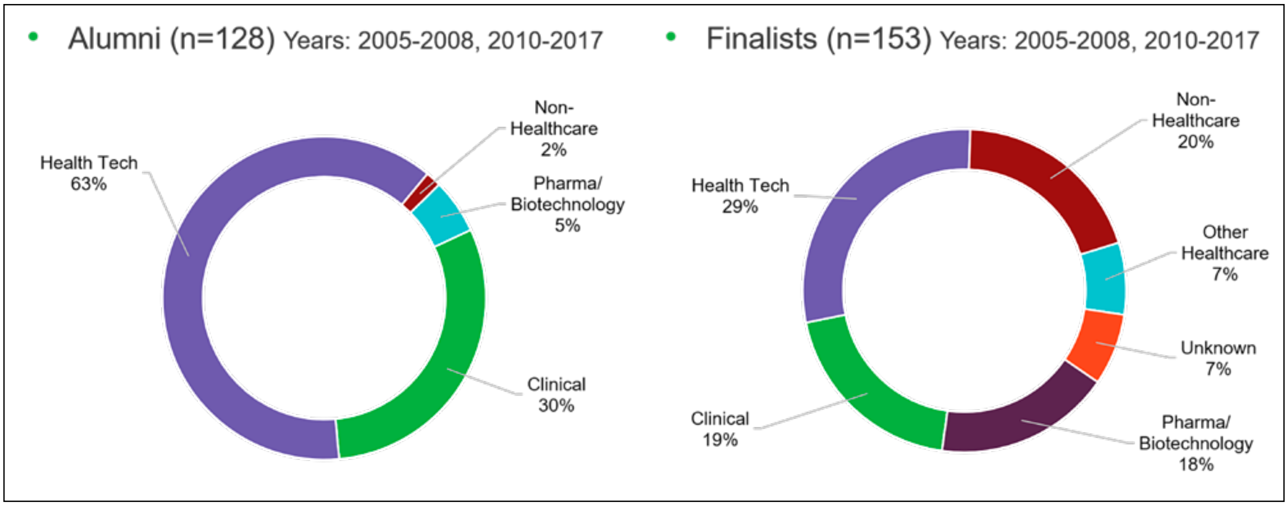

FIGURE 3 Career type by primary role, Stanford Biodesign alumni and comparison group (see text for explanation). Source: Stanford Biodesign 2020 Innovation Fellowship Alumni Survey.

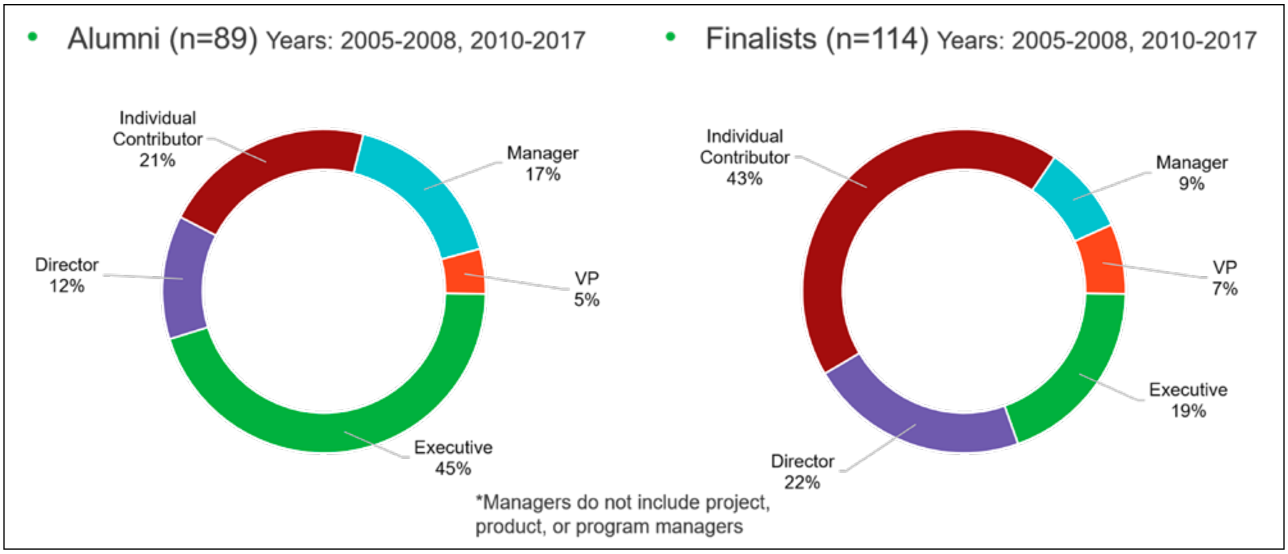

FIGURE 4 Leadership positions, Stanford Biodesign alumni and comparison group (see text for explanation). Source: Stanford Biodesign 2020 Innovation Fellowship Alumni Survey.

now have an opportunity to develop and test a more objective approach to assessing work quality in these critically important areas.

Conclusion

Designing, implementing, and sustaining assessment activities requires a significant investment of resources. Over the past 2 decades, we have refined our approach from an ad hoc, year-end review to a systematic tracking of career data of our alumni, resulting in major changes to our program. Next, we will continue to develop and validate instruments to better perform knowledge and skills assessment relevant to our specific training approach.

Our understanding of assessment in the areas of innovation and entrepreneurship training is still evolving. But we are encouraged that the evidence shows that this type of education does make a difference in the career choices, trajectories, and productivity of the participants.

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An Interview with . . .

Janet Hunziker, Director of the NAE's Frontiers of Engineering Program

RON LATANISION (RML): We're delighted to talk with you, Janet. For this issue of *The Bridge*, featuring selected papers from the US Frontiers of Engineering symposium, and coming on the heels of the FOE's 25th anniversary last year, we'd like to explore with you the origin of the program and your role in it.

JANET HUNZIKER: The program was approved by the NAE Council in 1994, and it was really at the impetus of **Dale Compton**, who was serving on the council at the time. The National Academy of Sciences had started a Frontiers of Science program in 1989. That program brought together nationally recognized—defined as those who had won prestigious academic awards such as the precursor to the Presidential Early Career Award for Scientists and Engineers—early-career scientists. Dale said to the council, 'We need to do this for engineers,' and they approved the start of a Frontiers of Engineering program. We received funding from the National Science Foundation as well as DOD, NIST, and the Engineering Foundation to launch the program, and we held our first meeting in 1995.

Bob Brown was the first chair of the US FOE—he served 2 years—and then he also was the first chair when we initiated the German-American FOE (GAFOE) program in 1998. So he was involved in the origin of not only the US but also the first bilateral program, with Germany.

Similarly, **Rob Wagoner** served as chair for the US meeting and subsequently as cochair for the FOE meeting with Japan (JAFOE) when we started that series in 2000. The US chairs and cochairs are always NAE members, and now they are often alumni too.

RML: How did you make the transition to setting up international programs?

MS. HUNZIKER: Those were at the request of entities in other countries. The German American Academic Council (GAAC) in Germany was already partnering with the NAS to carry out the German-American Frontiers of Science program, and that was going well, so they approached us to start the German-American FOE. When the GAAC dissolved, the Alexander von Humboldt Foundation (AVH) took over as our partner in 2001.

RML: That is interesting. I was a Humboldt fellow early in my career and I spent a year in Germany with their support.

Let's back up a bit and talk about the US version and the original concept. How did you go about putting together a program? Did Dale or Bob Brown or Rob Wagoner provide some help in identifying speakers and venues? How did that all come about?

MS. HUNZIKER: From the very beginning, Bob Brown was instrumental in helping us formulate the format for the meeting. The Frontiers of Science has eight sessions over 2½ days. They cover more science disciplines in the same amount of time but not at as deep a level. Bob said, 'We are engineers, and we need to change this a bit.' So we decided to cover four topics over the 2½ days, but with more speakers on each topic to provide a broader sense of the applications in each area.

The first step, then as now, is to select the topics. It's fascinating to look back and see what was covered at

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This interview took place November 9, 2021. It has been edited for clarity and length. Names in bold are NAE members.

the early meetings and what we are covering now. At the very first meeting, back in 1995, the session topics were Advances in Biotechnology (**Frances Arnold** was a speaker on directed evolution), Design and Manufacturing of Commercial Products, Engineering in the Urban Environment, and Information Technology.

CAMERON FLETCHER (CHF): How were those topics selected?

MS. HUNZIKER: I don't remember exactly, but I'm sure that Bob Brown had a lot of input and perhaps Dale as well, and probably Bruce Guile, director of the NAE Program Office at the time.

In the IT session at the first meeting, in 1995, David Patterson connected to the internet. It was amazing for everyone.

One interesting thing about that 1995 session on IT is that **David Patterson** gave a talk that included a demo connecting to the internet. It was amazing for everyone.

RML: A real demonstration! I remember when Chuck Vest became president at MIT in 1990, he was the first MIT president to have a computer in his office. It rolled through the institute like a snowball—everyone started putting computers in their office. It really was a seminal moment. People stopped writing letters—it was done electronically. It changed our world—sometimes for the better, sometimes maybe not. It was certainly a major change in the way we function.

In the current context do you have a committee that helps you identify speakers and set the agenda in terms of topics?

MS. HUNZIKER: I get the ball rolling with the chair (or, in the case of the bilaterals, the cochairs) by sending a list of five or six possible topics; these come from various sources, including recommendations from previous participants. We conduct a survey after each meeting to assess how we did, and we also ask for suggestions of topics for future symposia. I look at what we've already covered—we don't want to repeat the same topics—and the chair or cochairs provide input and their own suggestions. I run the final list by **Al Romig** for approval. With the bilateral planning we want to make sure that the session topics represent areas where both sides have expertise. We don't want to pick a topic where one side would have difficulty finding good organizers or speakers.

Next we pick the session organizers, who are also early-career engineers, as this is a meeting organized both by and for that particular cohort. At this point we have a substantial alumni group, and I typically go to them first to find session organizer candidates. The job of the organizers is to plan the presentation topics and recommend speakers. Since they've attended a meeting, they know what works in terms of the kind of talk we need for a technically sophisticated but nonspecialist audience. For the bilaterals, each session has two organizers—an American and someone from the other country (or region, in the case of the European Union)—and two speakers from each country. The two sides work as a team to plan their session. For both the US FOE and bilateral FOEs, the final list of speakers and topics is approved by the symposium chair or cochairs.

RML: Is there is an effort to align the bilateral meetings with the US meeting in terms of topics?

MS. HUNZIKER: They're separate. Each meeting has its own organizing committee, which serves for one meeting, and the topics are considered separately. Occasionally there's some overlap; for example, we've recently had quantum computing as a session topic at a US meeting and a bilateral meeting. But the participants are not the same so this is not an issue when a topic is covered at two different meetings.

RML: How are the cochairs identified?

MS. HUNZIKER: As I mentioned earlier, FOE chairs and US cochairs are always NAE members. Every year after the NAE election the Membership Office runs a list of members under age 50 or 55, and we select from that. There are now 140 NAE members who are FOE alumni—they participated in an FOE meeting and were subsequently elected to the NAE—so they bring that experience to their service. There are another 22 NAE members who became involved with the program after their election.

I don't want to imply that participating in Frontiers meetings is a track to election, but I am always delighted to see FOE alumni on the list of newly elected NAE members.

RML: I would say that those elections are a testimonial to the fact that FOE attracts really good young people. When I look at what they've accomplished, they are truly deserving of membership.

CHF: I have a couple of questions. Are the FOE participants who go on to be elected to the NAE predominantly speakers or participants or is it a mix?

MS. HUNZIKER: It's a mix. I haven't looked at that particular datapoint but because there are more general participants than speakers or organizers, I would guess that more general participants are subsequently elected. There is a competitive selection process for the US FOE meeting, which then trickles across to the bilaterals because we don't do a separate nomination and application process for those meetings.

CHF: That was my second question: How do you identify the general participants (as opposed to the presenters)?

MS. HUNZIKER: For the US FOE, NAE members get an email from the president in mid-February, asking for nominations for that year's US FOE meeting. In addition, we reach out to chief technical officers and VPs of corporate engineering and research, federal lab directors, deans of engineering, and others who are not NAE members. We also look at recipients of distinguished awards. After the nomination period closes, we contact the nominees, tell them about the program, and ask them to apply to attend. Being nominated does not mean that one is automatically invited. This year we had 360 applicants for 83 slots.

RML: That's fantastic.

MS. HUNZIKER: Of the 100 attendees for the US symposium, we strive to have about 45 from industry, 45 from academia, and 10–12 from federal labs.

CHF: Like representation in the NAE membership. How are the applicants selected? It sounds a little like college admissions. And do you seek representation among the participants to align with the topics or are the participants from a much more general pool?

MS. HUNZIKER: In some ways it is similar to what I think college admissions officers go through because all the applicants are so strong and deserving to be invited. The organizing committee assists in the selection, and the chair makes the final selection based on their inputs. We want attendees at the meeting from all engineering disciplines, even if their expertise is different from the session topics. That's actually one of the nomination criteria: we want people who are interested in what's happening in areas other than their own and willing to engage with people who are doing that work.

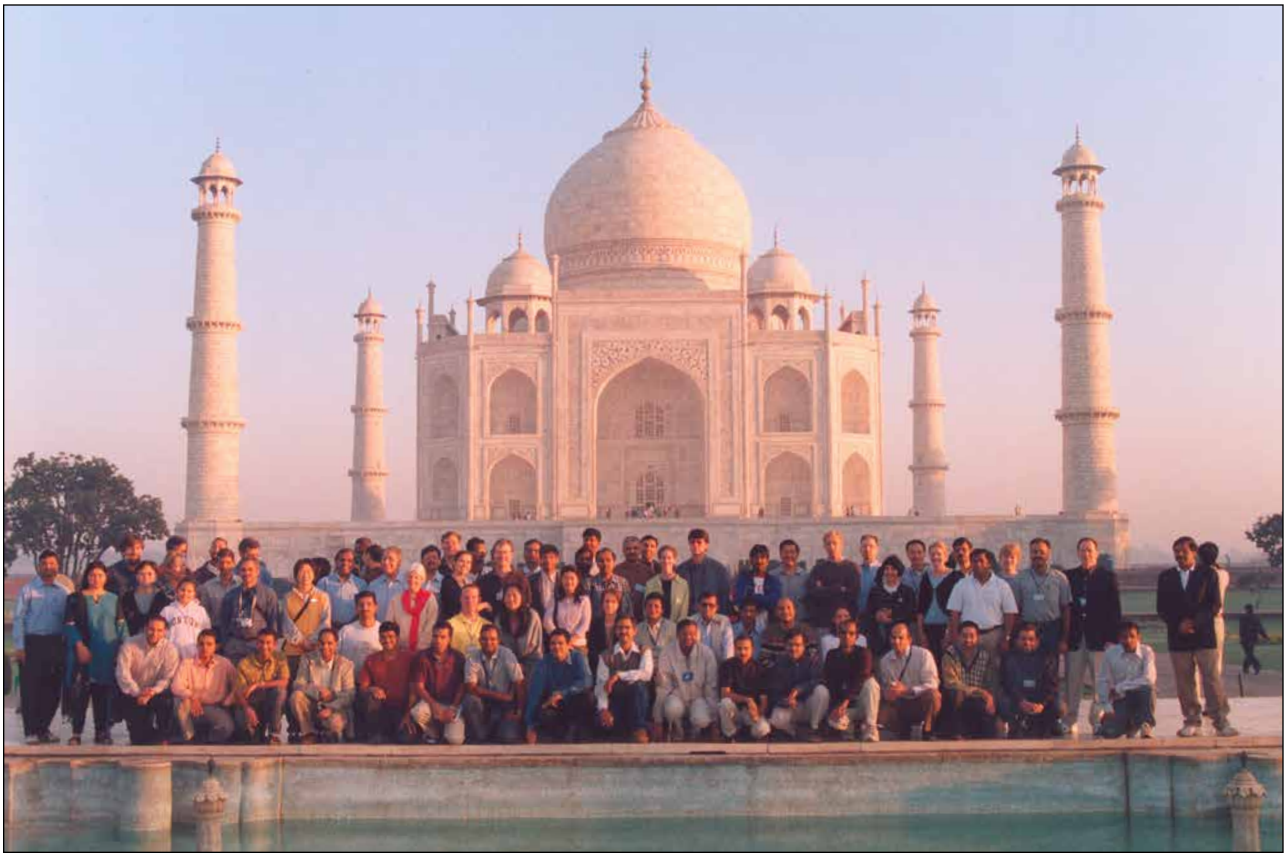
The goal of the program is to get people out of their silos for 2½–3 days and make connections that they can't make at their professional society meetings where they're with people in the same field.

We want people who are interested in what's happening in areas other than their own and willing to engage with people doing that work.

This is really where the ah-ha moments come, while listening to a talk about something very different from their own work but seeing where there are synergies in terms of techniques, approaches, and challenges. But it's not just sitting in an auditorium listening to technical talks. A lot of the magic happens during the informal times such as breaks and mealtime. That's one reason the pandemic has been really hard for us; we've moved to a virtual platform that captures some of the elements of the meetings, but it's not the same as talking face to face. The FOE meetings are about having a conversation with someone you wouldn't meet in any other setting and making that connection that leads to new ideas and possible collaboration.

CHF: I was involved in the Frontiers of Science Symposia for several years at its outset, from 1989 to 1994 or '95, after which the program was moved out to Irvine and I declined to move across the country. What a rewarding and exciting experience it was to be involved with those. Janet, I hear the same level of excitement and enthusiasm in your voice as you're describing what it's like to be at the FOE events.

MS. HUNZIKER: I went to the Beckman Center to observe a Frontiers of Science meeting in 1994 so I



Participants in the first Indo-US Frontiers of Engineering (March 1–4, 2006, in Agra) visited the Taj Mahal.

would see what a Frontiers meeting was like. I remember you there.

RML: In principle, the meeting should provide a broadening influence on the thoughts of these early-career attendees. If it were only related to their specialty, they can go to a professional society meeting and get that. This should be mind expanding. From people I know who have been participants, the reviews are raves. They just love it. Many of them keep in contact, which is even more important, and get to know one another. I think that is a testimony to the vision and the effectiveness of what you do.

MS. HUNZIKER: To that point, a participant at the first German-American FOE, in 1998, told me a couple of years ago that she's still collaborating with a German colleague she met at that meeting.

RML: That's great. How many bilateral meetings are there? And what other countries are involved?

MS. HUNZIKER: We have active programs with Germany, Japan, China, and the European Union. The program with India (2006–14) has been on hiatus because we haven't been able to raise funding for it.

CHF: How did the other bilateral symposia emerge? You indicated that the Germans approached the NAE; what about the others?

MS. HUNZIKER: My recollection is that the NAE may have been looking for an opportunity to do something with the Engineering Academy of Japan. This would have been in the late 1990s. The Japanese were receptive, and that program started in 2000. For the India program, we were approached by the Indo-US Science and Technology Forum. After the first Grainger Foundation grant came in 2008, we were able to start programs with the EU and China.

Actually, before the EU program was started, we had been approached by France and by some other countries about starting a bilateral with them; but there is a limit to how many bilaterals we can do, so working with an umbrella organization of European academies of engineering was a better approach. I have to give credit to former NAE executive officer Bill Salmon (1986–98) for finding us a European partner for the EU-US meeting. Euro-CASE[1] organizes inputs from the European academies, and for the individual meetings we work with different national academies of engineering. So far we've partnered with academies in the UK, France, Finland, and Sweden, and for the 2022 and 2023 EU-US FOE meetings, we will work with the Slovenian Academy of Engineering.

CHF: For the EU symposia, is there consideration to not include Germans since they have their own FOE program?

MS. HUNZIKER: Since the bilateral with Germany was our first, and the Humboldt Foundation wanted to maintain it, we have continued to have a separate GAFOE meeting after starting the EU-US FOE. Germans are involved with the EU-US FOE as well through acatech's membership in Euro-CASE.[2]

RML: How do you see the future evolving with Frontiers? You mentioned that there's a limit to how many bilaterals, for example, are manageable, unless you extend staff, I would guess. How do you see the future in terms of where you would like to go programmatically or in terms of interactions with other nations?

MS. HUNZIKER: Funding is the biggest constraint. This is a good chance for me to call out FOE's wonderful sponsors. A grant from The Grainger Foundation provides annual core support for the program with additional funding from government agencies such as NSF, DARPA, and DOD and from individual contributions. We also get in-kind support when companies, universities, and federal labs host meetings. And this year we received grants from **Fran and George Ligler** and from FOE alum **Rob Wagoner** and his wife Robyn. The Liglers' grant is going to support alumni engagement, and the Wagoners' gift is in the form of an endowment. We've also launched an alumni challenge, again thanks to the Liglers and the Wagoners.

You're right that adding more programs means adding staff; we're pretty maxed out in terms of what we can do now. I think we could add another program with current staff, and we're considering one called Five Eyes Frontiers of Engineering. It was suggested by **Al Romig** and would involve the five English-speaking countries that exchange national security and intelligence information: Australia, New Zealand, Canada, the UK, and the US. We've had a couple of meetings about this with the national academies in those countries but have delayed fundraising until after there is a clear path to in-person meetings.

It would be great if we could restart the India-US program because there's tremendous talent in India, and the five meetings we held with them were wonderful opportunities to bring together engineers from our two countries.

CHF: What about South America or Africa?

MS. HUNZIKER: The NAS and NAE worked together to hold a Brazil-US Frontiers of Science and Engineering in 2014. It was a one-off initiated and supported by NSF. The champion of that program left NSF, and we were unable to get funding for a second meeting. I think the National Academies would be very interested in initiating Frontiers-type meetings with Latin America on a regular basis.

We're considering a new FOE program with the five English-speaking countries that exchange national security and intelligence information.

We've tried to raise money to start a program that would involve maybe four or five countries in Africa, but that has also been very difficult. Covid put a brake on that as well, but even before that it was difficult to raise money for it.

The Arab-American Frontiers of Science, Engineering, and Medicine is staffed by Dalal Najib in the National Academies' Policy and Global Affairs Division, and they just held their eighth meeting in November.

CHF: Turning to a different topic, in the past few years I think you've really expanded your alumni outreach activities. Can you tell us what you do for your alums?

[1] The European Council of Academies of Applied Sciences, Technologies, and Engineering

[2] acatech [sic] is Germany's National Academy of Science and Engineering.

Attendees at the 2021 US FOE Symposium, September 22–24, at the Academies' Beckman Center in Irvine, CA.

MS. HUNZIKER: I think alumni engagement is really important. We don't want Frontiers to be just a meeting that people attend for 3 days and then that's it. We want to build a network of engineers and keep them engaged both with the NAE and with each other. One way to do this is by using the FOE alumni database to find candidates with a particular expertise for NASEM study committees and other engineering-related outreach. In fact, after this meeting I have a call with an NAS staff officer about some names to put forward for a study. The directory allows FOE alumni as well to access the database in the same way.

On the Frontiers of Engineering website, naefrontiers.org, the Alumni Spotlight features six alumni, and twice a week we post news about recent developments in the research and technical work of our alumni. Sherri Hunter is responsible for the Spotlight and Latest News features (among many other things) and I want to credit her for maintaining those elements of the website. We issue a newsletter twice a year and invite FOE alumni to the NAE's regional meetings where they can connect with other alumni and NAE members as well as participate in interesting technical programs.

I also want to mention the Armstrong Endowment for Young Engineers–Gilbreth Lectures. **John Armstrong** provided an endowment for this lectureship that is awarded to four FOE speakers who give their presentations at an NAE national meeting. At each FOE symposium we ask the attendees to vote on who gave the all-around best presentation, and that informs our selection of the Gilbreth Lecturers. One great thing about the national meeting is that local high school students attend, so we try to select speakers and topics that are particularly interesting to students and may inspire them to embark on engineering careers.

Finally, The Grainger Foundation Frontiers of Engineering Grants provide funding to US FOE attendees for joint research projects, and this is a great mechanism for supporting collaboration within the alumni network.

RML: I suspect there will be readers of this interview who may be interested in supporting the FOE. Could you give an indication of what the costs are? Or what's the best way to approach that?

MS. HUNZIKER: The program runs about $1 million a year. Thanks to some of our NAE members and others, we have held meetings at corporate, federal lab, and university sites. For the US meeting, in particular, that saves a substantial amount of money. We're going to hold the 2022 US FOE at Amazon. We were supposed to be at CU Boulder for the 2021 US FOE but they will host in 2023 instead. We are very grateful for that support.

RML: So anyone interested in providing support could simply reach out to you?

MS. HUNZIKER: Yes, or they could contact the NAE's development officer, Radka Nebesky (RNebesky@nas.edu). And many wonderful NAE members give to the program through Development Office solicitations for the NAE. We appreciate their gifts!

RML: Since the program was launched, I wonder what sorts of trends you've seen in terms of the participants? I'm thinking of current concerns about gender and equity and diversity, for example. Have you seen growth in the number of women, for example, among the participants? I would be delighted if you said yes because I have four granddaughters and I hope some of them are going to become engineers!

MS. HUNZIKER: I'm so glad you asked that question because at the US FOE for the past 3–4 years, we've had 48–49 percent female attendees.

RML: That's fantastic.

MS. HUNZIKER: Yes, it's really great. A couple of years ago, an attendee wrote on her postmeeting survey, "This was such an amazing experience. I walked in and there were all these women there! That's never happened to me at an engineering meeting before."

And when we held the meeting at Boeing in 2019, the dinner speaker, Joan Robinson-Berry, who at the time was vice president of engineering, modifications, and maintenance for Boeing Global Services, said, "I look across this audience and I see America." That is what we should be aiming for: a group of attendees who look like America. It is not enough for us to simply match the percentages in engineering for certain demographics. The most recent and current US FOE chairs, **Jennifer West** and **Tim Lieuwen**, respectively, have been very attuned to this.

In fact, at the September US FOE there were a number of attendees from R2 schools, which typically haven't been as well represented at the Frontiers meeting.

CHF: You mentioned the representation of women, what about Black and Brown people?

MS. HUNZIKER: The percentages are probably equivalent to this generation in the engineering profession. So we're meeting expectations there. We're reaching out with a number of mechanisms in the nomination process to try to get a diverse nomination pool.

CHF: So that might include outreach to HBCUs and Hispanic-serving institutions?

MS. HUNZIKER: Yes, as well as affinity societies. And a couple of alumni are diversity officers now at their institutions and are in positions to assist in this regard.

RML: I think we particularly need to engage more women—of every race, ethnicity, background. When my wife sees something technological that doesn't really seem appropriate, she says, 'You know, if there were women involved, they wouldn't have made that decision.' I think she's right.

We should be aiming for a group of attendees who look like America.

We are a diverse country but we seem to have a lopsided view on how to roll out technology and what technology is useful. We are a diverse population and yet we are making decisions on a much more limited basis. So I think what you just said, Janet, is really important.

MS. HUNZIKER: In closing, I want to reiterate that the FOE program is all about the people and the connections, both those that the NAE makes with the alumni and those they make with each other. In some cases attendees have said their participation was life changing in terms of the direction of their research and the connections they made. This is so beneficial for the engineering profession.

RML: Yes, it is. The Frontiers of Engineering is really an important part of the culture of the NAE, and you do a heroic job in managing it. I thank you on behalf of all the members—as well as many people who are not yet members and many who have not even been participants yet.

MS. HUNZIKER: Thank you for this opportunity to talk about the program.

NAE News and Notes

NAE Newsmakers

James L. Barnard, global practice and technology leader, Black & Veatch, has been honored with the American Society of Civil Engineers' (ASCE) **Outstanding Projects and Leaders (OPAL) Award** for design. The OPAL award is bestowed upon exceptional civil engineering leaders in recognition of their lifetime achievements. As a design practitioner in advanced water pollution control Dr. Barnard is recognized for his innovation and excellence in civil engineering design. The biological processes he developed for the removal of nitrogen and phosphorous from used-water facilities are applied worldwide.

Alan C. Brown, retired director of engineering, Lockheed Corporation, has been awarded the **2021 Daniel Guggenheim Medal** for his innovation and technical leadership of the design and production of the F-117, the first stealth fighter/bomber aircraft. The medal was established in 1929 to honor innovators who make notable achievements in the advancement of aeronautics.

Arup K. Chakraborty, Institute Professor, professor of chemical engineering, physics, and chemistry, Massachusetts Institute of Technology, was selected by the American Institute of Chemical Engineers to present the **2021 John M. Prausnitz AIChE Institute Lecture**. He presented his lecture, "Viruses, Immunity, and Vaccines," November 10 at the 2021 AIChE annual meeting in Boston.

Paula T. Hammond, David H. Koch (1962) Professor of Engineering and head, Department of Chemical Engineering, MIT, won the inaugural **Black in Cancer Distinguished Investigator Award**. Established through a partnership between Black in Cancer and the Emerald Foundation in response to racial abuse experienced by Black birdwatcher Chris Cooper in Central Park last year, this award recognizes Black excellence in cancer research and medicine. Professor Hammond gave the keynote address October 15 at Black in Cancer Week.

John L. Hennessy, director, Knight-Hennessy Scholars, Stanford University, and **David A. Patterson**, Distinguished Engineer, Google Inc., have been awarded the **Frontiers of Knowledge Award in Information and Communication Technologies** by the BBVA Foundation. Drs. Hennessy and Patterson are founders of the new scientific area known as computer architecture that designs the "brains" of computer systems. They were the first to devise a conceptual framework that provides the field with a grounded approach to measuring performance, energy efficiency, and the complexity of a computer.

M. Cynthia Hipwell, TEES Eminent Professor of Mechanical Engineering, Texas A&M University–College Station, received the **ASME Robert Henry Thurston Lecture Award**. The award is for an outstanding leader in pure or applied science or engineering to present a lecture on a subject of broad interest to engineers. Professor Hipwell's talk, "Heat-Assisted Magnetic Recording (HAMR): A Nanoscale Heat Transfer Adventure," will be delivered to ASME members January 21.

John L. Junkins, founding director of the Hagler Institute for Advanced Study at Texas A&M University, is the recipient of the **Kay Bailey Hutchison Distinguished Service Award** from the Academy of Medicine, Engineering, and Science of Texas (TAMEST). He is recognized for attracting and nurturing top-tier research talent in Texas through TAMU's Hagler Institute for Advanced Study. The award will be presented at the 2022 TAMEST Annual Conference: Forward Texas – Imperatives for Health, in San Antonio on January 11, and Dr. Junkins will give a presentation on the vision and history of the Hagler Institute on January 13.

Jay D. Keasling, Hubbard Howe Jr. Distinguished Professor of Biochemical Engineering, University of California, Berkeley, has been named a **Distinguished Scientist Fellow** by the US Department of Energy's Office of Science. Professor Keasling is recognized for "national scientific leadership in synthetic biology that has advanced DOE's strategy in renewable energy, especially the realization of biofuels and bioproducts that enable biomanufacturing at scale and inspire and grow the US bioeconomy."

Cato T. Laurencin, University Professor; Albert and Wilda Van

Dusen Distinguished Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering, of materials science and engineering, and of biomedical engineering; director, Raymond and Beverly Sackler Center for Biological, Physical, and Engineering Sciences; and chief executive officer, Connecticut Convergence Institute for Translation in Regenerative Engineering, University of Connecticut, has been **elected an international fellow of the Royal Academy of Engineering**.

John A. Rogers, Louis Simpson and Kimberly Querrey Professor of Materials Science and Engineering, Biomedical Engineering, and Neurological Surgery, Northwestern University, has received a **2021 Order of Lincoln**, the State of Illinois' highest honor for professional achievement and public service. Called "Lincoln Laureates," members of the Order of Lincoln are distinguished Illinois residents whose work uplifts communities around the state. Professor Rogers was selected for his pioneering biomedical technologies, which are poised to transform medical care.

J. Marshall Shepherd, Georgia Athletic Association Distinguished Professor and director, Department of Geography, Atmospheric Sciences Program, University of Georgia, is the recipient of the **2021 AGI Award for Outstanding Contribution to the Public Understanding of the Geosciences**.

John A. Swanson, University Support, University of Pittsburgh, Cornell University, and University of South Florida, was honored with the **2021 Cornell Engineering Distinguished Alumni Award** in recognition of his extraordinary leadership and vision, and the distinction he has brought to the college.

Maria C. Tamargo, professor, physical chemistry and inorganic chemistry, City College of New York, is the **2021 SACNAS Distinguished Scientist Award** recipient. The Society for Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS) cites Professor Tamargo for exemplifying its mission by showing unparalleled dedication to excellence in science, mentoring, and teaching. She was honored during the 2021 SACNAS National Diversity in STEM Digital Conference on October 28.

In honor of **Alfred A. Yee**, deceased president of Yee Precast Design Group Ltd., an endowed chair has been established at the University of Hawai'i at Mānoa's College of Engineering. The **Dr. Alfred A. Yee Chair of Sustainability and Resilience** will provide ongoing funding to recruit and retain outstanding faculty with expertise in sustainability and resilience, fueling competitive research, engineering sector resiliency solutions, and teaching in these critical areas. This is the College of Engineering's first endowed chair and was created by two anonymous $1 million gifts from the same donor. Dr. Yee helped design some of Honolulu's most complex structures, from the floating Arizona Memorial to Diamond Head Apartments, the first precast, prestressed concrete tower in the country.

At its annual meeting October 18 the National Academy of Medicine announced the election of new members, who included two NAE members. **Andrés J. Garcia**, executive director and Regents' Professor, Petit Institute for Bioengineering and Bioscience, Georgia Institute of Technology, was elected "For significant contributions to new biomaterial platforms that elicit targeted tissue repair, innovative technologies to exploit cell adhesive interactions, and mechanistic insights into mechanobiology." **Linda G. Griffith**, School of Engineering Teaching Innovation Professor of Biological and Mechanical Engineering, MacVicar Fellow, and director, Center for Gynepathology Research, Massachusetts Institute of Technology, was elected "For longstanding leadership in research, education, and medical translation; for pioneering work in tissue engineering, biomaterials, and systems biology, including developing the first 'liver chip' technology; inventing 3D biomaterials printing and organotypic models for systems gynopathology; and for the establishment of the MIT Biological Engineering Department."

The American Institute of Chemical Engineers announced 2021 prize winners; the award ceremony took place during the **AIChE** annual meeting November 7. **Kristi S. Anseth**, Tisone Professor and Distinguished Professor, Department of Chemical and Biological Engineering, University of Colorado Boulder, received the **Founders Award for Outstanding Contributions to the Field of Chemical Engineering**; **Zhenan Bao**, professor of chemical engineering, Stanford University, received the **Alpha Chi Sigma Award for Chemical Engineering Research**; **Stacey F. Bent**, Jagdeep and Roshni Singh Professor of Engineering, Stanford University, accepted the **Braskem Award for Excellence in Materials Engineering and Science**; **Arup K. Chakraborty**, Robert T. Haslam

Professor of Chemical Engineering and director, Institute for Medical Engineering & Science, MIT, received the **John M. Prausnitz AIChE Institute Lecturer Award**; **Liang-Shih Fan**, Distinguished University Professor and C. John Easton Professor in Engineering, Ohio State University, was given the **Institute Lecturer Award**; **Karen K. Gleason**, associate provost and Alexander and I. Michael Kasser Professor of Chemical Engineering, MIT, accepted the **AIChE Margaret Hutchinson Rousseau Pioneer Award for Lifetime Achievement by a Woman Chemical Engineer**; **Cato Laurencin** was honored with the **James E. Bailey Award** and the **Hoover Medal**; **Nicholas A. Peppas**, Cockrell Family Regents Chair in Engineering #6, University of Texas at Austin, received the **Warren K. Lewis Award for Chemical Engineering Education**; and **Doraiswami Ramkrishna**, H.C. Peffer Distinguished Professor, Purdue University, accepted the **William H. Walker Award for Excellence in Contributions to Chemical Engineering Literature**.

The Hagler Institute for Advanced Study at Texas A&M University announced its **Class of 2021–22 Hagler Fellows**. The fellows will collaborate with faculty, researchers, and students in the colleges of agriculture and life sciences, engineering, medicine and science; Texas A&M AgriLife Research; and the Institute for Quantum Science and Engineering. Among the eight new fellows are five NAE members: **Kevin G. Bowcutt**, principal senior technical fellow and chief scientist of hypersonics, Boeing Research and Technology; **Jacqueline H. Chen**, senior scientist, Combustion Research Facility, Sandia National Laboratories; **Jennifer H. Elisseeff**, Jules Stein Professor, Department of Biomedical Engineering, Johns Hopkins University; **Nancy R. Sottos**, Maybelle Leland Swanlund Endowed Chair and department head, Grainger College of Engineering, University of Illinois at Urbana-Champaign; and **Nikolay I. Zheludev**, professor and deputy director of the Zepler Institute, University of Southampton, and codirector, Photonics Institute (Singapore).

2021 Annual Meeting Highlights

For the second year in a row, the NAE annual meeting, October 2–3, 2021, was held virtually. The theme was *Engineering Adaptations to Climate Change*. Although we missed the opportunity to reconnect in person, the virtual format facilitated the participation of 817 members, family, and guests spanning national and international time zones.

NAE chair **Donald C. Winter** opened the public session by explaining the decision to conduct the event virtually, which was a result of the emerging coronavirus Delta variant. Acknowledging disappointment about another deferral of the induction ceremony for new members—a traditional highlight of the annual meeting—he reassured members of the classes of 2020 and 2021 that they will be properly recognized when it is safe to do so. He also called on members to join him in advocating for the engineering profession in order to overcome a pervasive lack of understanding of the role of engineering in today's society.

NAE president **John L. Anderson** echoed Dr. Winter's sentiments and thanked everyone for pivoting to an online platform out of an abundance of caution and concern for everyone's health and safety. He then shared a bit of the NAE's history, illustrating the strong role of engineering in serving the country in times of war—and, as the current pandemic demonstrates, he stressed that engineers address critical matters in times of peace as well. He also reminded the members that service is both a responsibility of NAE membership and a direct measure of the health and vitality of the National Academy of Engineering. He promised members that they should expect to be put to work!

With that, NAE executive officer **Alton D. Romig Jr.** introduced the class of 2021—104 new members and 24 international members.

During the awards portion of the program, the **Simon Ramo Founders Award** was presented to **William A. Wulf**, AT&T Professor of Computer Science and University Professor Emeritus, Department of Computer Science at the University of Virginia, "for outstanding accomplishments in academia, government, and industry and reinvention of the NAE to serve the nation and engineering profession after a period of organizational turmoil." The **Arthur M. Bueche Award** was presented to **John P. Holdren**, former assistant to the US president for science and technology and director of the Office of Science and Technology Policy, "for national and international leadership in policymaking for arms control, nuclear weapons security, energy resources for sustainable development, and efforts to address climate change."

On Sunday, October 3, Kate Crawford, research professor at USC Annenberg and senior principal researcher at Microsoft Research Lab–New York City, presented the Special Lecture in Engineering and Society. The title of her talk was "Atlas of AI: Mapping the World of Artificial Intelligence."

Dr. Romig introduced the **Forum on Engineering Responses to Climate Change** and presenters. Leslie Shoemaker, president of Tetra Tech, opened with a discussion of "Climate Equity and Blue-Green Innovations." **Timothy C. Lieuwen**, Regents' Professor, David S. Lewis Jr. Chair, and executive director of the Strategic Energy Institute, Georgia Institute of Technology, spoke about "Infrastructure Implications of Decarbonization." **Kenneth E. Washington**, vice president, Software Engineering, Amazon, considered "Technologies for a More Sustainable Future." **Mohammad Shahidehpour**, chair of the Robert W. Galvin Center for Electricity Innovation at the Illinois Institute of Technology, talked about the "Role of Distributed Power Systems in a Quest for Climate Change." And Catherine A. Peters, George J. Magee Professor of Geosciences and Geological Engineering and chair of the Department of Civil and Environmental Engineering at Princeton University, discussed possibilities for "Offsetting Greenhouse Gas Emissions with Carbon Mineralization, Capture, Utilization, and Sequestration." Deanne Bell, TV host and founder/CEO of Future Engineers, moderated the panel discussion and the many questions from the audience.

Monday was dedicated to the section meetings.

The next annual meeting will take place October 2–3, 2022, in Washington. Mark your calendars!

Remarks by NAE Chair Donald C. Winter

It is my great honor and privilege as the NAE chair to welcome all of you to the 2021 National Academy of Engineering annual meeting. I admit that I am disappointed that we have to meet virtually. Unfortunately, our hopes for covid-19 pandemic relief have been dashed with the emergence of the Delta variant. I believe that the decision to switch back to this virtual format was a prudent one, and I remain hopeful that next year we will be able to return to an in-person meeting. In particular, the induction ceremony is always a highlight of the annual meeting. While we will not be able to conduct the ceremony in the traditional manner today, we will properly recognize all those whose induction has been limited to virtual announcements when it is possible to do so.

For many of the new members this is also your first introduction to the academy. Election to the NAE is a high honor and I trust that you will take great satisfaction in being so recognized by your peers. I expect that your families also take great pride in this accomplishment. But while the NAE selects its new members based on an exhaustive search and evaluation process, it is much more than an honorific society.

The National Academy of Sciences was established in 1863 by act of Congress. Its charter directs the academy, "whenever called upon by any department or agency of the government, to investigate, examine, experiment, and report upon any subject of science or art." The National Academy of Engineering was founded in 1964 under that charter. I will let **John Anderson** describe the National Research Council, which is the academies' operating arm for such activities.

The academies' role as an advisor to the nation on technical matters has been a core responsibility for over 150 years. During this period, the academies have been relied upon to provide independent, objective, and nonpartisan advice with the highest standards of scientific and technical quality and integrity. To do so, the academies call on the nation's preeminent experts in science, engineering, and medicine. In this process, the often critically needed engineering perspective has been, and will continue to be, a major demand function for the NAE.

For those of you who have served on National Research Council committees, boards, or NAE programs, I thank you and ask that you continue to do so, perhaps at even greater levels of involvement. For those of you who have not yet done so, I encourage you to participate. I believe that you will find this form of service to be both intellectually challenging and most satisfying.

While our charter requires us to conduct investigations when requested, we are not limited to responding to governmental requests. There are occasions when important public policy issues that could benefit from NAE investigation are not the subject of such requests. In such cases, I believe that it is most appropriate for the NAE to look for ways to opine on such matters. I would like to take this opportunity to address one of those issues that is of particular interest to me.

I am concerned that there is a fundamental lack of understanding of the role that engineering plays in today's society. In a world where we often hear that "words matter" it is disappointing to hear how the terms *science* and *engineering* are used or misused by many in positions of influence. The word *science* has taken on new meanings as the basis for numerous policy decisions. Of course, we all want such decisions to follow the science, but it is easy to forget that science requires expert interpretation and evaluation and must be put in context to provide value. Furthermore, it is the application of science in the engineering of systems and solutions that serve society and that properly inform many crucial public policy decisions.

Perhaps most concerning is the all too typical omission of the term *engineering*. Anthony Fauci's article in the April issue of *Science* describing the development of the covid-19 vaccines is a good case in point. His article does an excellent job of putting the development of the covid-19 vaccine into the context of the evolving history of vaccines. He notes the many contributions of the teams that provided the biological tools for vaccine development and the work of those who adapted the tools to address covid-19. Unfortunately, the article fails to mention the significant efforts expended to formulate, produce, and distribute billions of doses in a remarkably short period of time—incredible engineering efforts enabling the vaccines to treat the world's population.

Another example is President Biden's choice of words on the occasion of the Mars landing in February. He tweeted, "Congratulations to NASA and everyone whose hard work made *Perseverance*'s historic landing possible. Today proved once again that with the power of science and American ingenuity, nothing is beyond the realm of possibility." Unfortunately, while *science* is referenced, the word *engineering* is missing. Of course, the landing was made possible by previous scientific investigations of the Martian atmosphere and the mission was enabled by the many scientific principles underlying space flight; but the incredibly complex spacecraft and its audacious landing sequence were the result of exceptional engineering efforts.

Why is all of this concerning? Because it goes to the heart of engineering's role in society. Engineering is how we *create* solutions to society's needs and wants. It is how we advance civilization for the benefit of humankind! Engineering is the creative venture that enables the successful application of science.

Without a public understanding of the unique role and value of engineering, our ability to attract the best and brightest will be put at risk as will the ability to properly educate them in the discipline and culture of engineering.

I believe that both the NAE and its members have a special responsibility to explain the unique nature of engineering, its value to society, and the great satisfaction that it can provide to its practitioners. That is an essential mission for the academy and is a role that many of us can and should take on. I ask that you join me in advocating for the engineering profession.

NAE President's Address

Welcome to the National Academy of Engineering's 2021 annual meeting. I'm **John Anderson**, president of the NAE, and it is my honor to address this very distinguished gathering and celebrate the introduction of our new members—the class of 2021.

This is our second year holding a virtual annual meeting. We are doing so out of an abundance of caution and concern for your health and safety. Thank you for pivoting to this online platform with us. And thanks to our wonderful staff for their hard work to make this a memorable meeting.

Thank you, **Don Winter**, for your service as chair and for your noteworthy comments on the importance of recognizing the contributions of engineering.

I will now share some details about the historical significance of the NAE, the National Research Council, and our sister academies.

In 1863 President Abraham Lincoln signed a congressional charter that created the National Academy of Sciences. The country was mired in the Civil War, and part of Lincoln's focus was to elevate the sciences and engineering and utilize their technical expertise for advancing the military capabilities of the Union.

The 50 initial members of the academy were scientists, engineers, and physicians from academia, industry, and government. Many of the engineers were classified as inventors and manufacturers. Today, the NAE carries the mantle of engineering—and a strong connection to industry as well as academia and government.

One of the first instances when the newly formed NAS was called upon to advise our young nation was to correct the accuracy of compasses on-board ironclad ships. These were powerful armored vessels that were developed by a Swedish engineer to deflect cannon balls and other fire. But the iron armor caused the compasses to deviate and could have led to dangerous situations at sea. The NAS was tasked with assembling a committee to study the problem and made recommendations that corrected the compasses on nearly 30 wartime ships.

I share this bit of history because I was reminded that engineering has a strong history of serving our country in times of war; however, we must continue to address critical matters in times of peace as well—as the current pandemic demonstrates.

In 1916 the National Research Council was formed by President Woodrow Wilson. The NRC works collaboratively with the National Academies "to bring into cooperation government, educational, industrial, and other research organizations" to advance science, aid the development of American industries, strengthen the national defense, and promote national security and welfare. Today, the NRC serves as the operating arm of the overall organization, called the National Academies of Sciences, Engineering, and Medicine (NASEM).

In 1964 the National Academy of Engineering was established under the same charter as the National Academy of Sciences to provide independent and objective advice to the government and public on matters of engineering and technology, and to advance the profession of engineering. In 1970 the National Academy of Medicine was established (originally called the Institute of Medicine).

Our mission dictates that service is an important aspect of NAE membership. Last year 55% of our members participated in at least one activity of the NRC or the NAE. One of my priorities is to increase this number. I view member participation as a direct measure of the health and vitality of the National Academy of Engineering. So we will attempt to put you all to work!

I emphasize that the Academies are not part of the government, and this is by design. Our work is independent and nonpartisan and there is no federal line item for us, nor any congressional appropriation, as many might think. This ensures that the important work we do remains objective, nonpartisan, and credible. However, a burden of this independence is our dependence on philanthropy. More than 50% of the NAE's operating budget derives from past and current donations by our members, foundations, corporations, and other friends.

When I ask you to donate to the NAE, you can be assured of two things: First, your donation is supporting very important work; and second, your donation is critical to the operations of the NAE. Our members are generous with their time and financial support, and I thank you for this.

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The first class of NAE members in 1964 had 25 members—52% from the business sector, 36% from universities, and 12% from national laboratories.

This year we elected 104 new members and 24 new international members from 17 countries. With our newfound skills in dealing with virtual meetings, honed over almost two years of the covid pandemic, we are in a better position to engage our international members in both NRC and NAE activities.

The demographics of the members being introduced today are very different. I congratulate the NAE members who served on our election committees and brought about this result. With intention and effort we have made some progress since 1992.

The class of 2021 also demonstrates the importance of immigration to the technical workforce of this country—33% of the US members elected this year were born outside the United States. Immigrants have contributed substantially to the success of this country, and we must ensure that we continue to welcome them.

We now have 2300 US members and 290 international members, representing multiple fields of engineering and bringing unmatched expertise and life experiences to advance the mission of the NAE.

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Science and engineering: What's the difference? To quote Theodore von Kármán (a member of the NAS, not NAE—he died the year before the NAE was created), the father of aeronautics and the first recipient of the US Medal of Science, "Scientists discover what is, engineers create what never was." As Dr. Winter noted in his address, engineering is about creating products, processes, and systems that address human needs—and sometimes anticipate human needs. The key word here is *create*.

The symbiotic relationship between science and engineering has produced great improvements in the quality of human life. Whether one is acting as a scientist or an engineer is not determined solely by one's educational degrees, rather it is determined by what the person is doing. Note that 20% of the new members being introduced today have no formal degree in "engineering."

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An example of the power of engineering to improve the human condition is found in the fight against covid-19, which unfortunately remains ongoing. In several public addresses, NAE member **David Walt** has laid out the contributions of engineers in this fight, which he summarizes in four areas: testing, protective equipment, vaccines and therapeutics, and data analysis.

He notes that within just a few weeks of the outbreak of covid-19, the full genetic code of the virus was determined with the help of DNA sequencers developed by engineers—much faster than was possible in previous pandemics. This advance led to the development of vaccines at near-record speed by scientists and engineers, and the scale-up of vaccine production to billions of doses that tilted the battle in favor of humans instead of microbes. This is a great example of the value of collaboration between science and engineering aimed at solving a global problem threatening all of us.

Engineering enabled the manufacturing and scaling of personal protective devices. Masks, gowns, and face shields are the first line of defense against covid-19. Scaling up the production of functional personal protective devices resulted from additive manufacturing—a technology based on 3D printing that enabled thousands of masks to be printed in a matter of hours.

From protective gear to diagnostics to vaccines to data analysis, engineering has played a major role in combating covid-19 in the United States and on a global scale.

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To support our mission, we have reorganized the NAE Program Office consistent with what I call "the four I's":

- Identify and inform the frontiers of engineering theory, practice, and policy
- Increase engineering talent through a strong commitment to diversity and inclusion
- Instill a culture of ethical and environmental responsibility in engineering
- Improve capabilities and competencies for complex systems engineering.

The second "I" recognizes the need to continue to open up the profession to new minds and new ideas. To do so will require a variety of learning paths to attract a diverse array of students to engineering who are able to compete on any playing field. We work to communicate and partner across traditional and nontraditional lines to foster a better understanding and appreciation of engineering. Two NAE programs focus on this goal.

The first is our effort to spark excitement about engineering in girls in grades K–12 and connect them to opportunities and role models. EngineerGirl programs build engineering leadership and confidence in girls around the country.

EngineerGirl is celebrating its 20th anniversary this year, and it represents one very exciting way that the NAE is speaking to different audiences. What began as a resource website is now a dynamic outreach platform that connects with girls, their parents and caregivers, and the educational community.

Since its inception, over 10,000 students, both boys and girls, have participated in the EngineerGirl annual writing contest.

The EngineerGirl Ambassadors Program, now in its fourth year, has introduced over 1500 middle and elementary school students to engineering. Some of the high school mentors lead online clubs where girls get to talk to women engineers from all over the US, and others have been meeting (outdoors during the pandemic) to work on design projects in teams, similar to what we do in universities to educate engineers.

I want to take this moment to thank the committed sponsors who have made these programs possible. The Chevron Corporation, Clark Foundation, Kenan Foundation, Lockheed Martin, Oracle, and others have made EngineerGirl a sustaining activity of the NAE. And the foresight and philanthropy of John McDonnell, former CEO of McDonnell Douglas, pushed us to develop the Ambassadors program and provided funding to launch it.

Many NAE members and friends over the years have also generously contributed to EngineerGirl as role models, as volunteers, and as donors. This is an example of how your contributions of time and financial resources make a difference.

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Another way we promote excellence in engineering through outreach is the Frontiers of Engineering program, which selects high-achieving engineers who are early in their careers to learn about leading-edge developments in fields beyond their own.

The program also brings together engineers from the US and other countries to promote the transfer of new techniques and approaches across fields. In addition to the annual US symposium, we have bilateral programs with the European Union, Japan, Germany, and China. This year we had greater interest from other countries hoping to partner with us on the FOE program.

These meetings are a forum for sharing ideas to generate new knowledge and technologies, innovative capacity, and economic vitality. There's also a grant program, for US participants, to encourage collaboration.

In its 25-year history, the FOE program has been so effective in recognizing and promoting career development that 140 of its alums have been elected to the NAE—including 13 in the class of 2021.

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The work of the National Research Council is the lever that enables collaboration and research to produce valuable consensus study reports that provide objective and nonpartisan advice with high standards of technical quality.

The NRC is organized into seven divisions that support standing boards and conduct important studies for the government and the public.

The convening power of the NAE and the other two academies is critical to providing the volunteer talent to address some of the country's and world's crucial problems.

As NAE members, many of you will be called upon to serve on these committees and panels. Such member engagement is a critical aspect of your NAE service to the nation, and when you are asked to volunteer, I hope you will accept. It is an exceptional and very rewarding role that can have significant impact.

A few recent examples illustrate the range of opportunities and impacts of the NRC's work.

NAE members served on a consensus study by the Division on Engineering and Physical Sciences that produced a report this year on *Accelerating Decarbonization of the US Energy System*. The report lays out a policy roadmap and technology goals necessary to reach net zero carbon emissions by 2050. Several committee members testified before Congress, where the findings are informing legislation related to future energy policy.

NAE members made up half the committee that produced a 2020 report on *Innovation in Information Technology*. Its conclusions were cited by the National Science Foundation in its FY22 budget request to Congress.

NAE members also served on the study that produced the Transportation Research Board's 2020 consensus report *Leveraging Unmanned Systems for Coast Guard Authorities*, which recommended that the US Coast Guard proceed more aggressively and deliberatively in taking advantage of unmanned systems technology. The report prompted the chair and ranking member of a House committee to write to the commandant of the Coast Guard—and now there is a new Coast Guard Unmanned Systems office as specified in the report's recommendations.

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Broadening participation in engineering is a goal that ranks at the top of the NAE's responsibilities. When we find areas that do not foster diversity or that present obstacles to participating, we work to guide a better future.

The 2018 National Academies report on *Sexual Harassment of Women: Climate, Culture, and Consequences in Sciences, Engineering, and Medicine* makes it clear that systemwide changes that go beyond compliance are necessary to tackle systems, cultures, and a climate that enable sexual harassment to exist and therefore negatively affect the well-being of those participating in these fields.

A seminal step toward remedying the problem is the Action Collaborative on Preventing Sexual Harassment in Higher Education, where more than 60 colleges, universities, and other research institutions work to identify, research, develop, and implement efforts to address and prevent all forms of sexual harassment.

The action collaborative is in its third year and recently counted more than 60 new initiatives from among its members that focus on areas such as improving hiring practices and creating bystander intervention training.

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I again emphasize the expectation of service and volunteerism for NAE members. Keep in mind that *engineer* is both a noun and a verb—implying action. I turn to the words of Albert Einstein who said "only a life lived in service to others is worth living."

It is a great honor to be elected to the NAE, but like a university commencement, it is just the beginning. I look forward to working with you as we strive toward the betterment of this country, the world, and this organization. For that, I thank you in advance.

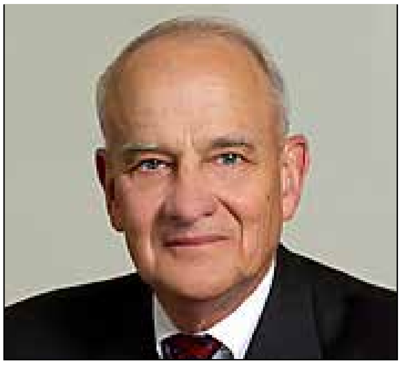
I also thank all the NAE staff who make our organization work so well. It is a wonderful group of individuals, and they make good things happen. We owe them a lot.

And I acknowledge the remarkable officers and councillors who govern the NAE. These individuals are elected by the members to serve the organization, and they do so with skill, selfless effort, and integrity.

I now turn to the most important part of this program: recognition of the NAE class of 2021. We will repeat this ceremony in person at the annual meeting in 2022, so that every member of the class of 2021 will have the opportunity to be properly introduced and walk across the stage of this auditorium to sign the membership rolls.

Al Romig, NAE member and executive officer, will now introduce the class of 2021. Congratulations to all of you!

2021 Simon Ramo Founders Award Acceptance Remarks by Wm. A. Wulf



The 2021 Simon Ramo Founders Award was presented to Wm. A. Wulf, AT&T Professor of Computer Science and University Professor Emeritus, University of Virginia, "For outstanding accomplishments in academia, government, and industry and reinvention of the NAE to serve the nation and engineering profession after a period of organizational turmoil."

I am profoundly grateful and honored to have received this award.

Although the award is to me, you should recognize that I owe deep gratitude to those who worked with me: my colleagues at the university, my graduate students, the companies and the people in those companies that hired me. All of these people are a part of everything I've done.

I want to offer a special thanks as well to the Selection Committee, the people who chose me for this award. I've been where you are now—on the selection committee—and I know how hard the work is. So thank you, thank you, thank you.

Again to all of you, thank you very much. I am profoundly honored.

2021 Arthur M. Bueche Award Acceptance Remarks by John P. Holdren

The 2021 Arthur M. Bueche Award was presented to John P. Holdren, Executive Office of the President of the United States, "For national and international leadership in policymaking for arms control, nuclear weapons security, energy resources for sustainable development, and efforts to address climate change."

While I never met Dr. Bueche—and wish I had—I did have the great privilege of meeting, at one time or another, nearly all of the previous recipients of the NAE award that bears his name. Indeed, I had the pleasure of working closely with—and learning from—a number of them, including **Jerry Wiesner**, **Jack Gibbons**, **Lew Branscomb**, **Bob Frosch**, **Chuck Vest**, and **Venky Narayanamurti**. My feeling of connectedness with the previous Bueche awardees adds to the pride I feel upon joining this extremely distinguished company.

I had aspired, from the time I was in high school, to a career studying, teaching, and advising around the great, intertwined, national and global challenges that sit at the intersection of science and engineering with societal well-being—particularly poverty and development, energy and environment, and national and international security. I decided to start with serious studies in engineering and physics, aiming to add, on top of that, at least passing familiarity with the ideas and tools of biologists (I married one), geologists, economists, and political scientists, among others.

I had the early benefit of terrific mentors at MIT, Lockheed, Stanford, Livermore, Caltech, and Berkeley, who were instrumental not only in broadening my education but also in connecting me to opportunities to engage with a wide array of national and global leaders in the interdisciplinary fields of interest I've mentioned—through, for example, committees of the National Academies, the Pugwash Conferences on Science and World Affairs, and engagement with such science-technology-and-society organizations as the AAAS and the Federation of American Scientists.

Each new opportunity led to other opportunities and new mentors, with the surprising result that I was actually able to get away with my wildly ambitious aspiration to have a career working on some of the world's most interesting problems in collaboration with some of the world's most interesting people.

Since leaving my position as President Obama's Assistant for Science and Technology at the end of his second term, I have been working on a book about what I've learned in my now five-decade-long career. In my brief remarks here, I will mention just four key points that will be in the book.

First, to understand and then to address successfully challenges such as climate change, the needed clean-energy transition, covid-19 and epidemics still to come, and management of the risks of nuclear weapons require *both* interdisciplinary integrators *and* people with deep specialized expertise in a number of natural science, social science, and engineering disciplines. We need to manage our nation's educational system and our reward system to ensure that we encourage, train, and productively engage plenty of both, and while we're at it, teach them to work together.

Second, we need to lift our game in STEM education nationally, not simply to train the disciplinary and interdisciplinary science and technology experts we need to tackle so many of the biggest societal challenges; but also to produce the tech-savvy workers that this century's jobs require, and the science-and-technology-savvy citizenry that a democracy needs in order to function in an era when more and more of the decisions facing elected leaders have significant science and technology content.

Third, the needed new thrust in STEM education must include an expanded effort to inspire and nurture the participation of groups historically underrepresented in STEM fields, including most notably women, people of color, Hispanics, and Native Americans. (That underrepresentation is especially acute, I hardly need to mention here, in engineering.) As President Obama was fond of saying in this connection, you can't win the game with half the players on the bench.

Fourth, as so much recent experience has demonstrated, the needed degree of success in science and engineering applied to national and global needs requires partnerships—not only, as I've already stressed, across disciplines but also partnerships across government, academia, business, and NGOs, and, where appropriate, partnerships among nations. Notwithstanding all the factors that understandably divide countries across the world—and, today, particularly divide the United States and China and the United States and Russia—there are science-and-engineering-heavy issues where bilateral and multilateral collaboration is so much in our national interest, as well as in the national interest of our partners, that we should strive to maintain such collaboration despite nearly all other differences. In my view the issues where international collaboration is essential include climate change, pandemic disease, threats to the ocean and the Arctic, nuclear reactor safety, some aspects of space exploration, and minimizing the risks from nuclear weapons and nuclear-explosive materials.

In closing, let me thank the National Academy of Engineering and the Bueche family for the honor of this award, and thank all of you here for your attention.

NAE Members Named to PCAST

President Joe Biden announced the members of the President's Council of Advisers on Science and Technology (PCAST), which advises the president and the White House on science, technology, and policy recommendations. Of the 30 PCAST members 20 are members of the National Academies of Sciences, Engineering, and Medicine.

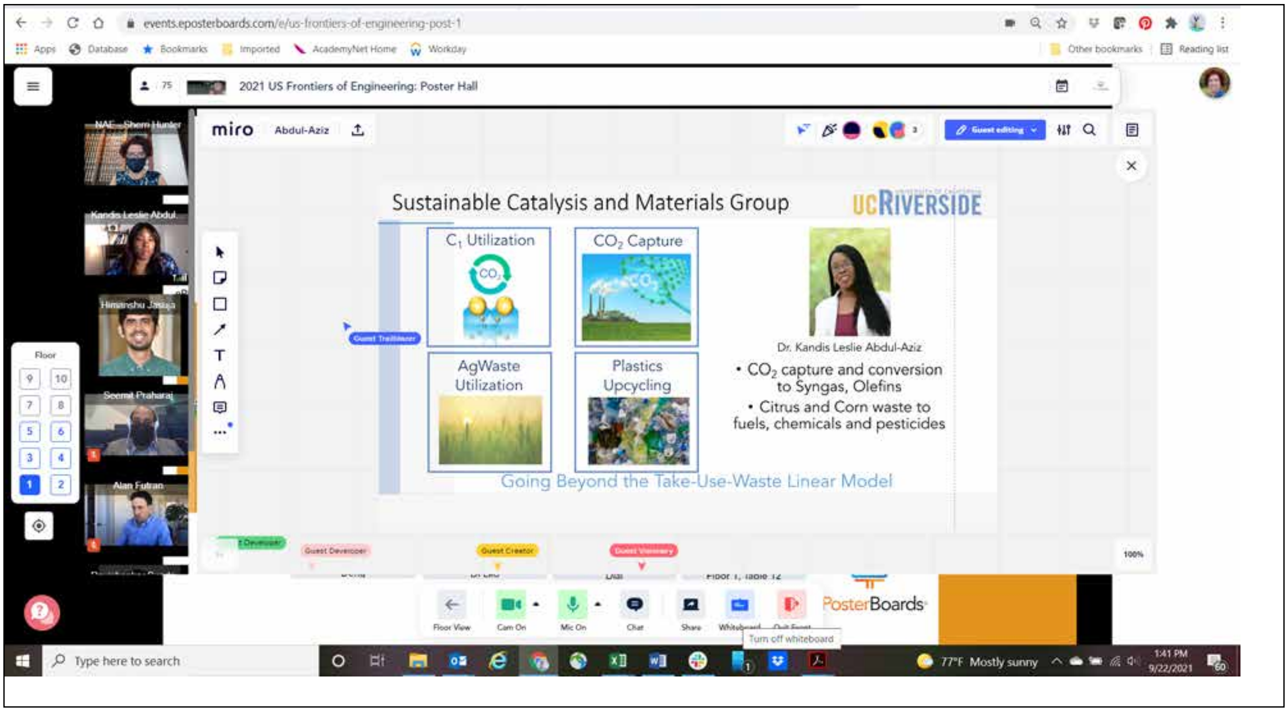
NAE members named to PCAST are **Dan E. Arvizu**, chancellor and chief executive, New Mexico State University, and former chair of the National Science Board; **William Dally**, chief scientist and senior vice president of research, Nvidia; **Andrea Goldsmith**, dean, School of Engineering and Applied Science, Princeton University; **Paula Hammond**, David H. Koch (1962) Professor of Engineering and head, Department of Chemical Engineering, Massachusetts Institute of Technology; **Eric Horvitz**, chief scientific officer, Microsoft; **Lisa T. Su**, president and CEO, Advanced Micro Devices Inc.; and **Kathryn Sullivan**, senior fellow, the Potomac Institute. We previously reported that **Frances Arnold**, Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, California Institute of Technology, was appointed cochair of PCAST.

The president's announcement is available at https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/22/president-biden-announces-members-of-presidents-council-of-advisors-on-science-and-technology/.

2021 US FOE Held as Hybrid Event

This year's US Frontiers of Engineering Symposium took place September 22–24 at the National Academies' Beckman Center in Irvine, California. **Timothy Lieuwen**, Regents' Professor and David S. Lewis Chair of the Daniel Guggenheim School of Aerospace Engineering at Georgia Tech, chaired the organizing committee and the symposium. The session topics were Investigating the Final Frontier: Engineering the Future of Space Exploration, Resilience in Pandemics: Data and Digital Infrastructure for Informed Decision Making, Transforming the Climate Change Discussion: The Role of Direct Air Capture, and Cybersecurity of Critical Infrastructure. Because of ongoing concerns about covid-19, the meeting was held as a hybrid event: about 65 percent of the attendees participated in person and the balance joined virtually.

Space exploration comes in many forms: sending satellites, probes, or rovers to explore a moon, planet, or asteroid on site; gathering information through observation and sensing to understand our galaxy and the universe; or sending people to explore Earth's Moon or Mars. The speakers in this session discussed the importance of engineering for space



Dr. Kandis Abdul-Aziz's poster session.

exploration through talks on in-space assembly and servicing, space-based astronomical observatories, gathering asteroid dust guided by visible-wavelength images, and efforts to enable crew health and performance during extravehicular exploration.

The second session focused on how engineers can use data both to increase resilience in the current pandemic and to be better prepared to respond to future pandemics. Data collection from digital devices such as sensors can improve manufacturing and biomedical innovation; online platforms and healthcare dashboards can inform critical decision making and promote health equity. The first two speakers discussed applications in the education domain, covering testing strategies and data infrastructure for responding to covid-19 in higher education and the impact of data in operational decisions that balance the needs for community safety and education. The next talk covered digitalization of biomedical manufacturing to enable reduced nonconformance, advanced process control, real-time release, and real-time product quality. The session concluded with a presentation on ways data and advanced mathematical modeling can support effective healthcare decision making.

Direct air capture technology (DAC) is engineered removal of CO_2 from the atmosphere to mitigate the effects of climate change. It has global benefits, but there are many challenges. The session started with an overview of DAC, including technologies developed to overcome its unique challenges and the outlook for its role in a renewable energy future. The next two speakers elaborated on scaling up DAC technology, with perspectives from a large industrial company and a startup. The last speaker presented thoughts on policy and regulatory perspectives to enable DAC deployment.

The technical portion of the symposium closed with a session on the timely topic of cybersecurity of critical infrastructure. Critical infrastructures, which enable the economy, public safety and services, and national security, depend on software-based systems and interconnectivity, with a cyberphysical element. This session examined infrastructure risks and the resiliency design and practices that mitigate cyber-originated threats. Speakers discussed the present situation in critical security, efforts to secure complex cyberphysical systems of systems from cyber-originated threats and vulnerabilities that result from the convergence of infrastructures, and security design for industrial control systems.

Many of the presentations are available for public viewing at the 2021 US FOE List of Sessions at www.naefrontiers.org.

Some of the typical practices of in-person FOE meetings were adapted to facilitate equity with the virtual attendees. For example, technical sessions were livestreamed so virtual attendees could watch presentations and join in the discussion, and virtual poster sessions were held instead of breakout groups.

The custom of a dinner speech on the first night was maintained with a presentation by **Dorota Grejner-Brzezińska** (Ohio State), principal investigator for the NSF's Engineering Research Visioning Alliance. She invited attendees to submit their ideas for the next biggest technological, economic, or health challenge that engineering can address and the most complex short- and long-term engineering challenges.

Participants at this year's meeting will be eligible to apply for The Grainger Foundation Frontiers of Engineering Grants, which provide seed funding for US FOE participants at US-based institutions. These grants enable further pursuit of important new interdisciplinary research and projects stimulated by the US FOE symposia.

The 2022 US FOE will be hosted by Amazon in Seattle, September 21–23. The topics are Advances in Infectious Disease Diagnostics and Treatment, the Hydrogen Economy, Technology and Racial Justice & Equity, and Conversational AI.

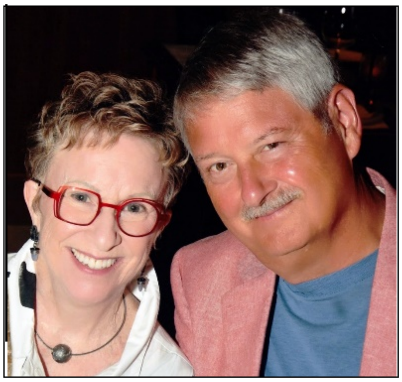
Funding for the 2021 US Frontiers of Engineering symposium was provided by The Grainger Foundation, National Science Foundation, Air Force Office of Scientific Research, DOD ASDR&E–Laboratories Office, Amazon, Cummins Inc., and individual donors.

The NAE has been hosting an annual US Frontiers of Engineering meeting since 1995, and also has bilateral programs with Germany, Japan, China, and the European Union. The meetings bring together highly accomplished engineers from industry, academia, and government at a relatively early point in their career, providing an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, which is increasingly important as engineering has become more interdisciplinary. The meetings also facilitate the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series, visit www.naefrontiers.org or contact Janet Hunziker at JHunziker@nae.edu.

Inspiring a Younger Generation to Invest in the NAE's Frontiers of Engineering

Frances and George Ligler



Robyn and Robert Wagoner

Frances and George Ligler and Robyn and **Robert Wagoner** have joined forces to fund a $200,000 matching gift challenge for the NAE's Frontiers of Engineering (FOE) program. The goal of the Ligler-Wagoner Challenge for Frontiers of Engineering (the FOE Challenge) is to ensure that the FOE continues and enhances its mission of bringing together the most promising young engineers to foster cross-disciplinary research collaborations that can last a lifetime. Gifts to the Wagoner Endowed Fund or the FOE general fund will qualify for a dollar-for-dollar match, doubling the donor's impact, until December 2024 or until the match is reached.

The FOE program brings together a select group of emerging engineering leaders from industry, academia, and government to discuss pioneering technical work and leading-edge research in various engineering fields and industry sectors. FOE alumni, friends, and other donors who join the Ligler-Wagoner FOE Challenge by making a gift or pledge will provide critical discretionary funding for FOE to enhance existing alumni networking opportunities and collaboration efforts.

For the past 27 years, Janet Hunziker has served as director of the FOE's US and bilateral program, overseeing more than 80 symposia and connecting with over 4800 participants. Without her dedicated support and service, FOE would not be the program that it is today. Take advantage of the opportunity to make a tribute gift in honor of Janet for her steadfast leadership and growth of the program. "My sense of wonder and admiration for Janet and FOE is as strong today as it was 25 years ago. We hope and intend to honor Janet for her long, selfless dedication to fashioning this terrific program," says Rob Wagoner. The Liglers share similar sentiments about Janet's work: "We were inspired by Janet's extraordinary service to the engineering profession in directing the program."

Fran and George Ligler have been long-time supporters of the NAE and FOE program. They have both nominated engineers who have participated in the annual FOE Symposia, and they have received very positive feedback about the program from those participants. "The Frontiers of Engineering program has been on the leading edge of promoting interdisciplinary engineering across engineering work sectors. We see the future of engineering as increasingly interdisciplinary and the FOE program as supporting if not accelerating this trend," comments George Ligler.

Rob Wagoner's passion for the FOE started early in his NAE years when, as a newly elected member, he participated in the first FOE symposium. "Attending was a wonderful, eye-opening experience—besides being a lot of fun! FOE is the most meaningful cross-disciplinary program that we have seen for young engineers." The Wagoners' involvement in FOE has spanned the past 26 years. Rob's initial participation in 1995 grew to organizing committee member in 1996, chair (1997–99), and cochair of the inaugural JAFOE meetings in 2000 and 2002. "There has never been a question whether we wanted to assist the FOE program," he says.

The Liglers and Wagoners believe in the FOE program and its impact on early- to mid-career engineers. The Ligler-Wagoner FOE Challenge was established to inspire past program participants to pay it forward and create more opportunities for future generations of engineers. As Janet Hunziker says, "it's all about the wonderful people who bring their enthusiasm and innovative ideas to the meetings. This program provides them with a unique opportunity for conversations with other highly accomplished, creative people whom they would not otherwise meet, opening new ways of thinking and opportunities for collaboration."

EngineerGirl Announces 2021 Class of Student Ambassadors

EngineerGirl is designed for girls in elementary through high school and offers information about various engineering fields and careers, questions and answers, interviews, an annual writing competition, and other resources on engineering. It is part of the NAE's ongoing effort to increase the diversity of the engineering workforce.

On September 14 the NAE announced the 2021 class of the EngineerGirl Ambassadors program. The 24 new ambassadors will participate in a yearlong program designed to build leadership skills in female high school students by helping them promote engineering to younger students in their community. Each ambassador will design, develop, and implement a project that will encourage younger girls—particularly those with little access to engineering role models—to think about engineering careers and give them practical experience in engineering design. They will work with local sponsors and receive guidance and support from EngineerGirl staff.

Following are the 2021–22 EngineerGirl ambassadors and their proposed projects:

Hira Ali (9th grade, Arlington, TX) is planning to create an engineering website to engage young students with articles, quizzes, and a monthly broadcast featuring engineering concepts and hands-on activities.

Chidalu Aniekwenagbu (11th grade, Lynn, MA) is developing an after-school program intended for 4th and 5th graders who attend KIPP Academy Lynn so they can

EngineerGirl 2021 Student Ambassadors

learn about the different fields of engineering.

Katie Auyeung (12th grade, Elk Grove Village, IL) will create an EngineerGirl club for 5th and 6th grade girls to meet twice a month to explore different engineering topics, including artificial intelligence, food, space, environment, buildings, medicine, and transportation.

Noor Azam-Naseeruddin (10th grade, Washington, DC) will use computer programing to teach young art students how to code; the students will create self-portraits, a Jackson Pollock painting, fractal art, and even a game by using computer coding techniques.

Aditi Baghel (12th grade, Phoenix, AZ) will teach a 2-week course to young girls on applied physics exploring how physics principles are used in engineering.

Sophia Benavente-Sayani (11th grade, Secaucus, NJ) will create an 8-week course for young girls examining the engineering design process, coding, chemistry, biomedicine, 3D design, and robotics.

Josephine Brumfield (11th grade, Austin, TX) plans to use the Kerbal Space Program to introduce elementary and middle school girls to aerospace and aeronautical engineering.

Kendell Clark (11th grade, Stephens City, VA) will organize events at a local library where middle school students can meet a diverse range of engineering professionals.

Victoria Corradina (11th grade, Farmingdale, NY) will introduce students to the different engineering courses offered in the Farmingdale School District by creating a virtual tour of elective classes from the perspective of past students.

Naomi Fernandez (12th grade, North Bergen, NJ) will develop a program to introduce elementary school students to various engineering fields through engaging activities and hands-on experiences.

Samantha Gary (12th grade, Palatine, IL) will create a lunchtime engineering club for elementary school girls that will introduce them to the different disciplines of engineering.

Annum Hashmi (11th grade, Palo Alto, CA) will create a virtual workshop series providing an introduction to robotics for young girls.

Anna Hill-Jones (10th grade, Chesterfield, MO) will develop a program where students from St. Louis will design and race cars while learning about physics and engineering principles.

E'LissaAnn Jones (11th grade, Roswell, GA) will host a short series of in-person events at local elementary schools combining engineering and entrepreneurship—girls will be introduced to science principles through hands-on activities and projects.

Elizabeth Megson (9th grade, Paxton, IL) will create a STEM day where university participants will teach girls about science and engineering and answer questions about different STEM fields.

Ashika Srivastava (12th grade, Atlanta, GA) plans to create an engineering magazine for girls that will feature information about the different engineering disciplines, interviews with women in engineering, puzzles, activities, and games.

Emilia Szczepaniak (11th grade, Butler, NJ) will teach middle school girls how to code by helping them build circuits with Arduinos and create 3D models at the Butler Public Library.

Lily Tucker (11th grade, Waxhaw, NC) will develop engineering kits that will be distributed to girls in community shelters and in foster care; the kits will include 3D-printed parts that can be assembled into a STEM toy and information on great women in engineering.

Micaela Venyo (12th grade, Belcamp, MD) will create a 2-hour weekly online program that will include kits for hands-on activities and virtual Q&A sessions with a diverse panel of female engineers.

Nichola Wells (10th grade, Orlando, FL) will organize a 5-week educational program tailored to 15 middle school students exploring how engineers use technology and the design process to prevent gun violence.

Grace Williams (11th grade, Pensacola, FL) is creating a weekend engineering club for 8th grade girls to learn engineering through projects and guest speakers.

Kimberly Wu (12th grade, Gilroy, CA) is developing an afterschool program where girls will learn engineering through activity-based robotics kits.

Zhilu Xie (12th grade, San Ramon, CA) will work with special needs students who lack engineering exposure by developing a course for them that includes civil) electrical, and mechanical engineering.

Shannon Yeow (12th grade, Chula Vista, CA) is organizing a 5-day engineering camp for elementary school students with a focus on civil) chemical, mechanical, computer, and electrical engineering.

Profiles of the student ambassadors and videos are available at the EngineerGirl website (www.engineergirl.org/2021-ambassadors.aspx).

The EngineerGirl ambassadors receive support and project funding of up to $250, leadership development, networking and engagement opportunities, and a certificate and letter of recognition from the National Academy of Engineering.

EngineerGirl is part of the NAE's ongoing effort to increase the diversity of the engineering workforce. The EngineerGirl Ambassadors program is made possible by a generous grant from John F. McDonnell.

NAE Introduces New Suite of Initiatives: Focus on People, Systems, and Culture

As part of its 2021–26 strategic plan the NAE is launching a new program portfolio targeting interlinked objectives across the guiding themes of *people*, *systems*, and *culture*. This focus primes the NAE to amplify its work and impact in

- identifying and informing the frontiers of engineering theory, practice, and policy;
- increasing engineering talent through a strong commitment to diversity, equity, and inclusion;
- instilling a culture of ethical and environmental responsibility in engineering; and
- improving capabilities and competencies for complex systems engineering.

"The new direction of NAE programs reflects the expanding influence of engineering in our society, and the need to expand public awareness of engineering's contributions to society," said NAE president **John L. Anderson**. "With this new portfolio, the NAE will promulgate the value of an engineering mindset for business, government, and daily life in support of its core mission: advising the nation."

"The fresh program focus will drive industry and global engagement to envision engineering practices that transcend technology," said NAE executive officer **Alton D. Romig Jr**.

- **Practices for Engineering Education and Research (PEER)** will conduct studies, workshops, and other activities focused on engineering education and related research at the precollege and higher education levels. This program will consider the entire educational system, contextual influences on that system, and how elements of the system affect each other, convening researchers and practitioners in engineering education and publishing analyses to guide change.
- **Cultural, Ethical, Social, and Environmental Responsibility in Engineering (CESER)** will help expand understanding of how cultural, ethical, and social circumstances and the natural and constructed environment affect the practice of engineering. The program will promote consideration of these elements through studies and workshops and engagement with engineers, educators, industry leaders, professional societies, government entities, and the public.
- **Inclusive, Diverse, and Equitable Engineering for All (IDEEA)** will conduct outreach designed to support and encourage equitable and inclusive involvement of youth, their families, and the educational community to explore and engage with engineering. Programs will include EngineerGirl, an internationally recognized NAE outreach effort, now in its 20th year, that engages middle- and high-school girls in learning about the exciting opportunities of engineering and introduces them to inspiring role models.
- The **Forum on Complex Unifiable Systems (FOCUS)** is a multistakeholder initiative to advance understanding of complex technical and social systems and to identify unifiable approaches to better manage them. The forum will explore both perennials and frontiers of complexity in health, security, democracy, urbanization, infrastructure, research and education, the economy, transportation, the environment, modern work, and civic life. It will publish perspectives with ideas, insights, and topical commentaries to guide executive decision making.

NAE programs will continue to support collaborative activities, such as studies and workshops, with its sister academies of sciences and medicine, the UK Royal Academy of Engineering, Chinese Academy of Engineering, and International Council of Academies of Engineering and Technological Sciences.

"We hope to inspire an engineering identity and responsibility beyond individual work and purely technical interests," said Guru Madhavan, Norman R. Augustine Senior Scholar and senior director of NAE Programs. "These initiatives will build on the NAE's track record in shaping engineering *for* people, systems, and culture to also focus on the people, systems, and culture *of* engineering."

New NAE Program Staff

Shanice Jackson

SHANICE JACKSON is a senior program assistant working with both Beth Cady and Simil Raghavan on the NAE's new programs on Practices for Engineering Education and Research (PEER) and Inclusive, Diverse, and Equitable Engineering for All (IDEEA). Before coming to the Academies, Shanice worked in the banking industry, where she mastered her customer service skills and gained experience in different aspects of the finance industry. Her past employment also includes work at the Fairfax (VA) County Department of Neighborhood and Community Services as activities facilitator for the David R. Pinn Community Center, where she customized different educational programs and helped organize field trips for the summer program. In both positions she was dedicated to creating a very positive experience for clients and community members. Shanice graduated from

Virginia State University with a BA in mass communications. She can be reached at 202-334-2347 or SSJackson@nae.edu.

MAIYA SPELL works with Deborah Young on the NAE Awards Program and with David Butler on two projects, on Indoor Exposure to Fine Particulate Matter and Practical Mitigation Approaches and on Extraordinary Engineering Impacts. She is a native of Baltimore who received her bachelor's degree in public health science and a certificate in Black women's studies from the University of Maryland, College Park. Her hobbies include cooking, singing, and listening to music (she is a big fan of hip-hop and R&B), and before the coronavirus pandemic she enjoyed going to open mic/poetry nights. She also enjoys nature, especially oceans and lakes. She can be reached at 202-334-2334 or MSpell@nae.edu.

KOMAL SYED is an assistant program officer working on the workshop on Connecting Efforts to Support Minorities in Engineering Education and supporting the president's Racial Justice and Equity Committee (RJE) and Business Advisory Committee (PBAC). Before joining the NAE staff, Komal was a 2021 Christine Mirzayan S&T Policy Fellow working in the Academies' Policy and Global Affairs Division. She recently completed her PhD in materials science and engineering at the University of California–Irvine where she was a Provost PhD Fellow; her research focused on process-structure-property relations in ceramic materials exposed to extreme environments. She was also an active volunteer at UCI in various roles, such as mentoring undergraduate engineering students from minority backgrounds and organizing forums to address graduate student issues (e.g., mental wellbeing, work/life balance) in collaboration with the UCI Office of Access and Inclusion. With her interest in science policy, she completed an online certificate course in science policy and advocacy for STEM scientists, in which she learned effective strategies for scientists to interact with policymakers. She was the winner of the 2020 annual elevator pitch competition at UCI, with her 2-minute pitch about improving childcare policies for graduate student parents.

Maiya Spell

Komal Syed

Komal likes to spend her free time exploring local nature trails with her husband and toddler son. You can reach her at KSyed@nae.edu.

Mirzayan Fellow Joins Program Office

Bethany Gordon

BETHANY GORDON is a PhD candidate in the University of Virginia's Convergent Behavioral Science Initiative; she received her BS in civil and environmental engineering in 2017 from UVA. She researches applications of behavioral science to improve equity through design of the built environment. Her dissertation research focuses on the relevance of critical racial history in prioritizing distributive justice for large-scale infrastructure projects. Bethany is an NSF graduate research fellow, UVA SEAS Dean's Scholar, and a GAANN (Graduate Assistance in Areas of National Need) teaching fellow. As an impact-driven scholar, she has pursued experiences to understand how her training as an engineering researcher translates into policy. She has served in leadership roles for 500 Women Scientists and the Science Policy Initiative at UVA, as well as actively participating as a member of the National Science Policy Network. As a Mirzayan Fellow, Bethany is excited to work with the NAE's Cultural, Ethical, Social, and Environmental Responsibility (CESER) initiative and to explore the policy landscape in DC.

Calendar of Meetings and Events

2022	
January 1–31	2022 election of new NAE members and international members
January 1–April 1	NAE Awards call for nominations
February 3–4	NAE Membership Policy Committee meeting
February 9	Announcement of Class of 2022 newly elected NAE members and international members
February 9	NAE Council meeting Beckman Center, Irvine, California
February 10	NAE national meeting Beckman Center, Irvine, California
Late February–Late April	Call for new nominations for 2023 election cycle (from current members/international members only)
March 1–31	Election of NAE officers and councillors
March 15	NAE regional meeting Medtronic, Minneapolis, Minnesota
March 30	NAE regional meeting University of Arizona, Tucson

Meetings are held virtually unless otherwise noted.

In Memoriam

Arthur G. Anderson, 94, retired vice president, International Business Machines Corporation, died August 31, 2021. Dr. Anderson was elected in 1975 for contributions and leadership in computer technology.

Mary Baker, 77, technical director, technical fellow, and chair, ATA Engineering Inc., died September 7, 2021. Dr. Baker was elected in 2019 for computer simulation methods for structural mechanics problems and engineering leadership.

Max W. Carbon, 99, professor emeritus of nuclear engineering, University of Wisconsin–Madison, died June 23, 2021. Professor Carbon was elected in 2012 for establishing engineering educational programs for nuclear reactor design and safety.

Robert C. Crooke, 93, retired president, Global Marine Inc., died February 14, 2021. Mr. Crooke was elected in 1981 for outstanding contributions in the development of our nation's submerged lands through the design and implementation of heavy work systems from floating platforms.

Hans K. Fauske, 85, regent advisor and emeritus president, Fauske and Associates LLC, died September 27, 2021. Dr. Fauske was elected in 2016 for contributions to nuclear and chemical reactor safety.

Shun Chong Fung, 78, retired senior research associate, ExxonMobil Research and Engineering Company, died July 21, 2021. Dr. Fung was elected in 2007 for the investigation of factors underlying the deactivation and reactivation of catalysts, and for application of the findings in commercial practice.

Paul H. Gilbert, 84, director emeritus, Parsons Brinckerhoff Inc., died February 6, 2021. Mr. Gilbert was elected in 1997 for the execution of complex engineering projects, and for contributions to professional development.

George J. Gleghorn, 94, retired vice president and chief engineer, TRW Inc., died August 27, 2021. Dr. Gleghorn was elected in 1990 for contributions to the development of advanced scientific and communications satellites and the technology of spacecraft systems engineering.

Peter T. Kirstein, 86, professor, University College London, died January 8, 2020. Professor Kirstein was elected a foreign member in 2009 for contributions to computer networking and for leadership in bringing the internet to Europe.

Tso-Ping Ma, 75, Raymond John Wean Professor, Yale University, died April 6, 2021. Professor Ma was elected in 2003 for contributions to the development of CMOS gate dielectric technology.

John B. MacChesney, 92, retired fellow, Bell Laboratories, Lucent Technologies, died September 30, 2021. Dr. MacChesney was elected in 1985 for leadership in the invention of processes to make glasses for optical fiber and for transfer of these processes to manufacturing.

Malcolm MacKinnon III, 85, retired managing member, MacKinnon-Searle Consortium LLC, died June 24, 2019. Admiral MacKinnon was elected in 1998 for the design of two new classes of Navy nuclear submarines and for development of the Navy's Sealab II undersea habitat.

James F. Mathis, 95, retired vice president, science and technology, Exxon Corporation, died April 11, 2021. Dr. Mathis was elected in 1990 for outstanding research management in the petroleum industry and for application of chemical technology to the public welfare.

Henry McDonald, 84, distinguished professor, University of Tennessee, Chattanooga, died May 25, 2021. Professor McDonald was elected in 2000 for leadership of a major national aeronautical laboratory, development of the block implicit method for computation fluid dynamics (CFD), and coinvention of a valuable medical-assist device.

Ross McKinney, 95, professor emeritus, University of Kansas, died September 18, 2021. Professor McKinney was elected in 1977 for contributions to the development of biological wastewater treatment processes and to the advancement of the environmental engineering profession.

James J. O'Brien, 91, consultant, James J. O'Brien, PE, died December 31, 2020. Mr. O'Brien was elected in 2012 for development of standards of practice for computerized scheduling of construction projects and capital programs.

Paul Penfield Jr., 88, professor of electrical engineering, Massachusetts Institute of Technology, died June 22, 2021. Professor Penfield was elected in 1994 for contributions to very large scale integration (VLSI) simulation and to the theory of active networks and for leadership in engineering education and microstructures research.

Ronald F. Probstein, 93, Ford Professor of Engineering Emeritus, MIT, died September 19, 2021. Professor Probstein was elected in 1977 for contributions to the fields of hypersonics, rarefied gas flow, desalination, and water purification.

Hermann Statz, 92, independent consultant, died June 14, 2020. Dr. Statz was elected in 1991 for leadership in research on microwave devices and lasers.

Henrik Topsøe, 74, executive vice president, Haldor Topsoe A/S, died August 9, 2019. Dr. Topsøe was elected a foreign member in 2013 for development of hydrodesulfurization catalysts and elucidation of their active sites.

Thomas A. Vanderslice, 88, retired CEO, TAV Associates, died October 9, 2020. Dr. Vanderslice was elected in 1980 for invention, innovation and management leadership ranging over the technologies of high-vacuum systems, information, communications, transportation, and energy.

Julia R. Weertman, 92, Walter P. Murphy Professor Emerita, Northwestern University, died July 31, 2018. Professor Weertman was elected in 1988 for exceptional research on failure mechanisms in high-temperature alloys.

Robert J. Weimer, 94, professor emeritus, Colorado School of Mines, died August 25, 2021. Professor Weimer was elected in 1992 for application of stratigraphic principles to exploration, and for promoting continuing professional education.

Willis S. White Jr., 94, retired chair, American Electric Power Company Inc., died July 4, 2021. Mr. White was elected in 1983 for contributions to establishment of a national energy policy and leadership in research and development of electric power supply.

Peter Whittle, 94, emeritus professor, University of Cambridge, died August 10, 2021. Professor Whittle was elected a foreign member in 2016 for contributions to the mathematics of operations research and statistics.

Laurence R. Young, 85, Apollo Program Professor of Astronautics Emeritus and professor of health sciences and technology, MIT, died August 4, 2021. Professor Young was elected in 1980 for introduction of systems analysis to human spatial orientation and contributions to biomedical engineering education.

Zhemin Zheng, 96, professor, Institute of Mechanics, Chinese Academy of Science, died August 26, 2021. Professor Zheng was elected a foreign member in 1993 for contributions to the theory and application of explosion mechanics.

Invisible Bridges

Mirror, Mirror, on the Wall

Beth Cady is director of the NAE's Practices for Engineering Education and Research (PEER) program.

Engineering education in the United States has undergone periods of reform for many years, often in response to reports predicting a loss of technological innovation and global leadership that prompt calls to increase the numbers of engineers in this country. And the numbers of students earning bachelor's degrees in engineering have increased dramatically over the past 20 years. This is encouraging news. Yet White men still earn the vast majority of those degrees and constitute the vast majority of engineers working in industry and academia.[1]

[1] According to the National Science Foundation's 2019 Science and Engineering Indicators (https://ncses.nsf.gov/pubs/nsb20197/data), of the 118,000 engineering bachelor's degrees awarded in 2017 White men earned 47 percent and White women earned 12 percent. Both Asian and Hispanic men earned approximately 8 percent, but Asian and Hispanic women earned less than 3 percent of degrees. Black men also earned 3 percent of those degrees, but Black women and American Indian men and women each accounted for less than 1 percent. According to Carnevale and colleagues (2021), 56 percent of working engineers are White men; women of all races are 16 percent, with White women the largest share of that group at 9 percent. While Asian men are 12 percent of that workforce, Asian women are only 3 percent. Black men (4 percent) and Black women (1 percent) as well as Hispanic men (8 percent) and Hispanic women (2 percent) constitute a very small proportion of the engineering workforce. Carnevale AP, Smith N, Quinn MC. 2021. Mission not accomplished: Unequal opportunities and outcomes for Black and Latinx engineers. Washington: Georgetown University Center on Education and the Workforce.

Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

The reasons for this are numerous and varied,[2] but rather than address the underlying systemic issues that maintain the status quo, one of the most popular responses to the problem is to "increase the pipeline." This approach calls for getting more young people from populations that have been traditionally marginalized and minoritized in engineering interested and prepared for undergraduate study in engineering and then having them graduate with an engineering degree. Increasing the input to the system, the rationale goes, will cause a corresponding increase in the output from that system.

The pipeline metaphor is flawed, and is itself leaky, on many levels; it assumes only one entry point (generally middle school), and does not allow for complexities along engineering education and career pathways such as starting later in life, stopping for a period of time, or moving into engineering from another field. Many have written about these problems with the pipeline metaphor.

But there is another, deeper problem with the pipeline metaphor: it ignores the culture, climate, and curricula of engineering education. The pipeline functions like Skinner's black box—we observe the inputs (entering college students) and outputs (those with engineering bachelor's degrees) without considering or examining what happens to the students between those two milestones. It's important to retire that metaphor from use.

To effectively diversify engineering and engineering education, we must delve into that box. Simply bringing more Black and Brown people, White women, LGBTQIA+ individuals, and people with disabilities into institutions and programs with a long tradition of excluding individuals from those populations will, at best, drive them to disciplines with more welcoming cultures. At worst, those who manage to complete their degree and enter engineering work are more likely to end up with negative experiences and possibly deleterious impacts on their health and wellbeing as well.[3]

Words like grit, rigor, resilience, and fit are used to signal to anyone whose identity or identities are exclud-

[2] National Academy of Engineering. 2018. *Understanding the Educational and Career Pathways of Engineers*. Washington: National Academies Press.

ed from engineering that they must either change or ignore that part of themselves in order to fit into the mold of an engineer. Thus, even for capable students excited about studying engineering, it can be difficult to reconcile these aspects of one's identity with an "engineering identity" (typically male, White, heterosexual, and nondisabled). Having to constantly monitor one's behavior to hide or minimize parts of identity is exhausting and diverts energy from what **Sam Florman** rightly called "the existential pleasures of engineering."

Encouraging people to change themselves in order to be an engineer has significant consequences. It discourages the participation and retention of those who do not "fit" the majority type and, as former NAE president **Bill Wulf** explained in an NAE report two decades ago, it has important opportunity costs:

> Without diversity, the life experiences we bring to an engineering problem are limited. As a consequence, we may not find the best engineering solution. We may not find the elegant engineering solution.
>
> As a consequence of a lack of diversity, we pay an opportunity cost, a cost in designs not thought of, in solutions not produced. Opportunity costs are very real….[4]

Those concerns remain as true today as when they were written. One area of change needed is in the culture and perceptions of who is and can be an engineer.

We can begin by acknowledging the heuristics and biases that we all bring to the table and that often unconsciously inform how we make sense of the overwhelming amount of information that we encounter daily. These cognitive shortcuts make decisions easier by reducing the amount of information processing needed. But they also increase errors because important information may be overlooked or stereotypes activated.

For example, the fundamental attribution error and the related correspondence bias lead us to greatly overestimate how much personal characteristics like innate intelligence and motivation contribute to behavioral outcomes like test scores (e.g., "I did well on the test because I am smart"—or "I did not do well because I am not smart"). Conversely, we greatly underestimate the role of situational context in those outcomes (e.g., it is less typical for an individual to crow that "I did well on the SAT because I attended a well-resourced school that offered test prep sessions," or to acknowledge that "I did not do well on the SAT because I needed to work to help support my family and could not study as much as I needed").[5]

Relatedly, actor-observer bias leads us to attribute others' behavior to personal causes but use situational contexts to explain our own. Thus if I don't do well on an exam, I may blame lack of sleep due to my job rather than my innate intelligence or study habits, but attribute others' poor scores to their lower intelligence or lack of work ethic to study rather than their need to work instead of study.

More insidiously, our perceptions of other people can be affected by ingroup-outgroup bias, which leads us to favor individuals we consider to be in our "ingroup," whether we're categorizing by gender, race, neighborhood, team, or any of a number of identities that we all hold. Because of the strength of these biases, we tend to give similar attributional consideration to members of our ingroup (this is called the group-serving bias or ultimate attribution error). So if all the students who look like me fail a test, I'm likely to think they also have contextual excuses, while simultaneously not giving that consideration to students who are dissimilar to me.

We also tend to ignore or not carefully consider information that contradicts our existing beliefs while trusting evidence that supports those beliefs (confirmation bias). So if I believe that hard work and motivation are the only ingredients needed to become an engineer and thus everyone has an equal chance to become one (the myth of meritocracy), I might not consider evidence to the contrary, such as differences in access to quality education at all levels, bias (implicit or explicit) against individuals from minoritized populations, or historic systemic racism and sexism that studies clearly show mean that not everyone has an equal chance of being an engineer.

This sense-making process also affects the ways we categorize people we meet for the first time. If I meet someone who seems similar to my idea of an engineer I use the representativeness heuristic to, correctly or not, classify them as an engineer. If a child asks what engineers are like I will likely describe the first known engineer that comes to mind (the availability heuristic). Without checking my reasoning, I could easily be contributing to stereotypes of who is and can be an engineer.

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[4] Wulf WA. 2002. The importance of diversity in engineering. In: *Diversity in Engineering: Managing the Workforce of the Future*. Washington: National Academy Press, p. 9.

[5] It should be noted that individuals from collectivist societies (like those of countries in Asia and South America) do this less than those from individualistic societies (like those of the United States, Germany, and Australia).

This is where the compositional diversity of engineering education matters. When the discipline is overwhelmingly White and male, those individuals will give different attributional considerations to Black and Brown students than to White ones. They will likely think of individuals similar to them as being a better representation of an engineer, and because of confirmation bias may not acknowledge evidence showing that individuals from marginalized populations are great engineers. This could have negative effects on both peer and student-faculty relationships as well as, beyond the classroom, opportunity and economic costs to innovation.

These heuristics and biases evolved as humans did. They helped our early ancestors recognize potential threats and act accordingly, making life or death decisions when confronted with unfamiliar people who could be enemies or friends or animals who could be prey or predators. Even today there is nothing inherently wrong with using these cognitive shortcuts to help us manage our behavior—without them we would not be able to whittle down all the information presented to us in order to make a decision.

Acknowledging that inherent heuristics and biases can produce inequitable results for students is an excellent place to start to ensure that engineering education does not remain "stuck in 1955."[6]

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[6] Sorby S, Fortenberry NL, Bertoline G. 2021. Stuck in 1955, engineering education needs a revolution. Issues in Science and Technology, Sep 13. Also see Chubin D. 2021. A revolution for engineering education. Issues in Science and Technology, Oct 5.

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