Winter 2022

FRONTIERS OF ENGINEERING

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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Mission Statement of *The Bridge*

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

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LINKING ENGINEERING AND SOCIETY

News and Notes

President’s Perspective

Philanthropy: Wellspring of the NAE’s Work and Impacts

John L. Anderson

The public phase of the *Campaign for the NAE: Leadership in a World of Accelerating Change* was announced at the 2022 NAE Annual Meeting in October. The announcement was kicked off with a dynamic 90-second call-to-action video,[1] to build excitement for the campaign, the NAE, and engineering in general. This unprecedented $100 million multiyear campaign will firmly position the National Academy of Engineering to achieve its vision, mission, and strategic plan, while ensuring its capacity to continue as the trusted source of engineering advice for creating a healthier, more secure, more equitable, more sustainable, and joyful world.

Why Philanthropy?

There is no line item in the federal budget for the National Academies of Sciences, Engineering, and Medicine (NASEM) and the academies do not receive any direct appropriations from the federal government. Contributions from foundations, the private sector, and individuals enable the NAE to address critical issues on behalf of the nation and the engineering community. *Sixty percent* of the NAE’s revenue derives from philanthropy.

Many NASEM activities are mandated by acts of Congress and federal agencies, which reimburse expenses. But our work extends well beyond fulfilling federal government requests, as we very effectively demonstrated in the early days of the pandemic: In April 2020 the NAE launched the NAE Covid-19 Engineering Call to Action, an incubator that engaged members and hundreds of students to innovate engineering-based products and methods to address the crisis. This and other pivotal NAE initiatives are funded largely and sometimes wholly by philanthropy.

Understanding NAE Funding

The NAE operating budget for calendar year 2022 is $13.5 million. This includes funds for programs, studies, and convening activities ($4.0 million) and awards ($1.4 million), and anticipated contributions to the NAE independent fund ($1.7 million), more than half of which comes from NAE members and donors who contribute far beyond dues and meeting fees (these total only about $0.5 million).

Although many costs are fixed, costs are continually evaluated for efficiencies. Recent cost-saving measures include the transition to electronic delivery of the member directory and annual report, realignment of support staff, renegotiation of external contracts for IT support services, decreased investment management fees, and reduced meeting and travel expenses.

The overall NAE endowment is about $100M (as of end-July 2022), half of which is committed to ongoing programs and activities including the NAE’s awards, Frontiers of Engineering, EngineerGirl, the Office of Outreach and Communications, *The Bridge*, and *Memorial Tributes*, among others.

Each year a draw is made from the NAE *unrestricted* endowment, which is capitalized at about $50 million as of June 30, 2022. This endowment is the product of 50-plus years of philanthropy from those who support the NAE’s vision and work. Unrestricted funds are essential to the NAE’s ability to take prompt action on emerging matters of import to the nation and the engineering community, like the Covid-19 Call to Action.

To grow the endowment and establish a larger base for the annual draw, in 2016 the NAE initiated the multiyear *Campaign for the NAE: Leadership in a World of Accelerating Change*, by then-Chair Gordon England, then-President Dan Mote, and the NAE Council. This

[1] Online at https://www.youtube.com/watch?v=C1XTKnQS6xM.

campaign—the first of its kind in the NAE's history—will ensure that the NAE endowment can continue to support both the academy's core operations and the advisory and actionable outcomes of its programs.

Philanthropy's Uses and Impacts at the NAE

To date we have secured more than $51 million of our $100 million goal. Recent successes in fundraising have enabled the NAE to undertake new initiatives related to our mission. These include creation of the President's Business Advisory Committee (PBAC) and Racial Justice and Equity (RJ&E) Committee; inception of the annual Special Lecture on Engineering and Society, for which John B. Slaughter was the compelling inaugural speaker in 2020, and which this year focused on the timely topic, "Meeting the Energy-Climate Challenge," by John P. Holdren; and establishment of the NAE's Office of Outreach and Communications, which works with all NAE units and NASEM divisions to ensure that the voice of engineering is heard—loud, proud, and often.

Major gifts also supported an international series on pandemic-related engineering advances and best practices for the development, production, and dissemination of interventions. And the newly named Grainger Foundation Frontiers of Engineering symposia series reflects an exceptional $10 million endowment to support this noteworthy program, which for more than 25 years has been bringing together early-career researchers and practitioners in myriad cutting-edge engineering areas, to share the excitement of their work and forge cross-disciplinary networks and collaborations.

I am profoundly grateful to the members, friends, and partners who have demonstrated their generous support and steadfast commitment to the NAE. But we have much more to do.

Funding is needed to sustain and build our mission-centric programs on Practices for Engineering Education and Research (PEER), Cultural, Ethical, Social, and Environmental Responsibility in Engineering (CESER), and the Forum on Complex Unifiable Systems (FOCUS). The funds will also support the NAE's outreach program on Inclusive, Diverse, and Equitable Engineering for All (IDEEA), which includes EngineerGirl, a dynamic feature that recently celebrated its 20th anniversary and has proven very effective in engaging and sparking the curiosity of K-12 students in engineering.

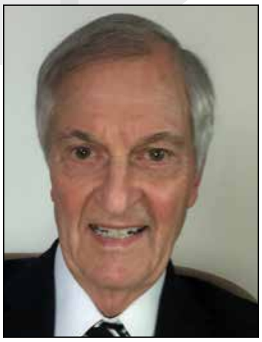
The success of this landmark campaign to ensure the strength and effectiveness of the NAE depends on our members, institutional donors, and friends. Together, we can increase engineering talent through a commitment to equity and inclusion, instill a culture of ethical and environmental responsibility in engineering, improve capabilities and competencies for complex systems, and foster a commitment for engineering to enhance quality of life for all.

If you have questions or would like to make a gift or multiyear pledge to the *Campaign for Leadership in a World of Accelerating Change*, please contact me or Radka Nebesky, director of development (RNebesky@nae.edu or 202.334.3417), or Stephanie Halperin, associate director of development (SHalperin@nae.edu or 202.334.1842). With your help we will succeed!

LEADERSHIP IN A WORLD OF
Accelerating Change
CAMPAIGN FOR THE NATIONAL ACADEMY OF ENGINEERING

Editor's Note

Frontiers for Engineers and for the Country



Ronald M. Latanision (NAE) is a senior fellow at Exponent.

I knew little of the NAE's Frontiers of Engineering program before I became editor in chief of *The Bridge* in 2012. But over the years since, I have been more and more impressed by its approach to engaging young, rising engineering leaders.

Established in 1995, the goal of the Frontiers of Engineering (FOE) program is to bring together outstanding early-career engineers from all engineering disciplines and from industry, universities, and federal labs 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. Additionally, this approach establishes lifelong contacts among a network of the next generation of engineering leaders. The meetings focus on pioneering technical work and leading-edge research in selected, varied engineering fields and industry sectors.

FOE is integral to the culture and impact of the Academy. As always, young people are the future and the select FOE participants represent that future for the NAE, the nation, and the planet! FOE expands, enlightens, and challenges these young folks.

Each year when I look at the FOE program, I wish that I could have been present. This year is no exception. The 2022 Grainger Foundation Frontiers of Engineering Symposium was hosted by Amazon and featured sessions on advances in infectious disease diagnostics and treatment, conversational AI, technology and racial justice and equity, and the hydrogen economy.

These topics represent an important part of our societal and engineering future. For one, the global Covid-19 pandemic has not only imposed immediate changes on daily life, work, education, and commerce but also ushered in new thinking about the ways—and places—we work, study, and live. As indicated in the fall issue of *The Bridge*, on Microbiomes of the Built Environment, buildings of all kinds—offices, homes, schools, hotels, hospitals, and more—are used by a public that is concerned about its health and the capacity of buildings to reduce risks and assess health conditions.

Likewise, there is a growing sense in the AI community that AI can simulate human consciousness. I wonder if it is more likely that AI can mine data that it curates and then construct what appears to be human thought by assembling a mirror of the data it curates. With a population that is now so seemingly easily misled and misinformed, this seems a crucial point in our technological history.

It is true that the technical advances behind AI are exciting and can be implemented meaningfully and usefully. But there are important social and ethical issues associated with various applications of AI, concerning, for example, privacy, monitoring, manipulation, and differential impacts related to characteristics such as race/skin color and gender. I believe that this is an extremely important topic to be addressed and that corporate America could set the standard for AI technological transparency, accountability, and responsibility in a way that engages social scientists. Both the European Union and the White House have recently introduced legislation that would provide some guidance for AI safeguards. A future *Bridge* issue will explore this important topic.

In the case of hydrogen, it is demonstrably clear that the sea level is rising, glaciers are melting, and global temperatures are warming. Whether these are consequences of natural climate oscillation or climate change that is accelerated by anthropogenic activity is the subject of some scientific debate and even more political discourse. In any case, engineered solutions are necessary to manage all of this going forward.

But it seems to me that there is a collective solution that has received almost no attention: desalination on a global scale and the transition to a hydrogen economy. The former is practiced widely in the Middle East and could be scaled up globally to produce freshwater for human consumption and irrigation for drought-ridden farms. Likewise, some of that water could be split using sunlight to produce molecular hydrogen and oxygen. The former would serve as a global energy source. *This can be done*. What is required is the public and political will to do it.

We live in a technology-intense world and engineers and technologists must become a major part of the conversation in all three branches of government. And these experts must be of all races, ethnicities, and genders! Exclusion is not an option.

It is time for change on many levels. Engineers and technologists must run for public office and/or make themselves available for appointment to positions in government bodies. I personally hope that someday soon a president of the United States will stand before a microphone and say something like "I am going to commit this nation to a hydrogen economy going forward. In order to do that we will need a photoelectrode that is durable, efficient, and cheap in order to use sunlight to split water into hydrogen and oxygen. Sunlight and water are both free and know no national or geopolitical boundaries. This is a means of energy independence for legacy and nonlegacy nations all over this small planet. I therefore call on the materials science community to develop such a photoelectrode." Then a representative from the Materials Genome Initiative will come to a microphone and say, "Madam President, MGI is up to this challenge and we will develop and deploy that photoelectrode." (I have four granddaughters!)

The Materials Genome Initiative provides the basis for such a conversation. It is reshaping materials education and practice in service to societal and national needs. A product of the White House Office of Science and Technology Policy (OSTP) during the Obama administration, this program is demonstrably able to design materials with required properties from first principles in a fraction of the time and at a fraction of the cost of the traditional empirical materials development of the past. This is a consequence of the unprecedented convergence of computational and experimental tools and the will of the materials science and engineering community to embrace this approach. What was required then, as now, was both the public and political will to respond.

Once again, FOE has hit a home run, in my view!

I am also very pleased to include in these pages a contribution from the MIT Microelectronics Group on a subject that is of enormous consequence to the US economy and national security: reestablishment of leadership in semiconductors and microelectronics. From fundamental science to workforce development to deployment, Jesús del Alamo and his colleagues identify opportunities to regain this country's standing and leadership. There is much to do but this article should serve as a guide for action in response to the CHIPS and Science Act of 2022.

Finally, I note that in this issue we take a temporary hiatus from the interview feature and the *Invisible Bridges* column. Both will return in the spring.

As always, I welcome your comments (RLatanision@exponent.com).

Guest Editor's Note

The Grainger Foundation Frontiers of Engineering 2022 Symposium

Timothy C. Lieuwen

Timothy Lieuwen (NAE) is Regents' Professor and David S. Lewis Jr. Chair, Guggenheim School of Aerospace Engineering, Georgia Institute of Technology.

The winter issue of *The Bridge* is typically dedicated to papers from the annual US Frontiers of Engineering symposium, held in September each year. As the current chair of this event, I am the guest editor of this issue, which features a selection of papers from the 2022 US FOE meeting, hosted by Amazon in Seattle.

The first thing you may notice since last year's issue is that the name of the US-based program has changed, in recognition of the endowment gift of $10M from The Grainger Foundation, received earlier this year. (You may still see "US FOE" now and again when we refer to the meeting informally or when the shorter term works better in a particular context.)

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.

The technical sessions at the 2022 US FOE covered the following topics:

- *Microbes: The Good, the Bad, and the Ugly*, cochaired by Gabriel Kwong (Georgia Institute of Technology) and Anita Shukla (Brown University); talks covered bacterial electrophysiology, preventing biofilm-associated infections, precision delivery of probiotics, and microbial bioprocessing.

- *Technology and Racial Justice and Equity*, organized by Brooke Coley (Arizona State University) and Khalid Kadir (University of California, Berkeley), with presentations on impacts of inequity in the transportation sector, cultural characteristics of engineering education that maintain exclusivity and inequality, the hidden curriculum in engineering, and constructing more nuanced and resilient engineering identities.

- *Hydrogen: A New "Universal" Energy Carrier for the Carbon-Free Future?*, cochaired by Jesse Jenkins (Princeton University) and Iryna Zenyuk (University of California, Irvine); speakers described the role of hydrogen in a net-zero emissions energy system, DOE's Hydrogen Program, clean electrolysis, and the technologies and costs of H_2 production.

- *Conversational AI*, organized by Suma Bhat (University of Illinois at Urbana-Champaign) and Angeliki Metallinous and Jing Huang (Amazon Alexa AI), with talks about the current status and future directions of conversational AI systems, models for achieving natural human-machine communication, generative conversational networks, and techniques that provide situational context for improved human-machine understanding.

The meeting also included a breakout session to facilitate small group discussion of attendees' research and technical work, and a panel of Amazon scientists and engineers who discussed how their work is applied in a range of Amazon services. At dinner on the second night, Rohit Prasad, senior vice president and head scientist for Alexa, provided an interesting perspective on his career path and lessons learned. A list of the talks and speakers, abstracts of the presentations, and (where permission was granted) links to the slides of the presentations are all available at the US FOE website (naefrontiers.org).

We thank the sponsors of the 2022 US FOE meeting: The Grainger Foundation, Amazon, National Science Foundation, Air Force Office of Scientific Research, DOD OUSD(R&E)-Research, Technology & Laboratories, Cummins Inc., and individual donors.

The next US Frontiers of Engineering Symposium will be held September 11–13, 2023, hosted by the University of Colorado Boulder. With that meeting, I will serve my third and final year as US FOE chair.

We encourage you to nominate outstanding early-career 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.

Nature is inspiring the development of living and synthetic materials that can adapt to discourage microbial growth.

Bioinspired Materials–based Approaches to Address Antimicrobial Resistance

Caitlin Howell is an associate professor of biomedical engineering, University of Maine.

Caitlin Howell

The rise of antimicrobial resistance is one of the greatest global public health challenges; the World Health Organization (WHO 2021) places it in the top 10 concerns facing humanity. It causes nearly 5 million deaths globally each year (Antimicrobial Resistance Collaborators 2022), and in the United States alone, more than 2.8 million antimicrobial-resistant infections occur each year, leading to more than 35,000 deaths.[1]

The Postantimicrobial Age

Alarmingly, infections and deaths due to resistant organisms rose at least 15 percent in the first year of the Covid-19 pandemic (CDC 2022), painting a grim picture for future pandemics and other disease outbreaks expected to arise as climate change exacerbates cross-species viral transmission (Carlson et al. 2022).

Although new antimicrobial compounds continue to be discovered, the pace is slowing—while the appearance of new antimicrobial-resistant organisms increases at a rapid rate (WHO 2021). The increase in resistance is further accelerated by the widespread presence of antimicrobials not only in healthcare facilities but in the environment, often due to overuse in agriculture. Antimicrobials are commonly fed to cattle, pigs, and poultry to boost

[1] Centers for Disease Control and Prevention (CDC), The AMR Challenge, 2018–19 (https://www.cdc.gov/drugresistance/intl-activities/amr-challenge.html).

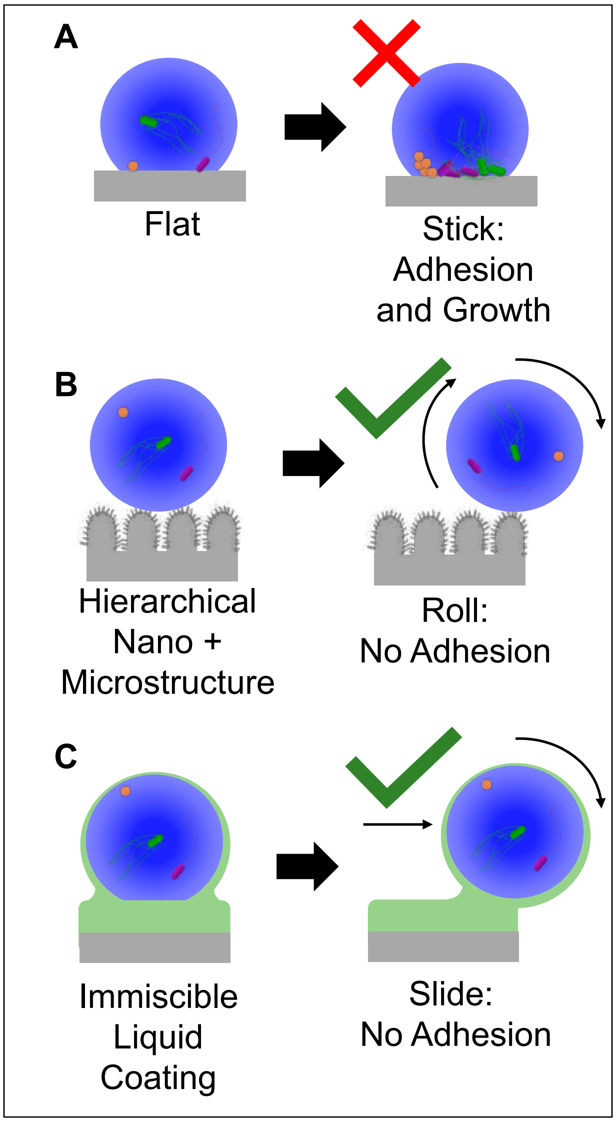


FIGURE 1 Examples of a microbe-containing droplet interacting with (A) a typical flat surface, (B) a lotus-inspired textured surface, (C) a bioinspired liquid layer.

their weight—a practice that is estimated to expand by 11.5 percent across all continents by 2030 (Tiseo et al. 2020).

Addressing the burgeoning crisis of antimicrobial resistance requires a coordinated and multifaceted effort that brings together communities, healthcare facilities, industry, and agricultural partners as well as other stakeholders. The development and implementation of new technologies and materials will also be important to provide the necessary tools and devices, which must not unintentionally serve as colonization, growth, and proliferation sites for microorganisms. Although a significant amount of excellent research has focused on this goal (Truong et al. 2022), there remains a critical and persistent need for innovation as the antimicrobial crisis worsens.

Nature's Approaches to Controlling Microbes

Over millions of years, nature has developed multiple ways to direct or stop microbial growth on surfaces (figure 1), leading to microbial control mechanisms that are elegant and effective and that discourage the development of resistance.

For example, cicada (Ivanova et al. 2012) and dragonfly (Bandara et al. 2017) wings are covered with nanopillar arrays that rupture the membranes of microbial cells. Lotus plants have hierarchically structured, wax-covered bumps on the surfaces of their leaves, which water droplets simply roll off, cleaning away adherent microorganisms in the process (figure 1B) (Barthlott and Neinhuis 1997). The scales of the mako shark are patterned in such a way that water flowing over them creates vortices, making it more difficult for microorganisms to adhere (Choi et al. 2020). Pilot whale skin has a nanopatterned surface that is perfused with an enzyme-laden gel that breaks the chemical bonds of organisms attempting to colonize the surface (Baum et al. 2001).

These are only a few of the myriad ways that nature controls, reduces, or eliminates the adhesion of microbes on surfaces.

Bioinspired Liquid Layers

Interest in another bioinspired antimicrobial solution is growing: liquid coatings. Inspired by the way mucosal tissue controls large bacterial cohorts in humans, this approach involves the use of a mobile, dynamic, and sacrificial liquid barrier between microorganisms and the surface they may contaminate (figure 1C).

Critically, the aim with liquid coatings, like human mucosal tissue, is not to kill microbes but to change their environment to discourage activity that is harmful. In one example, liquid coatings can stop microbes from forming irreversibly adhered slimy coverings around themselves, known as biofilms. When a surface is coated in a water-immiscible liquid, biofilms and the bacteria in them have been shown to simply slide off (Regan et al. 2019).

The fact that liquid coatings can be applied on a broad range of medically and industrially relevant materials—from glass to metals, rubbers (Howell et al.

2018), and filtration membranes (Shah et al. 2022)—has unlocked new tools in the fight against antimicrobial resistance.

Studies of the performance of liquid coatings in complex environments (e.g., in living systems) have further demonstrated their potential to maintain effectiveness against the challenges of difficult and dynamic conditions. In proof-of-concept experiments in vivo using urinary catheters, one of the most common and infection-prone medical devices (Tambyah and Oon 2012), liquid coatings performed beyond expectations, reducing not only surface adhesion by some of the most aggressive infectious microbes but also overall surface protein contamination (Andersen et al. 2022). Similarly, tests using liquid-coated vs. uncoated hernia meshes in a device-associated infection model showed a significant reduction in the amount of adherent bacteria as well as a decrease in harmful inflammatory markers (Chen et al. 2017).

While the results from liquid coatings are promising, they—like most approaches to address the problem of microbial growth on surfaces in this age of antimicrobial resistance—are based in the concept that a simple, nonadaptive surface can resist colonization in a complex, microbe-containing environment. That may be true in some circumstances, but in others it can be a very challenging goal because part of what makes these environments so complex is their tendency to change with time. On static surfaces, changes often result in either a depletion of the functional component of the material (e.g., antimicrobial compound, liquid coating) or a covering of the functional surface by proteins or other compounds produced by the growing microorganisms.

In nature, the most successful examples of materials that remain effective at reducing or eliminating microbial colonization long-term are *living* materials, which can change and adapt to maintain their functionality amid changes to their surroundings. As mentioned above, lotus leaves, shark scales, pilot whale skin, and human mucosal tissue all possess the ability to either heal when damaged or be replaced as needed, in addition to being able to signal to the overall organism when more drastic measures (e.g., movement away from or out of a particular environment) are required. In extreme environments with very high microbial densities, such as mucosal tissue, "good" microbes are recruited to participate in maintaining a healthy dynamic equilibrium in a variety of ways (Lynch and Pedersen 2016).

A New Way to Think about the Problem: Working with Bacteria

Researchers are just beginning to uncover the depth of complexity of "good" microbes in the human microbiomes and the extent to which they affect overall health (Schmidt et al. 2018). The human body, particularly the gut, is home to 10^{13}–10^{14} bacteria, fungi, viruses, and archae (Gill et al. 2006) whose metabolic and trophic activities protect and contribute to the body's normal functioning (Fan and Pedersen 2021). Healthy gut ecosystems help reduce multiple metabolic diseases (Fan and Pedersen 2021) as well as anxiety, depression, and other brain and psychiatric disorders (Morais et al. 2021). Research has also uncovered how systems seemingly unrelated to the gut, such as the lung, respond to the microbial community through pulmonary-intestinal cross-talk (Dumas et al. 2018).

Living materials can change and adapt to maintain their functionality amid changes to their surroundings.

As understanding of how the microbiome affects overall health continues to grow, new approaches will be needed to translate this knowledge into therapeutic applications. One method of applying microbiome knowledge to the creation of therapeutics is the development of a synthetic microbiome, or an engineered system of "good" microbes. Although many promising approaches are in active development, several challenges remain, including maintaining the right balance of organisms and composition of the surrounding environment (Mabwi et al. 2021).

Inspired by the observation that natural microbiomes are constantly in a state of dynamic change mediated by feedback loops, liquid coatings are being used in hybrid living-nonliving materials systems that can both sense microorganisms (Dixon et al. 2022) and enable a targeted response such as delivery of compounds to either stop or encourage growth (Marquis et al. 2020). The system makes use of an embedded vascular network filled with a functional fluid, much as the vascular systems of living organisms are filled with blood or other transport fluids. When a water-soluble nonliving

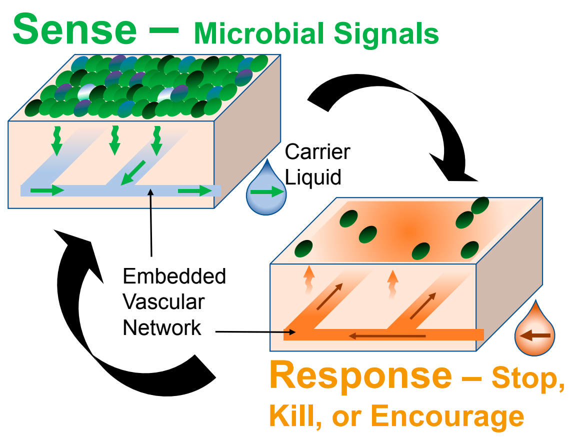


FIGURE 2 Schematic illustration of an embedded vascular network interacting with a microbial surface layer.

material substrate is used, compounds produced by the microbes at the interface can diffuse into the fluid in the channels below and be collected for analysis (figure 2). Likewise, active compounds can be introduced into the channel network and diffuse up to the surface to affect the microbes growing there. Recent work has shown how this approach can be used to sense the development of a group of microbes over time (Dixon et al. 2022) and then tightly control the location of those microbes, resulting in a defined pattern (Marquis et al. 2020).

Hope for the Postantimicrobial Future

Looking to nature to inform the development of effective, nonchemical materials strategies to control microorganisms on surfaces is already opening new doors in the race against antimicrobial resistance. The identification of novel natural strategies is ongoing, while the application of such strategies is becoming more and more sophisticated with advances in materials science.

The further development of nature-inspired approaches, particularly those that seek to work with microbes rather than against them wherever possible, will play a critical role in helping the global community continue to adapt to life in the postantimicrobial age.

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Advances in synthetic biology and machine learning enable new engineering approaches to enhance plastic degradation via enzymes.

"Life...Finds a Way": Sustainable Capture and Upcycling of Plastics by Microbes

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Plastics, widely used for their low cost and durability, pose a grand environmental challenge. Every year, more than 380 million tonnes of plastics are produced globally, using 6 percent of produced petroleum (Zhu et al. 2016). Less than 10 percent of these materials are reused or recycled, leading to significant waste accumulation and environmental pollution; for example, an estimated 8 million tonnes of plastic leak into ocean systems each year (Geyer et al. 2017).

Plastic-related environmental damage is estimated to cost at least $75 billion annually. Most of the damage is attributed to waste from consumer packaging, encompassing plastics such as polystyrene (PS), high- and low-density polyethylene (HDPE and LDPE), and polypropylene (PP) (Geyer et al. 2017; MacArthur et al. 2016; UNEP 2014).

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Lack of Infrastructure for Recycling Plastics

A small fraction of total plastics is recycled because of a lack of economical solutions. Many consumer plastics are thermoplastics, which in theory can be infinitely melted and recycled into new plastic products in a process called *mechanical recycling*. However, these plastics tend to degrade in quality with each round of recycling because of contamination with dyes, labels, and the materials they once contained. These recycling limitations may be mitigated to a degree by proper sorting, cleaning, and/or chemical pretreatment, but these steps are labor-intensive, costly, and don't work in practice (Li et al. 2022).

Chemical recycling, in which plastics are chemically converted to other materials, is energy-intensive and similarly sensitive to contaminants, which can poison the catalysts that mediate the chemical conversion and frequently produces low-value products (Rahimi and García 2017).

In light of these challenges, there is a critical need for new technologies that can process or sort mixed plastics waste streams and depolymerize the most abundant plastic wastes (HDPE, LDPE, PP, and PS) into valuable "upcycled" commodity chemicals.

Using Biology to Degrade and Upcycle Plastics

Biological systems, namely microorganisms, have evolved over millions of years to thrive in their native environment by capturing and converting available carbon, hydrogen, nitrogen, and oxygen, along with other trace elements. More importantly, they do this in environments with a complex mixture of "food," toxins, and "nonfoods," effortlessly sorting needed nutrients from other environmental components.

Degradation

In resource-poor environments, "life finds a way" by evolving novel enzymes or biomolecular protein-based catalysts that can assimilate carbon from even recalcitrant materials such as plastics. Microbes have been reported to degrade HDPE (Devi et al. 2015), LDPE (Sen and Raut 2015), PP (Jeon and Kim 2016), and PS (Ho et al. 2017). These microbial partners, frequently viewed as nuisances or pathogens, offer new hope for the development of sustainable recycling of plastics.

The use of microbial systems to deconstruct plastics would mitigate the high energy requirements of chemical recycling with near-ambient processing and could improve economics by eliminating the need for expensive metal catalysts, sorting, and perhaps pretreatment.

Upcycling via Synthetic Biology

Biology can not only degrade recalcitrant materials such as plastic, it can upcycle or convert them into new products via cellular metabolism. Biological systems leverage complex metabolic pathways, or biochemical reaction networks, to convert inputs like plastic into energy and cellular building blocks that frequently resemble industrial chemicals. These chemical transformations are mediated by enzymes encoded in genes that form a part of an organism's DNA. Metabolic engineers introduce new enzymes to this network, remove others, or balance the abundance of enzymes to drive carbon through the pathways to specific products.

These changes are frequently implemented with tools from the field of synthetic biology (synbio) to build efficient microbial cell factories. For example, other recalcitrant substrates such as lignocellulose found in agricultural residues have been upcycled by microbial systems into value-added products such as biofuels, fine chemicals (e.g., fragrances), and commodity chemicals such as ethyl acetate (Hillman et al. 2021; Ragauskas et al. 2014).

Microbes, frequently viewed as nuisances or pathogens, offer new hope for the development of sustainable recycling of plastics.

Aside from waste upcycling, synbio is involved in nearly all aspects of modern life, from products such as cold-active laundry detergents, alternative "meat" burgers, thin films used for touchscreens, and cancer treatments (Voigt 2020).

Discovering and Engineering Enzymes for Plastic Degradation

Utility and Limitations of Plastic-Active Enzymes

The discovery of enzymes that can break up carbon-exclusive polymer backbones is paramount, as this first degradative step is the most chemically difficult processing step because of the strength of carbon-carbon bonds that make up plastic polymers.

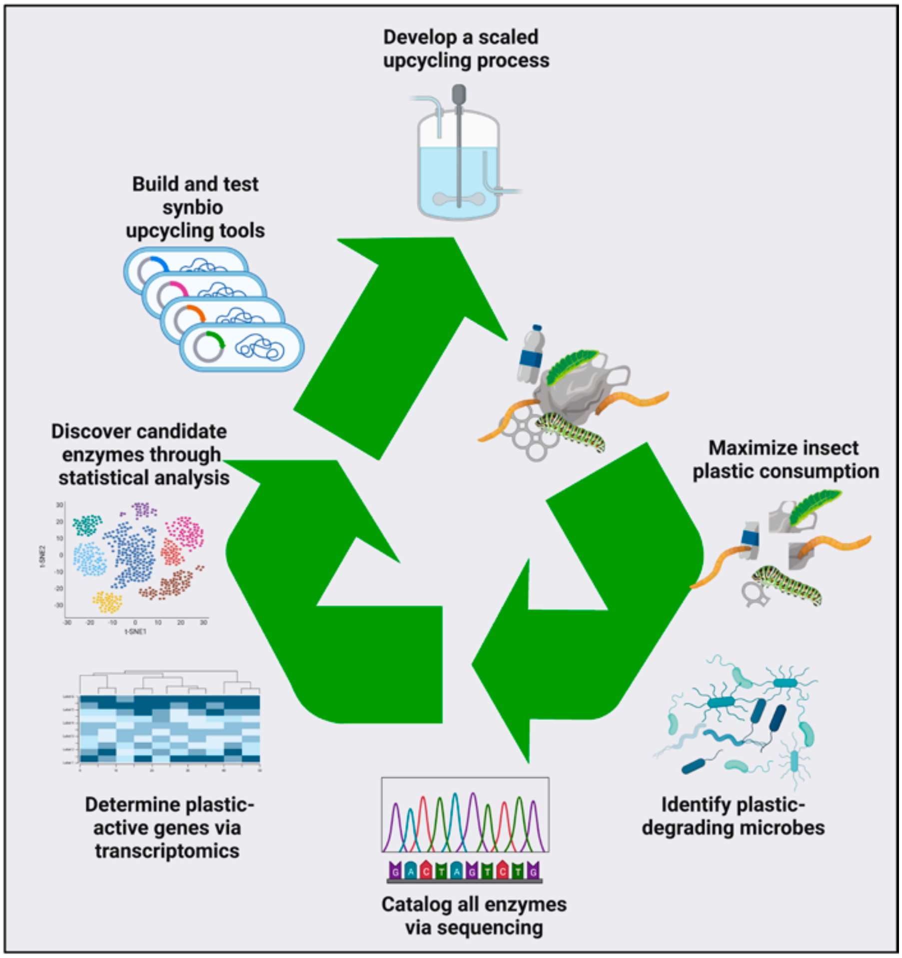

FIGURE 1 Plastic-degrading enzyme discovery and upcycling process engineering. Microbial communities (such as those in an insect gut) are enriched for plastic-degrading organisms by consuming a plastic-containing diet. Plastic-degrading microbes are isolated from the enriched communities and sequenced for enzyme discovery. Bioinformatic data science methods uncover, first, genes highly active in plastic-active communities, and then plastic-degrading enzymes.

Some progress has been made toward the isolation of efficient enzymes for the degradation of other plastics. For example, PETases that degrade polyethylene terephthalate (PET) were first identified seven years ago from microbes that lived in plastic-contaminated soils (Yoshida et al. 2016). The activity of this enzyme is enhanced at higher temperature, degrading plastic wastes in hours and days rather than in decades when no enzyme is used (Son et al. 2019). But these operating conditions also degrade the enzyme over time, requiring periodic and expensive inputs of fresh enzyme. Recent advances in machine learning and mechanistic insight into how protein structure controls performance have been leveraged to tweak the initial discovery and make supercharged PETases that are almost 40 times more efficient and stable even at elevated temperatures (Lu et al. 2022).

Plastic-Eating Insect Larvae

Despite the successes of PETases, they are unable to degrade plastics such as HDPE, LDPE, PP, and PS, which account for the majority of all postconsumer wastes. Enzymes for these non-hydrolysable plastics remain elusive, but a handful of biological systems have been reported to degrade these materials. The most promising among them include insect larvae such as the yellow mealworm (the larvae of flour beetles) that can consume plastics such as PS as their primary nutritional source, even when they contained toxic components (Brandon et al. 2020; Yang et al. 2015a,b).

The microbes living in the gut of plastic-eating insect larvae are essential for the organism to consume plastic and express enzymes central to plastics degradation (Yang et al. 2015b). To identify these promising new enzymes, the Solomon and Blenner labs at the University of Delaware are isolating and studying microbes from the gut microbiome of the yellow mealworm (*Tenebrio molitor* larvae). We have assembled a growing library of plastic-degrading microbes that we are studying through integrated systems biology and synbio approaches (figure 1). With data science, we are sorting through these massive datasets to discover novel enzymes that can efficiently tackle the plastics crisis and deploy these enzymes in new microbial factories to sustainably produce needed medicines, fuels, materials, and chemicals.

Questions to Be Addressed

Although microbial systems offer exciting promise for a sustainable future, many questions remain before bringing this technology to industrial scale, such as:

- Which microbes can process waste plastics?
- Which enzymes degrade plastics such as HDPE, LDPE, PP, and PS?
- What is the chemical fate of plastics that are degraded by microbes?
- What is the molecular mechanism for enzymatic plastic degradation?
- How can enzymes be engineered to enhance the rate of degradation?
- How can microbes be engineered to produce needed materials, medicines, and chemicals?
- How do microbes collaborate or work together to efficiently degrade plastics?
- What process equipment is needed to support industrial-level scale-up of plastic handling and upcycling?

Conclusion

Microbes from diverse environments such as landfills and the digestive tracts of worms have evolved to express enzymes that can break down difficult substrates, like plastic, for sustenance. Advances in data science and molecular sciences such as next-generation sequencing have greatly accelerated enzyme discovery. Parallel advances in synthetic biology and machine learning enable new engineering approaches to enhance plastic degradation via these enzymes.

Synthetic biology can extend plastic degradation to upcycling by rewiring an organism to biochemically transform its carbon source (plastic) into a useful industrial compound. Coupling biological tools with engineering principles, this technology can be scaled for large-scale plastics upcycling. Using microbes to degrade plastic, an industrial process can be developed that is self-sorting, with different microbial processes tied to individual plastics.

Moreover, leveraging biology provides the potential for an economic plastic waste handling solution by eliminating the need for mechanical sorting, reducing energy costs by operating near ambient conditions, and turning plastics into higher-value materials.

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When the problem statement accounts for the sociopolitical nature of the problem, opportunities emerge to reimagine and innovate systems toward equity and justice.

Engineering Solutions for Justice:
Transformative Approaches to Address Transportation-Related Disparities

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How a problem is defined influences its possible solutions. Transportation is recognized as the largest contributor to greenhouse gas emissions (GHG) in the United States (28 percent), and most such emissions are from passenger vehicles (EPA 2020).

Technical problems call for technical solutions. When defining the problem of transportation GHG and health-harming pollutant emissions in technical terms, the focus of analysis is typically the tailpipe and the associated problem statement is: Tailpipes emit criteria air and climate pollutants that contribute to pollution exposure and climate impacts.

But this strictly technical focus does not account for disparate exposures and impacts. For example, GHG emissions drive climate change, and the impacts and health risks of climate change disproportionately affect communities of color (Bullard and Wright 2012; Cushing et al. 2022; US GCRP 2018), as evident in Jackson, Mississippi, and Puerto Rico.

Technical *and* Sociopolitical Problem Framing

For transportation-related emissions, one technical solution is electric vehicles. But while electric vehicles offer an opportunity to reduce emissions exposure and climate impacts, eliminating exposure disparities requires a more expansive problem framing that goes beyond the technical orientation to comprehensively address the sociopolitical nature of the problem.

Racial-ethnic disparities in exposure to traffic-related air pollution, including nitrogen oxides (NO_x) and particulate matter (PM), are well documented (e.g., Clark et al. 2017). A recent study found that low-income people of color in major US cities are exposed to 28 percent higher NO_2 than high-income, non-Hispanic whites (Demetillo et al. 2021). Another found that people of color experience a 14 percent disparity in fine particulate ($PM_{2.5}$) exposure compared with the US population average (Tessum et al. 2021). Disproportionate exposures contribute to racial-ethnic disparities in asthma, preterm birth, cancer, and mortality (Apelberg et al. 2005; Riddell et al. 2021; Southerland et al. 2021).

An automobile-dominated transportation system disadvantages communities of color and low-income communities.

The following problem statement embraces the technical and sociopolitical dimensions of the transportation system: The automobile-dominated transportation system disadvantages communities of color and low-income communities. Framed this way, the statement expands the focus of analysis to the entire automobile and transportation infrastructure and enables full consideration of issues to maximize equity benefits and develop a just solution in the energy transition.

Automobile-Related Issues

Nonexhaust Emissions

As the transition to electric vehicles reduces exhaust PM emissions, nonexhaust emissions—e.g., from tire, brake, and road wear and road dust resuspension—will become an increasingly important source of traffic-related PM emissions. Unlike exhaust emissions, nonexhaust emissions are largely unregulated because they are difficult to control (OECD 2020). Yet California emissions inventories show that such emissions account for 95 percent of PM_{10} emissions and 80 percent of $PM_{2.5}$ emissions from traffic (OECD 2020).

The impact of electrification on nonexhaust emissions will be influenced by regenerative braking systems and vehicle weight (Harrison et al. 2021; OECD 2020; Piscitello et al. 2021). Regenerative braking systems reduce brake wear, but electric vehicles weigh more than similar gasoline vehicles (Requia et al. 2018), increasing tire wear, road wear, and road dust. The problem is exacerbated by consumer preferences for larger vehicles and greater driving range (Libby 2020; OECD 2020).

Without targeted policies, some studies suggest that the increased vehicle weight of electric cars will increase nonexhaust emissions to an extent that electrification will have little effect on total traffic-related PM_{10} and $PM_{2.5}$ emissions (Harrison et al. 2021; Timmers and Achten 2016).

Battery Production

Battery production for electric vehicles (and other uses) requires the extraction and processing of minerals and metals such as lithium, cobalt, manganese, graphite, and nickel (IEA 2021). Projections based on current and expected electrification policies estimate that demand for raw materials used in battery manufacturing will grow ninefold between 2020 and 2040 (IEA 2021).

Resource extraction contributes to environmental degradation and has human rights impacts. Lithium mining, for example, is a water- and energy-intensive process that may contaminate drinking water and deplete water resources—about 500,000 gallons of water are required to produce 1 ton of lithium (Agusdinata et al. 2018). More than half of global lithium resources are beneath the salt flats of the “lithium triangle,” an arid region of the Andes that covers parts of Chile, Bolivia, and Argentina (Agusdinata et al. 2018). In Chile’s Salar de Atacama, lithium and other mining activities have consumed 65 percent of the region’s water supply (Amui and Nkurunziza 2020).

With regard to human rights, lithium mining activities exploit Indigenous territories and fail to uphold Indigenous rights (CIEJ 2019; Marchegiani et al. 2019). Cobalt mines in the Democratic Republic of the Congo are the sites of human rights violations and child labor (Amnesty International 2016; Amui and Nkurunziza 2020).

The Biden-Harris administration plans to establish a domestic lithium battery supply chain, with domestic extraction and refining of lithium (DOE 2022; White House 2022a). The resulting impacts will affect Indigenous land rights and environmental concerns in the United States (Bosler 2021).

Auto Manufacturing

Auto manufacturing processes are sources of PM and volatile organic compound (VOC) emissions (D'arcy et al. 2016; Kim 2011). VOCs are known to cause sensory irritation, headaches, fatigue, nausea, respiratory effects, neurological toxicity, and lung cancer (Mølhave 1991; Rumchev et al. 2007).

Auto painting is the largest source of VOCs (Kim 2011). In Detroit, the Stellantis Mack Assembly Plant, a new low-emission hybrid car plant and the city's first new auto assembly plant in 30 years, has been cited six times for air quality violations since opening in September 2021, all of them due to paint solvent and chemical odors and their health impacts on nearby residents (Grzelewski 2022; Mahoney 2022). The plant is located in a poor, majority-Black neighborhood. The US Environmental Protection Agency launched a civil rights investigation to determine whether racial discrimination influenced plant emissions permit approval (Mahoney 2022). This example demonstrates that pollution from auto manufacturing sites may exacerbate environmental injustices in communities of color.

Electricity Generation

Electrification will increase electricity demand, and annual demand is predicted to be 81 percent greater in 2050 than in 2018, mostly due to electrified transportation (Zhou and Mai 2021). Electrification may shift emissions spatially from on-road exhaust systems to electric generating units (EGUs).

Health and equity benefits of electrification depend on the cleanness of the power generation mix. Fossil fuels are currently the largest sources of US electricity generation (61 percent); renewable energy sources produce 20 percent of electricity generation.[1] Studies show that electric vehicles powered by coal or the current grid mix increase air quality health impacts; renewable sources decrease such impacts (Huo et al. 2015; Tessum et al. 2014; Weis et al. 2015).

Power plants are disproportionately located in communities of color (Bullard et al. 2008; NAACP et al. 2016) and the Black population is most exposed to $PM_{2.5}$ from coal electric generation (Tessum et al. 2021). One study found that Black people are the most exposed US population to emissions from all fossil fuel–fired EGUs and consequently have the largest mortality rates from those $PM_{2.5}$ emissions (Thind et al. 2019).

[1] US Energy Information Administration, What is US electricity generation by energy source? (as of Feb 2022) (https://www.eia.gov/tools/faqs/faq.php?id=427&t=3).

Freeway Construction: An Infrastructure Inequity Issue

Automobile-centric practices increase automobile dependency. From 1950 to 2016, during national freeway system construction, total vehicle miles traveled (VMT) increased 690 percent in the United States, which now also has the highest rate of vehicle ownership per capita (Frey 2018). Light-duty and truck-related VMT are projected to keep growing (FHWA 2021).

In response to increased vehicle traffic, the dominant US transportation planning strategy is to expand and build new roadways. From 1993 to 2017, the country's largest 100 urbanized areas added new freeway lane-miles at a faster rate (42 percent) than population growth in those areas (32 percent) (Bellis et al. 2020).

Electric vehicles powered by the current grid mix increase air quality health impacts.

But transportation policies and planning too often fail to consider their community impacts. Following the Federal-Aid Highway Act of 1956, freeway construction and urban renewal inequitably affected poor communities of color, predominantly Black communities (Bullard et al. 2004; Kruse 2019; Rose and Mohl 2012). Communities of color were deliberately targeted for freeway construction, resulting in the demolition, division, and displacement of neighborhoods as well as the destruction of local economies (Bullard et al. 2004; Kruse 2019; Rose and Mohl 2012). At the same time, studies show that communities of color have lower vehicle ownership and drive less, yet are more likely to live near high traffic roads and bear a greater exposure and health burden (Kerr et al. 2021; Pratt et al. 2015; Rowangould 2013).

Infrastructure investments routinely prioritize roadways over other modes of transportation (Wilson 2020). As a result, communities of color continue to be divided, demolished, and displaced by new construction and expansion projects. The *Los Angeles Times* found that over the last 30 years, federal road projects have continued to disproportionately force out Black and Latino residents (Dillon and Poston 2021).

Furthermore, studies have documented the induced demand effect, whereby added freeway capacity leads to new traffic (Bellis et al. 2020; Hymel et al. 2010). This can prompt new calls for expansion and feed the cycle of construction and congestion that devastates communities of color.

One Solution: Targeted Freeway Removal

The transition to electrification under the current transportation planning paradigm will perpetuate the harms caused by an automobile-dominated transportation system. But when the problem statement is expanded and oriented to address the sociopolitical nature of the problem, opportunities emerge to reimagine and innovate the US transportation system toward equity and justice.

Efforts to reduce disparities should address root causes and repair harm (Untokening Collective 2017). One solution is to reconnect communities divided by freeways. Several highway removal projects have occurred and more are planned (Gunts 2021), largely in response to the advocacy of community-based organizations.[2]

Black and Hispanic communities continue to be divided, demolished, and displaced by new highway construction and expansion projects.

A study that modeled the air quality and neighborhood impacts of rerouting Oakland's Cypress Freeway and replacing it with a boulevard shows that this strategy reduces near-roadway concentrations along the original alignment (Patterson and Harley 2019). However, such removal or rerouting projects must be coupled with antidisplacement policies to ensure that intergenerational residents benefit from air quality improvements and are not excluded through environmental gentrification.[3]

Federal and municipal governments are grappling with how to ensure equitable outcomes in reconnecting communities as they endeavor to repair harm from freeway division through highway removal. Federally, the bipartisan infrastructure deal invests $1 billion in the Reconnecting Communities Pilot Program, and the Inflation Reduction Act provides an additional $3 billion for Neighborhood Access and Equity Grants (US DOT 2022; White House 2022b).

At the state level, several projects—the I-375 Improvement Project in Detroit, Michigan, the I-81 Project in Syracuse, New York, and Rethinking I-94 in St. Paul, Minnesota—aim to redress racial and economic harm. The construction of I-94 led to the destruction of more than 700 homes and 300 businesses in the Rondo neighborhood in St. Paul; the loss of the 700 homes alone resulted in the loss of $157 million in intergenerational wealth (Reconnect Rondo 2020).

To support this new transportation system with fewer freeways, transportation and infrastructure investments should prioritize public transit and other sustainable modes of transport, such as walking, biking, and rolling.

Conclusion

Innovative, justice-focused solutions are possible when engineers ground technical work in its social and political contexts. When the guiding principle is the reduction and elimination of harm, it enables innovative solutions and creative imagination to achieve justice. In this case, that includes solutions like (re)designing communities and technologies that reduce automobile dependency and prioritize environmental justice, infrastructure equity, and transportation justice.

The question now is: What innovative, justice-focused solutions are possible when embedding the sociopolitical nature of problems becomes standard engineering praxis?

Acknowledgment

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[2] See, for example, Congress for the New Urbanism, Completed Highways to Boulevards Projects (https://www.cnu.org/our-projects/highways-boulevards/completed-h2b-projects).

[3] As explained in Patterson and Harley (2019, p. 2), "Urban green space, aimed at addressing environmental injustice, can make a neighborhood more desirable, potentially leading to gentrification and the displacement of the residents for whom the green space was created."

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Stereotypes need to be discarded to change the conversation around engineering to reflect this truly admirable, exciting, and engaging field.

Resilient Engineering Identity

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Monique Ross

Broadening participation in engineering is a long-standing challenge for the discipline that is being investigated by engineering education scholars from many angles—K-20 curriculum, teaching and learning, experiences, and pathways, to name a few. This paper presents an understanding of engagement and persistence in engineering using the construct of identity as the guiding framework.

Identity

Identity is a complex theoretical construct that has been widely studied across disciplines. It was established in psychology to understand how people determine who they are, fundamentally.

Identity scholars have developed explanations for how people arrive at an answer to this most basic question through mechanisms such as structure-agency dialectic, communities of practice, and competing identities. The structure-agency dialectic suggests that people can arrive at who they are either by ascribing an identity to themselves (agency) or being ascribed an identity (structure[1]) (Burke and Stets 2009). However, some scholars would say that these enactments of identity are not done in isolation but rather in concert with one another, *structuration* (Giddens 1984): while people might

[1] "Structure" here refers to social structures or patterned social arrangements in society (e.g., norms, values, and expectations).

ascribe an identity to themselves, this identity can be either affirmed or disrupted by the structures around them. For example, I might say I'm an engineer but if my advisor, instructors, and/or peers say otherwise, I may decide I am not.

Because people are typically socially situated in spaces, it is hard to state with certainty that one's identity is solely something that can be individually claimed rather than constructed in the context of a system. A system might be a community of practice[2] or space, where tacit knowledge, norms, and values are shared and situated learning can happen (Wenger 1999).

Communities of practice—classrooms, offices, professional organizations, afterschool programs—are arguably where identities, especially those tied to roles, are acquired and practiced. Folks who participate in communities of practice may be rewarded with "membership" in the community, resulting in further affirmation of their identity. But those who do not conform to prevailing identity concepts in these spaces may be relegated to the margins or "sojourner" status: they pass through or exist in the space but never achieve full membership (Wenger-Trayner et al. 2015).

The goal is to create spaces where racialized and gendered identities are no longer a competing identity but rather a confluent identity with engineering.

To add another layer of complexity, people assume as many identities as they have roles in their life. One person might identify professionally as an engineer, researcher, educator, and mentor. This multitude of identities may at times compete based on the setting, context, and other inhabitants of a space. Such competition creates a salience hierarchy, as a person feels compelled to move an identity to the top of the hierarchy in a process called identity negotiation, an internal, context-specific negotiation to decide which identity is more relevant (salient) in the moment, relegating competing identities to the bottom of the hierarchy. This is mostly a harmless process—unless one's hierarchy includes other, socially constructed identities like race, ethnicity, and/or gender.

Racial Identity

Along with role identities (e.g., engineer, educator, researcher), people are often ascribed identities related to race, ethnicity, and gender (among others). These identities are another layer in an individual's salience hierarchy and are subject to identity negotiation.

For example, as a person who identifies as African American, Mexican American, a woman, and an engineer, I might find myself negotiating my identity based on the community of practice in which I find myself. If I am at a meeting of the Association for Computing Machinery, I might find my identity as a woman most salient, whereas at a Society of Women Engineers meeting I might feel my identity as an African American is more salient. The necessity to negotiate identities can be more complex depending on the situation and its duration, and if I find that I must negotiate away one or more fundamental aspects of my identity (in a process called compartmentalization; Bell 1990), I might decide that the context, space, or profession is not for me. This brings us to the professional identity of engineer.

Engineering Identity

The research literature suggests that one's ability to identify with a profession through what is considered a professional identity can have immense impact on their engagement and persistence in a field (Godwin et al. 2016; Huff 2014; Huff et al. 2018; Perez et al. 2014). Engineering is no exception.

Stereotypes

Researchers who focus on how to increase participation and retention in fields like engineering and computer science have used their understanding of individuals' interest in engineering, recognition by others in engineering, and self-assessed performance/competence to measure their identity as an engineer (Godwin et al. 2016; Ross and Godwin 2016; Ross et al. 2017). This tried-and-true approach to understanding engagement has held up largely when studying people who align with the norms of those who occupy the field as the majority—White men, who are the basis for the stereotypes and tropes associated with being an engineer.

[2] The concept of a community of practice has roots in education as a means of facilitating learning.

These images and ideals have dominated mainstream media and been propagated through the education system, creating the illusion that only "nerdy," mostly White men exist in and succeed in engineering and computing (Cheryan et al. 2015; Dou et al. 2020; Master et al. 2021).

In addition to being male, engineer stereotypes include social ineptitude, tinkering, lack of creativity, love of math, poor communication skills, and limited/myopic interests. This image, constructed from the historical participation of a particular subset of the population, has resulted in a professional identity of an engineer that is limited and that perpetuates unequal patterns of participation in engineering and computing.

Resilient Engineering Identity

Scholars must acknowledge that what constitutes an engineering identity has variation. The most widely accepted description of an engineer does not apply to those least represented in the field of engineering—or even, arguably, most engineers: not only those who differ from the stereotype in terms of race and gender but also those who see themselves as creative, socially engaging, great communicators, and fun. The entrenched prevalence of the stereotype means that engineers who are women, Black, Latinx, or Indigenous have to make the ongoing effort to construct and affirm a more individualized definition of their identity that includes personal identity/self—a racialized and gendered variant (Ross et al. 2021).

The individually constructed convergence of identities results in a *resilient engineering identity*, based not solely on interest, performance/competence, and recognition but also the multiple social identities that a person is ascribed. Through analysis of narratives from Black women across the engineering spectrum—from undergraduate programs to engineering industry over more than 10 years—I defined the resilient engineering identity, which encapsulates the racialized, gendered engineering identity and can withstand the challenges of being marginalized in the engineering field (Ross et al. 2022).

So What?

These findings provide the grounding for pragmatic and practical means of fostering a resilient engineering identity—one not subject to the identity negotiation that jeopardizes the participation of diverse people in engineering. As University of California, Davis, chancellor Gary May (2022) puts it, "Diversity is everybody's job." With that in mind, following are some simple steps:

> *Persistent images and ideals create the illusion that only "nerdy," mostly White men exist in and succeed in engineering.*

- *Be mindful* about how an engineer is defined, described, or pictured and avoid stereotypes. The work of practicing engineers is social in nature. Engineers are creative and can apply their creativity to finding solutions—and their interests are seldom myopic. Stereotypes need to be discarded to change the conversation around engineering to reflect this truly admirable, exciting, and engaging field.
- *Create supportive spaces* for Black, Brown, and/or women engineers (and any other identities that do not conform to the cisgender, White, male norms). Traditional communities of practice force participants to conform to norms and values that are in direct contradiction with their other identities. The goal is to create spaces where racialized and gendered identities are no longer a competing identity but rather a confluent identity with engineering. This can be done through the establishment and support of ethnic engineering professional organizations (e.g., the National Society of Black Engineers, Society of Hispanic Professional Engineers, Society of Women Engineers), minority engineering programs, and employee resource groups. Historically Black colleges and universities (HBCUs) should also be actively supported through funds, recruitment, and engagement. HBCUs outpace all historically White institutions in the production of Black engineers, so this is an overlooked space for recruitment and support. Likewise, minority and Hispanic serving institutions also support students' multiple identities toward resilience.
- *Remember* that *engineering is social*. As such the human side of engineering must always be incorporated, including supporting one another in this profession.

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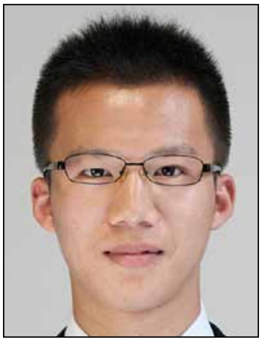
Advances in electrolysis techniques, materials, design, and diagnostic tools can make green hydrogen more economically competitive and accessible.

Green Hydrogen: The Cutting Edge in Clean Electrolysis



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Xiong Peng

Hydrogen is a chemically stable energy carrier that can be used to decarbonize various sectors. However, hydrogen produced by reformation or gasification of fossil fuels—and thus associated with a large quantity of CO_2 emissions—accounts for more than 90 percent of the global hydrogen supply.

As the energy landscape shifts toward renewable sources, green hydrogen, which is generated by renewable energy or from low-carbon power, can play a significant role in decarbonization and the achievement of carbon neutrality (Pivovar et al. 2021). Compared to electrons, hydrogen can help decarbonize sectors traditionally considered hard to decarbonize, including heavy-duty transportation, heavy oil upgrading, iron and steel, ammonia, synthetic fuel, and other chemical feedstock productions.

Water electrolysis using renewable electricity is one way to produce green hydrogen. The central piece to link renewable electricity to various decarbonization applications of hydrogen is a water electrolyzer, which uses electricity to split water into hydrogen and oxygen. With the growing availability of low-cost carbon-free electricity as a feedstock for electrolyzers, a positive feedback loop should be created: green hydrogen needs cheap renewables, and more renewables can be managed on the electrical grid by making green hydrogen. However, only about 2 percent of the world's hydrogen is produced by water electrolysis. Industrial-scale green

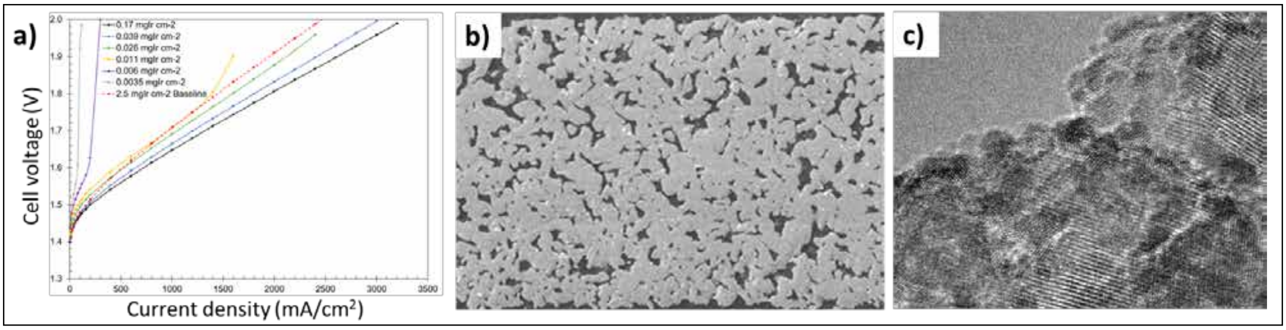

FIGURE 1 (a) Proton exchange membrane water electrolyzer (PEMWE) performance at low and ultralow iridium loadings; (b) cross section of developed porous transport layer for PEMWEs; (c) developed iridium nanoparticles supported by TiO_2 as anode catalyst.

hydrogen production requires large-scale electrolyzer deployment, which is associated with cost, efficiency, and durability challenges.

Types of Water Electrolyzers

There are two types of commercially available and technically mature water electrolyzers: alkaline water electrolyzers (AWEs) and proton exchange membrane water electrolyzers (PEMWEs).

AWEs are essentially massive chemical plants with a lifetime of 20–30 years. They have changed little since their first commercialization more than a century ago: they are still fed with a high concentration of potassium hydroxide (KOH) and typically operated at current densities of 0.2–0.6 A/cm^2 (ampere per square centimeter) and single cell voltage of 1.8–2.4 V. Because of their low energy efficiency, low operating current, and poor compatibility with renewable electricity, large-scale deployment of AWEs is not imminent. Their biggest advantage is low capital cost due to the use of inexpensive materials such as nickel, stainless steel, and KOH as electrolyte. In short, AWEs are old technologies that need innovations to improve their efficiency, dynamic operation, operating current densities, and partial differential operating pressure.

With the increasing need for pressurized hydrogen production at high purity, PEMWEs are gaining more attention, thanks to their zero-gap design and the use of a highly conductive polymer electrolyte, enabling dry cathode operation at high current density and efficiency. PEMWEs can also offer great synergy with highly intermittent renewable energies to utilize low-cost electrons to produce low-cost hydrogen, due to the capability of dynamic operation, as the electricity price dominates the electrolyzer operational cost.

But PEMWEs are operated in highly corrosive and oxidative environments, which require the use of expensive cell components such as platinum group metal (PGM), including iridium as anode catalyst and platinum as cathode catalyst, and platinized titanium (Ti) porous transport layers (PTL) and flow fields. PEMWEs are therefore typically used in niche markets such as submarine systems or hydrogen refueling stations. Their large-scale deployment likely faces challenges in a materials supply bottleneck, as the global annual supply of iridium is only a few tons. A critical research need for PEMWEs is to reduce PGM catalyst loadings while maintaining electrolyzer performance and durability.

Efforts to Improve Electrolyzer Performance

In my group we conduct fundamental research to understand how to achieve low PGM loading while maintaining PEMWE performance (figure 1a).

We have found that both the PTL/catalyst layer and catalyst/polymer-electrolyte interfaces play important roles in determining PEMWE performance (Peng et al. 2021). For example, there is an optimal interfacial contact area between the PTL and catalyst layer to balance the latter's in-plane electric conductivity and the water supply to the reacting zone. At the catalyst/polymer-electrolyte interface, advanced tools such as in situ grazing incidence small-angle X-ray scattering are used to characterize the polymer electrolyte adsorption behaviors at various catalyst surfaces.

My group also uses high-throughput manufacturing methods to engineer electrode structures with low transport resistance (Peng et al. 2020) and conduct catalyst ink characterization (Berlinger et al. 2021) to understand how ink rheology can affect catalyst layer structure and electrolyzer performance. For materials, we

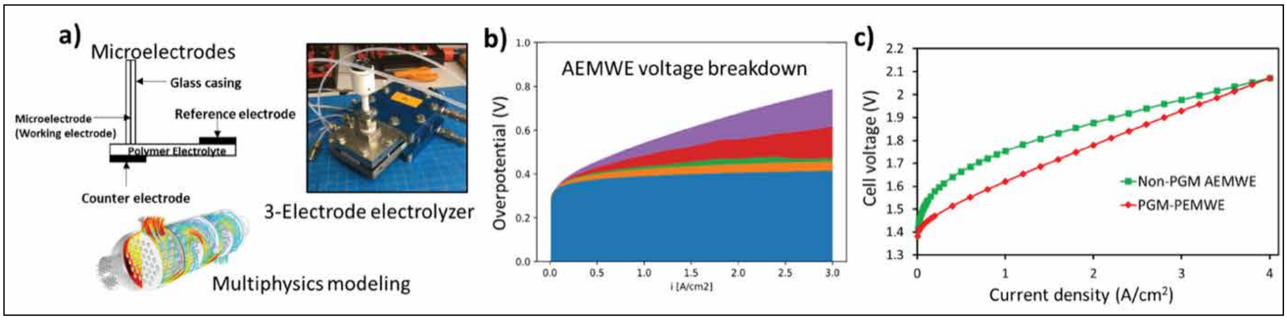

FIGURE 2 (a) Diagnostic tools for an anion exchange membrane water electrolyzer (AEMWE) to understand performance limitations; (b) AEMWE voltage breakdown; (c) performance comparison between a proton exchange membrane water electrolyzer (PEMWE) using a platinum group metal (PGM) catalyst and an AEMWE using a non-PGM catalyst: at higher current density, their performance is indistinguishable.

develop new materials such as advanced PTL (figure 1b) with porosity gradients and highly active and durable supported catalysts (figure 1c) for PEMWE application (Chatterjee et al. 2021).

On the alkaline side, a device that may combine benefits from both AWEs and PEMWEs is an anion exchange membrane water electrolyzer (AEMWE; figure 2). AEMWEs can use inexpensive cell materials, such as non-PGM catalysts and stainless steel PTLs, and thus avoid both high capital costs and the raw material supply bottleneck. AEMWEs also have a zero-gap design, which enables high operating currents and efficiency. AEMWE-related research has focused on developing highly conductive and durable anion exchange membranes and anion exchange ionomers. With the progress in developing anion exchange electrolytes, some startups are taking steps toward mass producing these materials.

In my group we use diagnostic tools such as microelectrodes, a 3-electrode membrane electrode assembly, and multiphysics modeling to understand complex transport behaviors (figure 2a), sources of overpotentials from different components (figure 2b), and the role of supporting electrolytes in AEMWE performance and durability. We have achieved excellent initial cell performance (e.g., 4 A/cm^2 at < 2.1 V) (figure 2c) and high current and durable operation (2.0 A/cm^2 for > 500h) using very dilute supporting electrolytes (0.1 M KOH or 1 wt percent $KHCO_3$) with complete PGM-free electrolyzer components.

Other emerging water electrolysis technologies (e.g., solid oxide electrolysis cells, photoelectrochemical electrolysis cells, and solar thermochemical electrolysis cells) have also been gaining a lot of research attention, because of their potential to reduce green hydrogen production costs by integrating with solar energy or waste thermal energy. Many of these emerging technologies are at lower technical readiness levels and require significant R&D efforts before deployment.

Looking Ahead

Future water electrolysis technologies will require highly efficient and durable systems that can be deployed at large scale (gigawatt to terawatt) and exhibit fast response to renewable electricity, so that future systems are not necessarily operated at a constant load but more likely in dynamic modes. This implies challenges for electrolyzer durability, as dynamic operation is likely to induce more degradation to electrolyzer components (Alia et al. 2019). Enhanced understanding of degradation mechanisms and mitigation strategies are needed to prevent electrolyzer failure.

To make green hydrogen economically more competitive and accessible, efforts are needed to further reduce electrolyzer capital costs and improve operational efficiency. This requires not only the use of cheap and durable materials but also the establishment of automated manufacturing facilities for electrolyzer stacks and balance of plant. Cheaper renewable electricity prices are also essential to enable a green hydrogen production price of less than $1/kg in the near future.

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Hydrogen can help decarbonize the economy, especially for the transportation, manufacturing, and chemicals sectors.

The Power of Being Negative:

Producing H_2 and Sequestered Carbon from Biomass and Waste Resources

Joshua A. Schaidle, R. Gary Grim, Huyen N. Dinh, and Robert M. Baldwin

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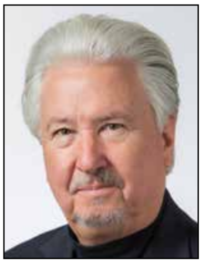

Robert Baldwin

Low-carbon hydrogen (H_2) can be generated through a number of pathways, including steam methane reforming coupled with carbon capture and sequestration (CCS), water electrolysis using renewable electricity, methane pyrolysis, and biomass and waste conversion. However, only the last of these offers a route to *carbon-negative* H_2 when coupled with CCS, thus providing both a service to the environment through carbon dioxide removal from the atmosphere and a valuable downstream product in H_2 (figure 1a).

Carbon-negative hydrogen is defined as H_2 produced with a lifecycle carbon intensity below zero. As one specific example, the carbon intensity of H_2 produced from biomass gasification with CCS has been reported as about −13 kg CO_2-equivalent/kg of H_2 (Al-Qahtani et al. 2021; Susmozas et

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Josh Schaidle is lab program manager for carbon management, Gary Grim is a researcher, Huyen Dinh is Distinguished Member of the Research Staff, and Robert Baldwin is principal scientist, all at the National Renewable Energy Laboratory.

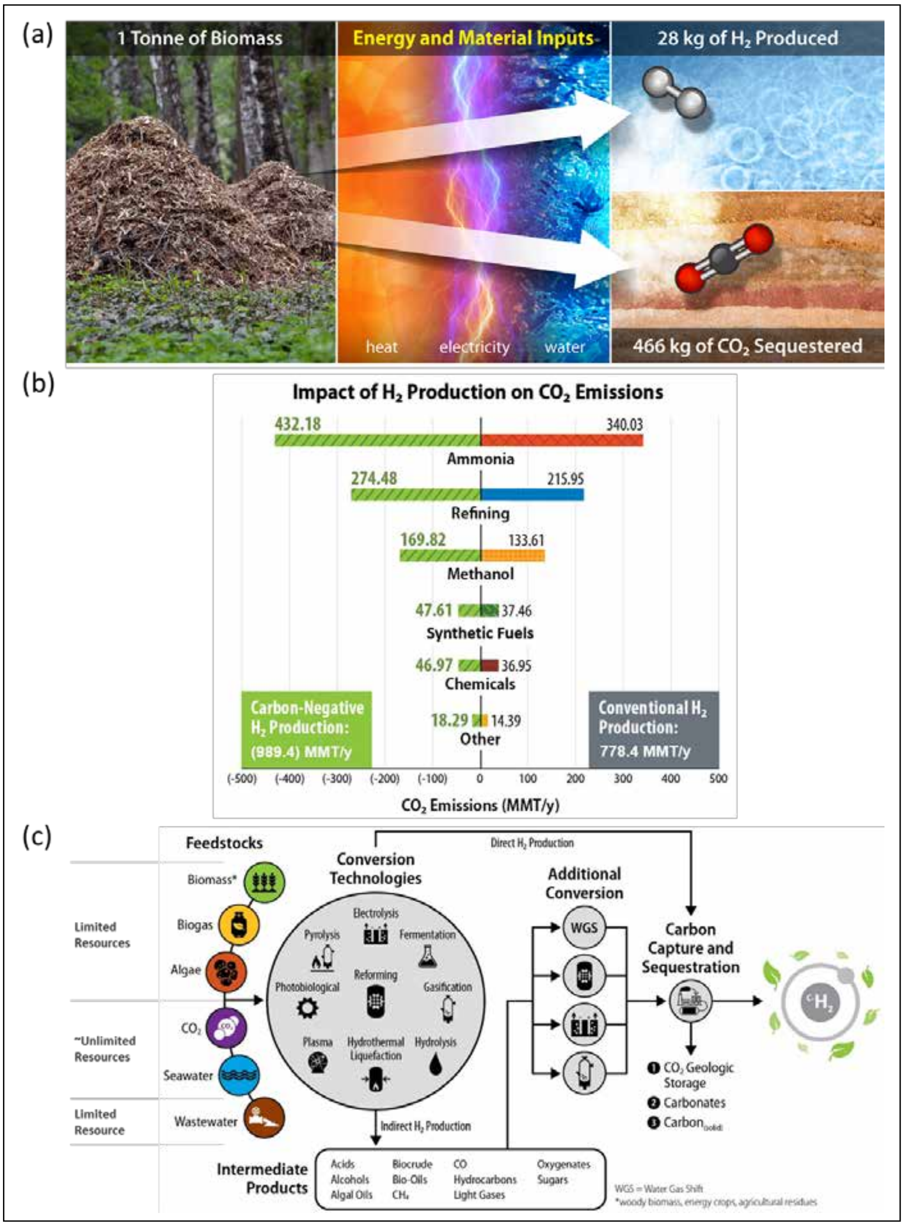

FIGURE 1 (a) Illustration of hydrogen (H_2) and carbon dioxide (CO_2) generation from waste biomass (mass quantities derived from Susmozas et al. 2016). (b) Potential global impact of replacing conventional fossil-derived H_2 with carbon-negative H_2 (assumed at −13kg CO_2-equivalent/kg of H_2). (c) Possible routes to carbon-negative H_2.

al. 2016). If it were possible to meet global H_2 demand (ca. 76 million metric tons per year) with carbon-negative H_2, nearly 0.8 billion tons of CO_2 emissions per year could be avoided *and* another 1 billion tons of CO_2 per year removed (figure 1b). For comparison, global CO_2 emissions are greater than 35 billion tons per year. Thus, carbon-negative H_2 could enable transformation of the worst CO_2-emitting processes, such as ammonia synthesis, into carbon sinks—highlighting the power of being negative.

Owing to its negative carbon intensity, this concept falls within a broad array of negative-emissions (or carbon dioxide removal, CDR) technologies, whereby CO_2 is removed from the atmosphere and durably stored in geological, terrestrial, or ocean reservoirs, or products (NASEM 2018). Depending on the feedstock, carbon-negative H_2 can be included in the class of CDR technologies called biomass carbon removal and storage, whereby the intrinsic value of biomass is seen as its stored carbon rather than its energy content. This pivot in thinking changes the approach to technology development, with carbon-negative H_2 being cited as a key component to achieving carbon neutrality in California by 2045 (LLNL 2020).

Biomass Feedstocks and Conversion Technologies

Potential biomass and waste feedstocks span terrestrial biomass (i.e., woody and herbaceous biomass, energy crops, agricultural and forest residues), biogas, algae, food waste, wastewater, waste plastics, and municipal solid waste; and a multitude of technologies, from early-stage to commercial, are available to convert these feedstocks into H_2 (figure 1c). These technologies include thermochemical, biochemical, electrochemical, and plasma pathways, and can be divided into two broad categories: direct and indirect. For direct routes, H_2 is produced directly in a single conversion step; for indirect routes, an intermediate product (e.g., ethanol or bio-oil) is first formed and then undergoes secondary upgrading to generate H_2.

The two most common and most mature technologies are direct hydrocarbon reforming and gasification, both of which rely on high temperatures to produce H_2 and other intermediates. These technologies are commercially available and represent promising near-term options for deployment of carbon-negative H_2 when paired with sustainable feedstocks such as biogas, renewable natural gas, or biomass.

But the high-temperature processes also face drawbacks such as high energy demand (e.g., heat) and scalability, especially downscaling to align with local feedstock availability. Early-stage, emerging pathways such as microbial wastewater oxidation, seawater electrolysis, and plasma activation offer potential solutions, but require research and development to prove out the underlying technology with concurrent derisking of scale-up and integration.

Challenges and Benefits of Carbon-Negative Hydrogen

While a substantial opportunity exists for both avoiding CO_2 emissions and removing CO_2 from the atmosphere through carbon-negative H_2, important challenges need to be considered:

- From a logistics perspective, the carbonaceous feedstock, CO_2 sequestration site, and H_2 off-take need to be colocated or at least reachable through transportation infrastructure (e.g., pipelines). This is termed the "tri-location" challenge.
- Competition for renewable resources (e.g., biomass) is expected to intensify and will affect supply and demand dynamics, leading to opportunities for technologies that can use low-value, large-scale feedstocks.
- Biomass and other carbonaceous waste feedstocks are typically heterogeneous and complex (figure 2). This complexity transcends molecular, meso-, and macroscales.
- Owing to this complexity, converting biomass and other waste feedstocks can be expensive. As an example, for the production of liquid transportation fuels, the refining of petroleum (excluding extraction) can cost about \$0.6/gallon,[1] while the conversion of biomass into a biofuel is estimated at \$2–\$5/gallon (DOE 2020). Looking more specifically at the levelized cost for H_2 production, biomass gasification with CCS is estimated at \$3.5–\$4/kg H_2 (nth plant assumption), whereas steam methane reforming of fossil natural gas with CCS is \$1.5–\$2/kg H_2 (IEA 2022; NETL 2022; Shahabuddin et al. 2020). Considering incentives through the US Inflation Reduction Act and assuming a carbon intensity of −13 kg CO_2-equivalent/kg of H_2, carbon-negative H_2 could receive a tax credit of about \$1.1/kg H_2 under the Carbon Sequestration Tax Credit 45Q or \$3.0/kg H_2 under the Clean H_2 Production Tax Credit 45V (note that these credits are not stackable).
- As a CDR technology, carbon-negative H_2 leveraging of biomass and waste resources can be more complicated in terms of monitoring, reporting, and verification when considering additionality, durability, and leakage (Carbon Direct and Microsoft 2021), as compared to solely technological solutions like direct air capture coupled with geological CO_2 storage.

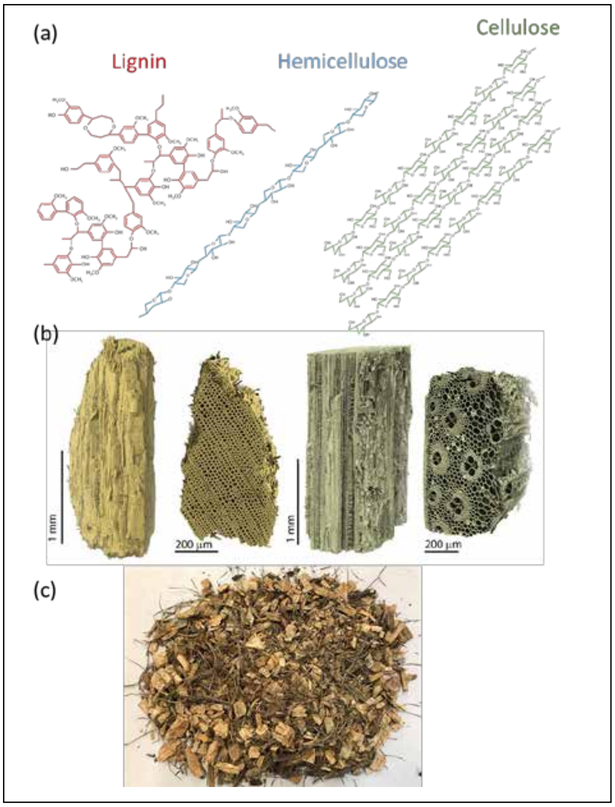

FIGURE 2 (a) Molecular structures of lignin, hemicellulose, and cellulose—key biopolymers in biomass. (b) Microstructure of pine (left) and corn stover (right) (adapted with permission from Cieselski et al. 2020, American Chemical Society). (c) Forest residues (mesostructures) including bark, needles, and branches (image courtesy of Jordan Klinger and Damon Hartley at Idaho National Lab).

[1] US Energy Information Administration, Gasoline and Diesel Fuel Update, Aug 2022 (https://www.eia.gov/petroleum/gasdiesel/).

Notwithstanding these challenges, carbon-negative H_2 can play a key near-term role in the transition to a net-zero emissions economy by (i) enabling decarbonization of industries that use H_2 as a chemical feedstock and (ii) removing CO_2 from the atmosphere.

Importantly, use of carbon-negative H_2 can be applied synergistically with other industrial decarbonization strategies (e.g., renewable heat and high-efficiency separations) to achieve even deeper emissions reductions (e.g., through its use to produce sustainable aviation fuel via hydroprocessing of fats, oils, and greases). Realization of this potential will depend on a concerted multifaceted approach to address critical knowledge gaps and expand the technology pipeline. It is also important to consider possible pitfalls of carbon-negative technologies, like creating a "perverse incentive" to use more H_2 than needed.

Moving Forward

To understand technology trade-offs and guide future research and development, comprehensive and rigorous life-cycle environmental, socioeconomic, and energy justice analysis of the carbon-negative H_2 pathways (especially beyond reforming and gasification), coupled with evaluation of feedstock supply chains and end-use scenarios for H_2 and captured carbon, are needed.

Carbon-negative H_2 may play a key role in the transition to net-zero emissions by removing CO_2 from the atmosphere.

To identify integration challenges and derisk commercialization, end-to-end pilot-scale demonstrations, combined with multiscale computational modeling of mature carbon-negative H_2 technologies like gasification, must be performed.

Finally, there is an expansive opportunity space for early-stage technologies to contribute to carbon-negative H_2 production, especially those that offer overall efficiency gains, can more readily use renewable energy inputs, and generate durable carbon products (as opposed to solely CO_2 for sequestration).

One possible scalable concept for the future that leverages advances in electrochemistry, materials science, and biomass processing is electrochemical reforming of biomass-derived intermediates such as sugars and alcohols (Dolle et al. 2022). This concept has the advantages of modularity, direct use of renewable electricity, liquid feedstocks, and membrane-enabled in situ separations of H_2 and CO_2 (or other carbon products). Although this technology offers the potential to overcome many of the challenges noted, it is still in its infancy. Thus, the community needs to pull together and map out "the adjacent possible" (Johnson 2010) in the field of carbon-negative H_2.

Considering the opportunity space for carbon-negative H_2 and its projected benefits, shouldn't we harness the power of being negative?

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Reasserting US semiconductor leadership must leverage the resources and talent of universities in education, research, and startup formation.

Reasserting US Leadership in Microelectronics: The Role of Universities

MIT Microelectronics Group

> *"US strength in semiconductor technology and fabrication is vital to US economic and national security interests." – Congressional Research Service (2020)*

The United States' longstanding leadership in semiconductors and microelectronics is under serious challenge. The solution: a concerted and ambitious national response that emphasizes manufacturing, research, innovation, and workforce development. In the ecosystem that has enabled US preeminence in microelectronics, universities play a significant role.

In this paper we describe the current challenges and identify opportunities and needs for US universities in education and workforce development, research, technology translation, startups, intellectual property, academic infrastructure, and regional networks to support US semiconductors and microelectronics.

Introduction

Microelectronics underpins the information society. Extraordinary progress in health, communications, computation, energy, transportation, and many

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The members of the MIT Microelectronics Group are Jesús del Alamo, Dimitri Antoniadis (NAE), Robert Atkins, Marc Baldo, Vladimir Bulović, Mark Gouker, Craig Keast, Hae-Seung Lee, William Oliver, Tomás Palacios, Max Shulaker, and Carl Thompson.
This article is adapted from a white paper of the same title posted on the MIT Microelectronics Laboratory webpage (https://dspace.mit.edu/handle/1721.1/139740).

other areas stems from revolutionary advances in microelectronics technologies over the past 50 years. And US leadership in microelectronics has brought enormous economic progress to the nation and deterred adversaries.

That commanding role, however, has eroded over time. Other countries are vigorously contesting US leadership in microelectronics, some at odds with US interests and values. As this country's leading-edge semiconductor manufacturing capacity has dramatically dwindled, concerns have grown about vulnerable supply chains due to natural disasters, trade disputes, or military conflict. Examination of the entire microelectronics ecosystem reveals weaknesses and gaps that the US government is committed to address through legislation passed in August by Congress and signed by the president.[1]

The terms "microelectronics" and "semiconductors" are often used as shorthand to refer to a variety of technologies involving multiple material systems, processes, and devices that perform various functions. Nanoscale, silicon-based CMOS (complementary metal-oxide semiconductor) logic technology is at the core of ubiquitous hardware technology. Equally strategic are memory technologies, signal processing, power electronics, communication chips, system integration technologies, sensors, and photonics, as well as the broader context of manufacturing equipment, advanced materials, packaging, circuit and system design and verification tools, and the large system integrator industry that aggregates everything for the end user.

The ever-expanding diversity of materials, processes, and functions makes microelectronics a rich and rapidly changing field of surprises and unexpected opportunities. Traditional geometrical scaling of logic CMOS will remain central to virtually all applications despite a slowdown in performance gains and increasing costs with new technology generation. Innovative application-specific architectures and algorithms will significantly enhance performance, as already evidenced by data-intensive artificial intelligence applications that solve previously intractable problems. New material systems, devices, and integration technologies are opening unprecedented capabilities in communications, memory, computation, power management, and interfaces with the human body.

[1] The CHIPS Act of 2022: Section-by-Section Summary, available at https://www.commerce.senate.gov/services/files/592E23A5-B56F-48AE-B4C1-493822686BCB.

Opportunities abound. Seizing them, however, is not straightforward. Hardware innovation is constrained by the lack of manufacturing system proximity to those doing the innovating. To ensure long-term leadership, US manufacturing of strategic semiconductor and packaging technologies must be prioritized and university activities have to get closer to it.

> *"Without scaling [to volume manufacturing], we don't just lose jobs—we lose our hold on new technologies. Losing the ability to scale will ultimately damage our capacity to innovate." – Andy Grove (2010)*

Universities in the Microelectronics Ecosystem

US universities, colleges, and community colleges contribute nearly the entire workforce of the nation's microelectronics ecosystem. Universities also generate most of the fundamental research that identifies early opportunities and showstoppers. It is in university labs that the application potential of a new technology is often recognized first, and universities often spawn the new companies that bring pioneering concepts to the world. Most major innovation hubs around the world are near university campuses.

US semiconductor manufacturing capacity has dwindled and is hampered by vulnerable supply chains due to natural disasters, trade disputes, and military conflict.

In the extraordinarily fast-moving field of microelectronics, US preeminence is challenged by aging university facilities and inadequate resources. Societal changes are also a factor as interest in "hard tech" among US students wanes[2] and, as explained below, the appeal of microelectronics eludes students.

[2] This is shown in the trends captured in 1959–2020 data from the National Center for Education Statistics Digest of Education Statistics table 325.47 (https://nces.ed.gov/programs/digest/d21/tables/dt21_325.47.asp). The point was also made in Whalen (2022).

FIGURE 1 MIT first-term freshmen fabricating solar cells in the MIT.nano clean room as part of a freshman seminar designed to attract undergraduate students to the semiconductor disciplines. Photo by Jesús del Alamo.

Education and Workforce Development

An educated, motivated, and diverse workforce is essential for any industry to thrive. To ensure US leadership in microelectronics, a dramatic expansion of the size and diversity of the microelectronics workforce is imperative. There is no more strategic convergence of university, industry, and government interests than the education of the next generation of technicians, engineers, scientists, and technical leaders in microelectronics.

US graduate and postdoctoral programs attract the best talent from all over the world. Most of this talent remains in the United States and joins the university ranks or goes to work in industry or national labs.

More than in other countries, US educational programs combine hands-on learning—involving project-based experiences, design exercises, and research projects—with a well-balanced grounding in fundamentals. They also offer industry internships at the graduate and undergraduate levels, for students to acquire practical skills, learn about career prospects, and contribute toward college costs.

Still, in the words of industry insiders, "the US educational system is failing to produce a sufficient number of American workers and students with the necessary STEM expertise to meet the needs of the semiconductor industry" (SIA 2019, p. 13). A number of factors explain students' declining interest in microelectronics-related disciplines:

- lack of awareness of how microelectronics can help address the world's most pressing problems (a motivation for undergraduates),
- the perception that this is a mature industry with little excitement ahead,
- lack of "physicality" (chips are hidden and of dimensions much smaller than human scale), and
- lack of awareness of fulfilling careers at the end of a demanding course of study.

This is a systemic failure that requires concerted collective action to correct. What's needed are

- systems-oriented multidisciplinary subjects,
- hands-on lab courses (figure 1),
- research experiences,
- design exercises using modern computer-aided design (CAD) tools,
- well-crafted internship programs in industry (often not available to freshmen just as they are about to select a major course of study), and
- support from industry mentors to attract students.

Research on pedagogy should explore new teaching methods that shorten the learning curve and facilitate the technology access needed to fulfill project requirements and internship experiences. Implementing these initiatives will require sizable investments in research and educational facilities and in staff support. Changes must not, of course, detract from teaching the fundamentals—more important than ever in these rapidly evolving disciplines.

A national microelectronics workforce development initiative must seek not just to expand the pool of

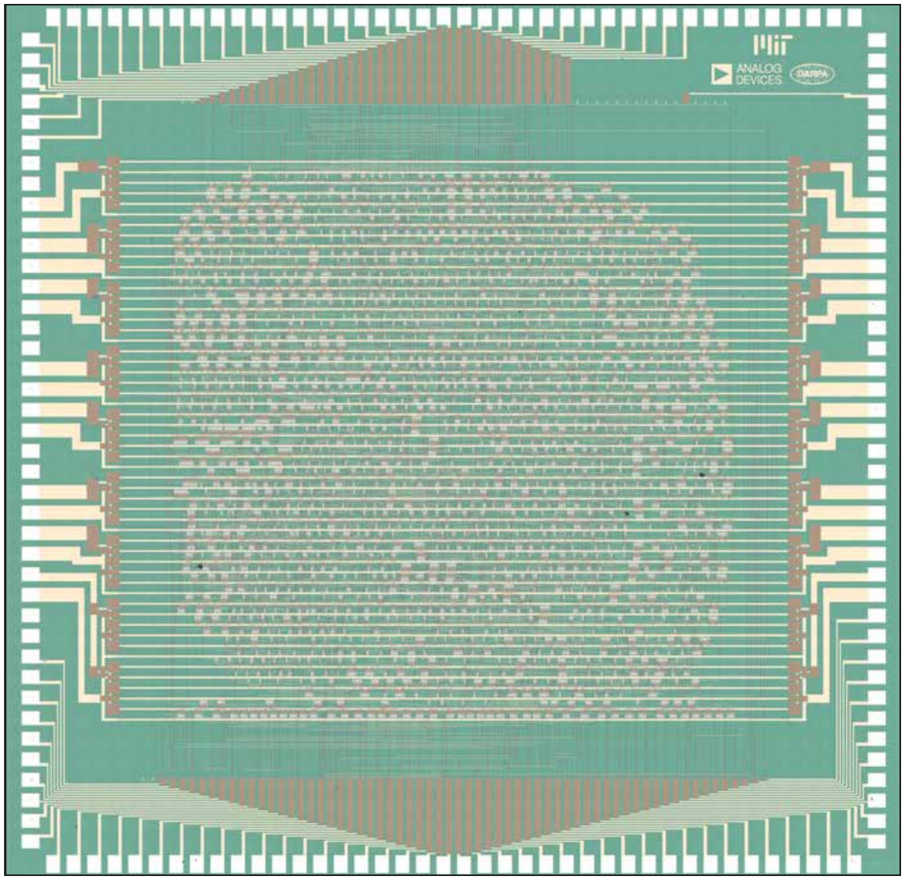

FIGURE 2 Example of microelectronics university research: RV16X-NANO, a RISC-V microprocessor that includes over 14,700 complementary carbon nanotube transistors fabricated at MIT in Prof. Max Shulaker's group. Photo courtesy of Gage Hills.

qualified graduates in relevant disciplines but also to dramatically enrich its diversity in every dimension. Scale-up of existing programs will not accomplish this. The involvement of underserved and other educational institutions that for too long have been on the sidelines of the microelectronics enterprise is imperative. Universities should open their facilities and share their resources and know-how with colleges and community colleges, and also support the creation of educational programs, hands-on and research experiences, and internship opportunities for their students. Outreach efforts to middle schools, high schools, and community colleges must expand and deepen their reach.

Many opportunities exist for economies of scale if industry and academia coordinate activities to develop and share resources and best practices.

Universities also should play a role in supporting the continuing education needs of the microelectronics industry workforce, as new materials, technologies, processes, and techniques emerge all the time. Universities originate many of these innovations and are in a privileged position to prepare the existing workforce to use them. Advances in online pedagogy make it feasible to create and share educational materials on a national scale.

Research

Curiosity-driven, single-investigator research is central to the modern university and the foundation upon which most innovative technologies are built. Multidisciplinary, vertically integrated, collaborative research with industry participation brings into focus promising technologies and facilitates commercialization. Partnerships among industry, universities, and national labs are routinely assembled by mission-oriented agencies for projects relevant to national security; for example, a collaboration with Analog Devices, under DARPA sponsorship, has enabled fabrication at MIT of a carbon nanotube microprocessor (figure 2).

In microelectronics, fundamental research in advanced lithography, strain engineering, scaled transistors, wide-bandgap semiconductors, THz devices, MEMS, 2D materials and devices, circuits and systems, and AI hardware, among many examples, has fueled technological innovations with tremendous economic significance. US universities have contributed to this expensive enterprise by pooling resources and creating and managing shared facilities that can support fabrication processes and materials.

But a chasm is growing between university facilities and the state-of-the-art tools and processes used in industry. Not only is the maximum wafer diameter that university facilities can handle in multistep fabrication mismatched with industry (at best, 150 mm vs. 300 mm; MIT Microelectronics Group 2021) but the performance, productivity, and reliability of university tools is in decline. This greatly limits competitiveness, university collaborations with industry and national labs, and technology translation. Problems are compounded by unaffordable equipment service plans and inadequate technical staff support.

Moreover, many research grants do not cover the true cost of research that requires large integrated facilities with multistep semiconductor fabrication processes. Faculty, in their role as facility administrators, must devote substantial efforts to raising additional resources within or outside the university to make ends meet. A culture of scarcity permeates the operation.

The United States urgently needs a national plan of sustained investment in both human and capital infrastructure. Investments are required to keep facilities relevant, for example with the establishment of 200 mm wafer diameter capabilities, the "sweet spot" for collaborations with industry and national labs and for technology translation (MIT Microelectronics Group 2021, appendix A).

The performance, productivity, and reliability of university tools is in decline, limiting university collaborations with industry and national labs as well as technology translation.

Also needed are mechanisms that provide stable support for equipment service plans and technical staff. A national coordination body should be established to provide users—not just at research universities but also at colleges, community colleges, startups, corporations, and national labs—with access to university facilities as well as unique resources such as a national 300 mm R&D center. It's worth noting that the Semiconductor Industry Association (SIA 2019) calls for the creation of a National Semiconductor Technology Center and this recommendation made it into the recent legislation cited above.

Research programs need to be expanded and their costs fully covered. A healthy mix of single-investigator grants, multidisciplinary vertically integrated programs, and collaborative university/industry/national lab initiatives over a broad intellectual front in a competitive framework is needed to support a diverse community of researchers and students.

Technology Translation, Startups, and Intellectual Property

Many effective technology transfer avenues from universities to industry exist. Companies that sponsor university research programs enjoy early and privileged exposure to research results through periodic updates, progress reports, formal project reviews, and informal interactions. But often the products of university research do not initially reveal their ultimate commercial value. This makes it difficult for companies to decide to license university intellectual property (IP) soon after it is conceived. For microelectronics hardware, the typical time for an invention to reach the marketplace is 10 years, as significant technology maturation is needed for the value of a new concept to become apparent.

Microelectronics technology maturation requires a toolset, a baseline of established process modules, functional block designs, and strict execution protocols that reflect the manufacturing environment. Shared university facilities generally cannot accommodate these needs. Instead, an effective path for translation of new university technologies is through partnerships with prototyping facilities, national labs, and commercial foundries. These entities embody the rigor of a manufacturing environment, with enough flexibility to embrace new disruptive technologies. Fostering prototyping facilities and subsidizing industry engagement with universities to promote technology maturation should be a high priority in a national microelectronics program.

University-generated tech startups also can have considerable impact. Innovation ecosystems around US university campuses attract venture capital, research labs in well-established companies, and startup incubators. Fostering the formation and growth of startups should be among the core goals of a comprehensive national microelectronics strategy. The US innovation and commercialization record is impressive, but obstacles include the high costs associated with development of microelectronics technologies and access to fabrication facilities. Startup activities could be fostered with subsidized access to university facilities (when compatible with the university's research and educational mission), broadening the user pool of shared facilities and thus lowering the costs and time involved for all players.

The inventors of a technology are often the best entrepreneurs to transition their innovations to market. Incentives to engage in technology translation activities can be created through translational fellowship programs that support students and postdocs outside their regular research activities as they explore the commercialization of the technologies they have created.

US universities can retain ownership of inventions created with federal funding under the Bayh-Dole Act. This legislation was established to foster an environment that stimulates and protects innovation and incentivizes its commercialization through commercial licensing.

US universities grant licenses to their patented and copyrighted inventions to both established companies and startups if the licensee demonstrates the technical and financial capabilities to develop the early-stage technology into commercially successful products. Research contracts with industry generally include terms that create options for the sponsor to license the IP generated by the research in a nonexclusive or exclusive form in a field of use. An exclusive license in a field of use is a crucial asset for a startup, as it confers to it a higher valuation and increases the ability to attract capital.

Recent research contracts with industry consortia have IP terms that severely limit the ability of universities to license technology in exclusivity, as required for starts up thrive. In effect, these terms disincentivize IP generation and prioritize existing companies at the expense of future companies. When mixing industry consortia and US government research funds, as is desirable in the launch of ambitious, multidisciplinary, multiuniversity research programs, IP terms are much more restrictive than those typical of US government contracts. The sheer size of these programs and the number of consortia players involved make IP negotiations highly unbalanced.

To ensure a greater role for public-private partnerships in microelectronics research, a new compact is needed for microelectronics IP generation and protection in a university environment. An organization of representatives from government, industry, academia, and the venture capital community should be created to generate policies and provide oversight.

Academic Infrastructure

To support university education, research, and IP generation and translation in semiconductors and microelectronics, a robust university infrastructure is paramount—not only the facilities and tools but also the staff support structures that make everything hum.

For advanced microelectronics research, universities need new 200 mm facilities that combine the performance, reliability, and reproducibility of commercial manufacturing tools with the flexibility to handle a variety of materials and sample sizes and shapes. These and smaller, more versatile research tools can be operated in an economically sound model if they are shared by investigators, educators, startups, companies, universities, colleges, community colleges, and national labs.

IP terms that limit universities' ability to license technology in exclusivity, as required for startups to thrive, disincentivize IP generation.

Attention to university infrastructure should extend to facilities for metrology, CAD, system design and prototyping, testing and packaging, and access to integrated circuit shuttle runs. These capabilities are often sited in private labs or otherwise out of reach for students. Shared facilities should support these resources for the use and benefit of the community, and CAD licensing arrangements and necessary cyberinfrastructure should be put in place to allow flexible access.

The human factor is as critical as buildings and instruments. Highly qualified, motivated technical staff are integral to successful operation. It is our experience that universities can create an attractive working milieu for hiring and retaining competent personnel even in a field rich in employment opportunities. But universities also face challenges of understaffing, scarce resources, and inadequate salaries. A toolset expansion and modernization program, as argued here, must come with a concomitant increase in the technical staff ranks with support for service contracts by outside professional entities.

Junior faculty play a singular role in university microelectronics activities. US universities hire junior fac-

FIGURE 3 MIT materials science and engineering undergraduate student Danielle Grey-Stewart at a microelectronics student research poster session, 2020 MIT Microsystems Annual Research Conference. Danielle is now pursuing graduate studies at Oxford University as a Rhodes scholar. Photo by Paul McGrath.

ulty to rejuvenate the faculty ranks, acquire new ideas, and launch new and promising research programs that expand university offerings. A national microelectronics program should invest in the creation of faculty positions at US colleges and universities and provide flexible career-initiation grants for equipment and research support in the early years of a faculty career.

In addition, a renewed partnership in microelectronics between industry and academia should recruit seasoned and experienced researchers from industry to participate in university education and research as visiting scientists, professors of practice, guest lecturers, and mentors. It is equally important to establish research sabbaticals for faculty and university research personnel at prototyping facilities and industry R&D laboratories.

Regional Network Efficiencies

The efficacy of the comprehensive and ambitious plan proposed here can be enhanced considerably by exploiting substantial regional network efficiencies. We see ample experience in our university community of highly effective, multidisciplinary, multiinstitution research programs that pool the capabilities and expertise of those best qualified, regardless of geography.

Accomplishing the goals articulated here will involve the engagement of institutions—universities, colleges, community colleges, middle and high schools, science museums—that have not traditionally been part of the US microelectronics enterprise. Furthermore, smaller educational institutions with distinguished educational or research programs that are limited in scope and size could enlarge their involvement under the proposed initiative. Widely expanding the number of players, scaling up their activities, and engaging a highly diverse population of students is essential to accomplishing the workforce education goals of this plan. It is in this quest that regional network effects can be helpful.

We envision a loose confederation of institutions that coordinate research, education, outreach, and internship activities at a regional scale. The notion of "region" will necessarily differ around the country, but might enable access within a 2- to 3-hour drive. Such proximity could support regular use of facilities and participation in programs as well as the development of daylong and multiday programs that cater to a geographically dispersed community.

Programs should facilitate access to technical expertise and shared experimental and design facilities if regional institutions are to support existing and new research and educational programs. Joint research projects should be created to engage neighboring institutions. Funding—from industry and perhaps also the government (federal and state)—for visiting appointments, internships, and summer research experiences will greatly assist this mission.

Educational facilities, content, and know-how can be effectively pooled at a regional scale through a mixed in-person/online approach, as demonstrated during the Covid-19 disruption. Similarly, outreach and industrial internship programs can be coordinated and expanded on a regional scale. Startup support and technology transition efforts also benefit from regional proximity by cataloguing regional resources and coordinating access protocols.

Across all these dimensions, regional-level meetings, conferences (figure 3), informal get-togethers, career fairs, startup exchanges, educational competitions, and other networking events can contribute greatly to the whole.

Conclusion

Universities are central actors in the microelectronics enterprise. Reasserting US leadership in semiconductors must leverage the resources and talent of universities in contributing fundamental understanding and innovative technologies, educating the next-generation workforce, and nucleating and nurturing startups that bring new, disruptive concepts to the marketplace. Achieving these goals will demand sound investments in upgrading the physical and human infrastructure of US universities and the launch of industry-academia collaborative programs.

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NAE News and Notes

NAE Newsmakers

John L. Anderson, NAE president, was honored to deliver the 2022 **AIChE William R. Schowalter Lecture** November 16 in Phoenix during AIChE's annual meeting. Other NAE members who have received this honor are **Eric S.G. Shaqfeh** (2021), Lester Levi Carter Professor of Chemical and Mechanical Engineering and chair, Chemical Engineering Department, Stanford University, and **Alice P. Gast** (2020), emeritus professor and former president, Imperial College London.

Santokh S. Badesha, corporate fellow and manager open innovation, Core Engineering Group, Xerox Corporation, is the recipient of the **2022 IET Mountbatten Medal of Honor** and the **IET Fellowship Award**. The Mountbatten Medal was awarded to Dr. Badesha for developing materials enabling the broad use of laser printing and the creation of color laser printing.

Lillian C. Borrone, retired assistant executive director, Port Authority of New York and New Jersey, is the recipient of the **2023 Frank Turner Medal for Lifetime Achievement in Transportation**, recognized as a trailblazer for women in transportation and for her substantial professional and volunteer contributions to transportation policy, administration, and research that aided in the advancement of safer and more reliable mobility for people and goods. She will receive the award at the Transportation Research Board's annual meeting in January.

Edmund Y.S. Chao, Riley Professor of Orthopaedic Surgery (retired), Johns Hopkins University, has been **inducted into the Academy of Engineering Excellence** of Virginia Tech's College of Engineering.

Karl Deisseroth (NAS/NAM), D.H. Chen Professor of Bioengineering and of Psychiatry and Behavioral Sciences, Stanford University, has been named a recipient of the **2022 Louisa Gross Horwitz Prize** for his foundational contributions to the advancement of optogenetics, a technology that has transformed neuroscientific research. He shares the prize with Peter Hegemann of the Humboldt University of Berlin and Gero Miesenbock of the University of Oxford. The prize will be presented at a ceremony in New York on February 16, 2023.

Farshid Guilak, codirector, Center of Regenerative Medicine, and Mildred Simon Professor of Orthopaedic Surgery, Washington University School of Medicine, was elected a **member of the National Academy of Medicine** at its annual meeting in October.

Naomi J. Halas, Stanley C. Moore Professor, Rice University, shares the **2022 Eni Award** with Peter Nordlander. Considered the Nobel Prize for Energy, the Eni Award is regarded as an international benchmark for research in energy and the environment. Drs. Halas and Nordlander were chosen for their research on antenna-reactor plasmonic photocatalysis for sustainable hydrogen generation and distribution. They developed new catalytic systems and devices capable of harnessing light energy to run important chemical processes, including the production of hydrogen.

Yassin A. Hassan, Royce E. Wisenbaker '39 Chair in Engineering Professor, Texas A&M University, has been honored with the ASME **2022 Fluids Engineering Award** for his outstanding contributions to the engineering profession and the field of fluids engineering. The award was presented August 4 at the Fluids Engineering Division summer meeting in Toronto, where Professor Hassan presented the plenary talk "High Resolution Experiments for Modeling and Simulation: From Nuclear Applications to Covid-19."

Kathleen C. Howell, Hsu Lo Distinguished Professor of Aeronautics and Astronautics, Purdue University, was chosen to **deliver the 2022 von Kármán Lecture in Astronautics** during AIAA's 2022 ASCEND in Las Vegas in October. Her talk was titled "An Orbital Transportation Network to Support the Cislunar Space Enterprise."

Chennupati Jagadish, Distinguished Professor, Research School of Physics, Australian National University, has been elected a **fellow of the Royal Academy of Engineering**.

The Regenerative Engineering Society (RE Society) has announced the new **Cato T. Laurencin Regenerative Engineering Founders' Award**, consisting of a medal and an honorarium. The award will recognize the accomplishments of individuals who have demonstrated leadership in the science and practice of convergence research as applied to regenerative engineering. The field was pioneered by **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, and the RE Society's founder. The inaugural award will be presented in 2023 at the RE Society's annual meeting.

Richard A. Meserve, president emeritus, Carnegie Institution for Science, is the recipient of the **Joseph A. Burton Forum Award**, presented by the American Physical Society to recognize outstanding contributions to the public understanding or resolution of issues involving the interface of physics and society. Dr. Meserve is cited for "outstanding service to science and to the nation in the safe, secure, and peaceful use of nuclear power and in the proper and powerful application of science in important legal matters, and for wise counsel on policy issues involving science."

Chad A. Mirkin, director, International Institute for Nanotechnology, and George B. Rathmann Professor of Chemistry, Northwestern University–Evanston, was awarded the **2022 Faraday Medal** on October 20 from the UK Institution of Engineering and Technology (IET). The medal is IET's highest award and recognizes Dr. Mirkin for "inventing and developing many of the tools, techniques, and materials that have defined the modern age of nanotechnology."

Sanjit K. Mitra, professor emeritus, electrical and computer engineering, University of California, Santa Barbara, has been elected **a member of the European Academy of Arts and Sciences**.

Chandrakant D. Patel, chief engineer and senior fellow, HP Inc., was honored with the inaugural **Next Gen Award** by the ASME Foundation. The award recognizes contributions by an outstanding engineering community leader to empower next-generation engineers to build a more equitable and sustainable future. Dr. Patel is a champion of the ASME Foundation's Community College Engineering Pathways initiative, which addresses the technical skills gap by providing training, networking, and employment resources to community colleges and their students.

Arogyaswami J. Paulraj, professor emeritus, Electrical Engineering Department, Stanford University, was **inducted into the Wireless Hall of Fame**. Dr. Paulraj is the inventor of multiple-input multiple-output (MIMO) wireless technology, which has increased the data capacity of wireless systems exponentially. He persisted in the face of skepticism and obstacles to nurture a revolutionary technology from inception to global adoption.

Kaushik Rajashekara, Distinguished Professor of Engineering, University of Houston, has been awarded the **Global Energy Prize**, bestowed by the Global Energy Association. The prize honors "outstanding scientific research and scientific-technical developments in the field of energy which promote greater efficiency and environmental security for energy sources on Earth in the interests of all mankind." Only three people were selected for the honor this year out of 119 nominations from 43 countries. Professor Rajashekara is the winner in the New Ways of Energy Applications category, for outstanding contributions to transportation electrification and energy efficiency technologies while reducing power generation emissions.

Peter W. Shor (NAS), Morss Professor of Applied Mathematics, Massachusetts Institute of Technology, has been named a recipient of the **2023 Breakthrough Prize in Fundamental Physics**. Recognized for "foundational work in the field of quantum information," he shares the prize with David Deutsch (University of Oxford), Charles Bennett (IBM Research), and Gilles Brassard (University of Montreal). The Breakthrough Prize Foundation highlighted Dr. Shor's contributions to the quantum information field, including the eponymous Shor's algorithm for factoring extremely large numbers, and for an algorithm to correct errors in quantum computers.

Winston O. Soboyejo, interim president, Worcester Polytechnic Institute, has been elected to two international academies of sciences and engineering. He has been named to the **Class of 2022 fellows of the World Academy of Sciences**. Considered the apex of scientific achievement, the honor is bestowed on scientists who have made significant contributions to the advancement of science in the developing world. Professor Soboyejo was also named a **fellow of the Nigerian**

Academy of Engineering, an institution for the promotion of excellence in engineering training and practice to ensure the technological growth of Nigeria.

John G. Speer, Endowed Chair for Metallurgical and Materials Engineering, Colorado School of Mines, has been awarded the **IFHTSE Medal,** which is awarded by the International Federation for Heat Treatment and Surface Engineering for internationally recognized distinguished achievements in heat treatment and surface engineering. Dr. Speer was honored for "his life-time achievement in physical metallurgy, development and heat treatment of advanced steel concepts from theory to practical application, with particular focus on his leading role in the development of the quenching and partitioning process."

Warren M. Washington, senior scientist, National Center for Atmospheric Research, has received the **2021 Nierenberg Prize for Science in the Public Interest**. (The formal event to honor this achievement was postponed until July 2022 because of the pandemic.) In lieu of a large, in-person lecture, Dr. Washington participated in a recorded interview at NCAR with fellow atmospheric scientist Vernon Morris.

Christopher J. Wiernicki, chair, president, and CEO, ABS, has been nominated by President Biden to serve on the **National Infrastructure Advisory Council**. The council advises the White House on how to reduce physical and cyber risks and improve the security and resilience of the nation's critical infrastructure sectors.

IEEE has announced the recipients of the 2023 Technical Field Awards. **Omkaram (Om) Nalamasu**, senior vice president and chief technology officer, Applied Materials Inc., is the recipient of the **Frederik Philips Award** "For leadership in research and development of semiconductor materials, processes, and equipment." **Radia J. Perlman**, fellow, Dell EMC, is the recipient of the **Eric E. Sumner Award** "For contributions to Internet routing and bridging protocols." **Daniela Rus**, Andrew (1956) and Erna Viterbi Professor, MIT, is named for the **Robotics and Automation Award** "For pioneering contributions to the design, realization, and theoretical foundations of innovative distributed, networked autonomous systems." **Rabab K. Ward**, professor emeritus, University of British Columbia, will receive the **Fourier Award for Signal Processing** "For outstanding contributions to advancing signal processing techniques and their practical applications, and for technical leadership." Awards will be presented May 5 at the 2023 IEEE VIC Summit and Honors Ceremony in Atlanta.

The Colorado School of Mines is celebrating 100 years of petroleum engineering by founding the new **PE Hall of Fame**. The 12 inaugural inductees are recognized as outstanding industry members through their contributions or leadership. NAE members inducted posthumously were **Lawrence B. Curtis**, retired vice president, Conoco Inc., considered the "father" of the tension leg platform that radically changed industry thinking about what is possible in deep water, hostile oilfield developments; **Lincoln F. Elkins**, petroleum consultant, a pioneer in enhanced oil recovery and contributor to the technology of reservoir and production engineering; and **Lloyd E. Elkins Sr.**, petroleum consultant, known as the "father of hydraulic fracturing."

From the American Physical Society, **Arup K. Chakraborty**, founding director, Institute Professor, Institute for Medical Engineering & Science, Massachusetts Institute of Technology, received the **2023 Max Delbruck Prize in Biological Physics** for his role in "initiating the field of computational immunology, aimed at applying approaches from physical sciences and engineering to unravel the mechanistic underpinnings of the adaptive immune response to pathogens, and to harness this understanding to help design vaccines and therapy." **Pablo G. Debenedetti**, dean of research and Class of 1950 Professor in Engineering and Applied Science, Princeton University, won the APS **Aneesur Rahman Prize for Computational Physics**. The award recognizes outstanding achievement in computational physics research. Dr. Debenedetti was cited "for seminal contributions to the science of supercooled liquids and glasses, water, and aqueous solutions, through ground-breaking simulations."

On September 19 the Hagler Institute for Advanced Study at Texas A&M University announced its **Class of 2022–2023 Hagler Fellows**. Included in the new class of 14 were NAE members **Dimitar P. Filev**, Henry Ford Technical Fellow, Ford Research and Innovation Center, Ford Motor Company, and **Mark J. O'Malley**, chief scientist, energy systems integration, National Renewable Energy Laboratory, and Leverhulme Professor of Power Systems, Imperial College London.

2022 NAE Annual Meeting Highlights

After two consecutive years of virtual Annual Meetings, 2022 marked the return to in-person assembly; the theme of this year's meeting was *Energy Transitions*. On October 2–3, 1033 members, international members, and guests were welcomed to the National Academy of Sciences building on Constitution Avenue. A reception and dinner were held Saturday, October 1, for three classes of new members, together with council members, members, and guests at the National Building Museum.

Also for the incoming members, a new feature was offered Saturday afternoon: *The Big Picture – Program and Activity Expo*. With tables and materials around the Great Hall and adjacent space, the expo provided one-on-one opportunities for new members to learn about the work of the NAE and the National Academies of Sciences, Engineering, and Medicine from the members and staff who lead the myriad programs, projects, and activities.

On Sunday, October 2, NAE chair **Donald C. Winter** and NAE president **John L. Anderson** addressed each of the three new member classes (of 2020, 2021, and 2022). They emphasized the Academies' important role in providing unbiased advice to the government. President Anderson thanked members who have served in these capacities and encouraged all members to serve: "Your induction to the NAE is like a university commencement: It is the beginning of an important service to the nation and the engineering profession."

Executive Officer **Alton D. Romig Jr.** emceed the three class inductions for the 363 new members in attendance: class of 2020 – 85 members, 18 international members; class of 2021 – 104 members, 24 international members; and class of 2022 – 110 members, 22 international members.

Next was the awards portion of the program, moderated by NAE vice president **Wesley L. Harris**. This year's **Simon Ramo Founders Award** was presented to **L. Rafael Reif**, president, Massachusetts Institute of Technology, "for pioneering leadership to reimagine and advance higher education, university-based entrepreneurship, the future of computing, the future of work, sustainability, and semiconductor technology." The **Arthur M. Bueche Award** was presented to **Ellen M. Pawlikowski**, US Air Force (retired), "for exceptional leadership of the development of space systems for national security, management of innovative, all-domain aerospace systems, and promoting diversity in engineering." The **2022 Gibbs Brothers Medal** recipient was **Frank L. Bowman**, US Navy (retired), "for lifelong marine engineering innovation of nuclear-powered warships and leadership in Navy and commercial maritime safety culture." And this year's **Bernard M. Gordon Prize for Innovation in Engineering and Technology Education Lecture** was delivered by Thomas C. Katsouleas, University of Connecticut. He and his fellow recipients—Jenna P. Carpenter, Campbell University; **Richard K. Miller,** Olin College of Engineering; and **Yannis C. Yortsos,** Viterbi School of Engineering, University of Southern California—received the prize earlier this year "for creating an innovative education program that prepares students to become future engineering leaders who will address the NAE Grand Challenges of Engineering." The recipients' acceptance remarks are included in this issue.

On Monday, October 3, **John P. Holdren**, Teresa and John Heinz Research Professor of Environmental Policy, Harvard's Kennedy School of Government, and codirector of the Science, Technology, and Public Policy program, the Energy Technology Innovation Project, and the Arctic Initiative in the School's Belfer Center for Science and International Affairs, presented the Special Lecture on Engineering and Society: *Meeting the Energy-Climate Challenge*. The lecture, in the Kavli Auditorium, was moderated by **Per F. Peterson**, Distinguished Professor, Department of Nuclear Engineering, University of California, Berkeley.

Dr. Romig introduced the **Forum on Transitioning to Net-Zero Carbon** and presenters. **Gavin P. Towler**, CTO & vice president, Research & Development, Honeywell Inc., opened with a discussion of *Navigating the Energy Transition*; **Sarah Kurtz**, professor, materials science and engineering, University of California, Merced, presented *Solar Power – Today's Success Poised to Be Tomorrow's Solution*; **José N. Reyes Jr.**, cofounder and chief technology officer, NuScale Power LLC, reviewed *Nuclear Innovations—Beyond Baseload Power*; **Kathryn A. McCarthy**, US ITER Project

NAE Class of 2020.

NAE Class of 2021.

NAE Class of 2022.

Director, Oak Ridge National Laboratory, explained *Fusion and Advanced Fission Energy—Key to Transitioning and Sustaining Net-Zero Carbon*; and Amy Halloran, director, Nuclear Fuel Cycle and Grid Modernization, Sandia National Laboratories, discussed *Challenges and Opportunities of the Next-Generation Grid*. Deanne Bell, TV host and founder/CEO of Future Engineers, moderated the panel discussion and the many questions from the audience.

A summary of the forum presentations and discussions will be published online, together with the Special Lecture, whose topic this year dovetailed with that of the forum.

On Monday afternoon members and international members participated in the NAE section meetings at the NAS Building and Keck Center. The meeting concluded with a reception and dinner dance at the JW Marriott Hotel in Washington, DC.

The next annual meeting will take place October 1–2, 2023. 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 2022 National Academy of Engineering Annual Meeting and the induction of the classes of 2020, 2021, and 2022. I am most pleased that we are finally able to have an in-person induction ceremony. I remember my own induction fondly and I trust that you will find today's ceremony as meaningful as I did.

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'm sure you 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 just 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 operating structure of the National Academies of Sciences, Medicine, and Engineering, but I will note that our 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.

I anticipate that the need for such engineering inputs will increase significantly in the next several years. The past two years have been difficult ones as we learned to deal with the Covid pandemic. Not surprising, but not all that well known, is the significant role that engineers and engineering processes played in developing, producing, and distributing the vaccines that have contributed immeasurably to the control of the virus and its impacts.

While we are learning to live with Covid, we need to recognize that its long-term effects go well beyond the world of health care. Covid has changed society in many ways, from where people choose to live to the nature of work itself. It is my belief that we are just starting to understand the impacts that such changes will have on our national infrastructure, and these impacts will need to be addressed by public policies, informed by engineers.

Add to that the public policy issues surrounding climate change and it is evident that our nation will need the NAE's advice and counsel in the years to come. The need for such knowledgeable advice becomes evident when one looks at just a small part of the problem, such as the transition from a hydrocarbon-based economy to one based on renewable sources of energy. Providing uninterrupted electric power 24 hours a day, 365 days a year, is massively challenging! The difficulties are evident in Europe, where the transition to solar and wind power has been complicated by varying weather conditions, early deactivation of nuclear power sources, and limits on natural gas availability from Russia.

The policies behind the transition from hydrocarbon-based energy sources to renewable sources need to be informed by engineering principles and judgments. As a systems engineer, I am dismayed by the limited perspective that appears to underlie many of these policies. Change, in the form of reduced CO_2 emissions, is typically the desired outcome. But change at what cost? And cost is not restricted to financial measures but can run the gamut from increased susceptibility to weather events to supply chain constraints for rare earth materials. Only by identifying and addressing the full range of collateral impacts can the full cost (and likely timing) be understood.

The transition of electric power must be engineered to be successful. It must consider the potential for reduced CO_2 emissions, the cost and timing of such reductions, and all of the associated implications. It will also need to consider a full range of alternative mechanisms for producing and distributing electric power, including evolving nuclear technology.

I am pleased to say that the NAE is embarking on the challenge. As one example, I will note a study, initiated and coorganized by the NAE, that is examining the potential for commercialization of new and advanced nuclear reactor technologies. This is a broad-based examination of the problem, examining safety, nuclear waste, and workforce issues as well as multiple technology options and implementation paths. Although it is but one facet of the challenge to transition away from a hydrocarbon-based electric power grid, it has the potential to materially affect national policy debates on the future direction of electric power generation.

I would be remiss if I did not note that this study was enabled by a most generous gift from NAE member **James Truchard.** This independent funding greatly aids the NAE's ability to independently and flexibly explore multiple alternative paths of development. All too often, studies requested by the federal government come far later in the policy development cycle and may be focused on specific alternatives.

We need more contributions to help the Academy provide the engineering leadership and advice that is sorely needed. We also need more members to participate on the related National Research Council committees and boards and NAE programs. For those of you who have served, 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.

Now it is my pleasure to introduce John Anderson, the distinguished president of the NAE, to deliver his address.

New Energy for the Grid and for the NAE: President's Address by John L. Anderson

Welcome to the 2022 National Academy of Engineering Annual Meeting. It is refreshing to see so many of you in person. I also welcome family and friends joining us today.

Before we start, I would like to express our sympathy and support for the residents who were in the path of Hurricane Ian, especially in Puerto Rico and Florida. This storm reminds us that there remain many challenges for engineering to secure the health and safety of our population. We will use our ingenuity to rebuild areas to be more robust and resilient—to secure the health and safety of our society.

In fact, this is relevant to the focus of this year's meeting. It is obvious that the climate is changing—and in dramatic ways. We must be responsive to those changes through programs and activities. And we must respond strategically with the urgency required.

One critical area of change is in the shift away from energy that relies on fossil fuels. *Accelerating Decarbonization of the US Energy System* is one of the National Academies' most cited reports. Released in 2021, it has been downloaded more than 18,000 times. Its committee members have testified to Congress and it has influenced policy on addressing climate change. The title of tomorrow's forum is *Engineers Leading the Energy Transition*. We can look forward to insightful talks—about both the challenges and the opportunities that await the engineering community.

Now, some background about the NAE for our new members. It is one of the three pillars of the National Academies of Sciences, Engineering, and Medicine, which serve the nation by providing independent, objective advice to inform policy; sparking progress and innovation to solve complex problems; and confronting challenging issues to benefit society. The Academies encourage education and research, recognize outstanding contributions that benefit society, and increase public understanding of science, engineering, and medicine.

Interestingly, the need to cultivate science and advance technology was amplified in response to the wartime needs of our country. It was against the backdrop of the Civil War that the National Academy of Sciences was chartered in 1863 by President Abraham Lincoln. At its inception, NAS was composed of scientists, engineers and technologists, and medical professionals.

In the shadow of World War I in 1916, President Woodrow Wilson approved the formation of the National Research Council to advance science, aid American industries, and promote national security and welfare. Membership was drawn from the government, various branches of the military, universities, and private research laboratories.

As technology advanced, the practices of engineering became more prevalent—and the need for engineering to have an explicit role in advising the nation became more pronounced. So in 1964 the NAE was established under the original NAS charter. This was touted as a "major landmark in the history of the relationships between science and engineering in our country."

The third pillar of the Academies was formalized in 1970, with the addition of the National Academy of Medicine, originally named the Institute of Medicine.

The National Academies of Sciences, Engineering, and Medicine are the trusted voice for evidence-based studies, reports, and discussions that address the science, engineering, technology, medicine, and policy issues of the day. The depth of knowledge and diverse perspectives that our members bring to the table make the reports and studies of the National Academies "the gold standard" of technical advice.

There is unity in our autonomy, and there is autonomy in our unity. But we serve one mission: to provide unbiased, evidence-based recommendations in service to our nation.

I'd also like to point out that a hallmark of the NAE is the significant representation of members from industry who bring expertise and perspectives about combining scale and costs not found in academia or government. Of the three Academies, the NAE is the only one with a significant membership from business—this is what makes the NAE unique within the Academies. Again, autonomy in our unity.

Many of you took part in the Big Picture Expo yesterday afternoon and became familiar with NAE programs as well as the NASEM program divisions. It was a great turnout. I hope you learned how to engage in the work of the Academies in ways that are meaningful to you.

Service is an important aspect of NAE membership. In 2021, 46 percent of our members participated in activities of the National Academies generally, and the NAE specifically, by serving on committees, lending their expertise to reports, and taking an active role in member elections. Your expertise and participation are needed as we continue to fulfill our mission.

So the message here is: Induction into the NAE is a "commencement." It is the beginning of important service to the nation and to the engineering profession.

We are committed to convening knowledge to provide engineering leadership on issues that all countries face. These issues include clean energy; access to potable water; food security; and protecting health and well-being during times of national crisis, such as pandemics and natural disasters.

The need for collaboration with members around the world has a new urgency. This year, we increased the number of members from underrepresented countries such as Singapore, South Korea, Taiwan, and Turkey.

Our membership representation reflects our values. The NAE elects more than half our members from the business sector—we are the source of expertise from industry. We continually work to broaden the membership numbers of women and individuals from underrepresented groups. A more diverse and inclusive Academy means that more constructive and creative ideas are brought to bear in our work. I also want to call your attention to the fact that a significant share of the incoming classes are naturalized citizens. Immigration is an obvious asset of the United States.

In 2021 the NAE revisited our strengths and, with input from members and staff, devised a new strategy to provide insights and leadership with a focus on *people, systems, and culture*. Our commitment to the nation, our profession, and our members is prioritized in "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.

In May the NAE Council approved the strategy's implementation plan that will help maintain our progress in reaching these goals.

It's important to point out that the National Academies are *not* part of the government, and this is by design. This ensures that the essential work we do remains objective and credible.

One result of that *independence* is our dependence on philanthropy. About 60 percent of the NAE's operating budget derives from past and current donations by our members, foundations, corporations, and other partners.

Your leadership, now more than ever, is critical to the success of efforts to advance the NAE to an even higher level. Engineers are at the heart of solving global-scale challenges that affect *all* people. These challenges create opportunities to learn, improve, and expand the engineering field, provided we are prepared to answer the call.

The *Campaign for the NAE: Leadership in a World of Accelerating Change* seeks to support effective, action-oriented activities that enable and empower the NAE to be the trusted source of engineering advice for creating a healthier, more secure, and more sustainable world.

Keep in mind that the word "engineer" derives from the Latin word for "ingenuity." This spirit of ingenuity is at the core of every engineer—a spirit of leadership to *create* what does not yet exist. It instills a need to tackle challenges, to find solutions, to create new things. This is what makes our practice and profession unique.

In closing, I would like to recognize the hard work, patience, and resilience of NAE members, staff, volunteers, and partners over the past two and half years leading up to this in-person meeting. We managed by working and collaborating electronically, seeing faces through computer monitors.

The technologies at our fingertips made our work possible, but it is the people—our members and staff—who ensured that the important work of the NAE continued uninterrupted.

I commend 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.

Also, I thank the remarkable officers and councillors who govern the NAE. They serve the organization with integrity and dedication.

Recognizing the work of so many reminds me of a quote by Helen Keller, "Alone, we can do so little; together, we can do so much."

I look forward to doing wonderful work with each of you.

2022 Simon Ramo Founders Award Acceptance Remarks by L. Rafael Reif

The 2022 Simon Ramo Founders Award was presented to Dr. L. Rafael Reif, president, Massachusetts Institute of Technology, "for pioneering leadership to reimagine and advance higher education, university-based entrepreneurship, the future of computing, the future of work, sustainability, and semiconductor technology."

2022 NAE Awards Committee chair Craig H. Benson, NAE president John L. Anderson, Simon Ramo Founders Award recipient L. Rafael Reif, and NAE vice president Wesley L. Harris.

It is incredibly meaningful to be honored with the Simon Ramo Founders Award, and being introduced by the eminent **Wes Harris** makes the honor even more profound. I am delighted to be recognized by the National Academy of Engineering and its members… because choosing to become an engineer was one of the most important decisions I ever made.

I did not start out with sky-high ambitions. I was just a kid in Venezuela from a very modest background, hoping for a decent job and a better life. Like many young people at the time in South America, I saw engineering as a ladder up to the middle class. I was also attracted to engineering thinking, and to the fun, logic, and rigor of engineering.

As my career unfolded at MIT, I gradually found myself in leadership positions: the head of a big lab, head of an engineering department, and eventually provost and then president. Along the way, I came to see that engineering had given me something I never expected: an extremely useful set of skills that helped me do what leaders need to do and are expected to do.

As a leader, one is often required to make important decisions under conditions of great uncertainty—which is exactly what engineering trains you to do. I can give you many personal MIT examples of that, from managing the unpredictable global financial crisis in 2008 to overseeing the uncertainty of Covid-19.

I am not the first to say this, but my own experience has taught me in unforgettable ways that leadership is a profound exercise in systems engineering. It may not be quite as hard as designing a space ship to Mars. But it takes many of the same kind of skills.

It takes the ability to break an overwhelming problem into manageable pieces, to drill down in the data until you uncover the opportunities, and to capitalize on the skills of an enormous team.

And it takes the courage to articulate your vision, to prototype and iterate (learning from your mistakes!) and to keep going until, with a little luck, you finally find the path that works.

We live in a moment when society is starving for principled, inspired, constructive leadership, in the face of immense global challenges. In a time of such tremendous need, I believe in the vision, potential, and capacity to do good of the members of the National Academy of Engineering—that includes all of you here tonight. And I trust you will each find many ways to contribute to move the needle in the right direction for the benefit of humankind.

I am deeply fortunate to have been welcomed into this transformative profession so many years ago, and I am profoundly grateful for the immense honor of this truly wonderful award.

Thank you.

Arthur M. Bueche Award
Acceptance Remarks by General Ellen M. Pawlikowski

2022 NAE Awards Committee chair Craig H. Benson, NAE president John L. Anderson, Arthur M. Bueche Award recipient Ellen M. Pawlikowski, and NAE vice president Wesley L. Harris.

The 2022 Arthur M. Bueche Award was presented to General Ellen M. Pawlikowski, US Air Force (retired), "for exceptional leadership of the development of space systems for national security, management of innovative, all-domain aerospace systems, and promoting diversity in engineering."

I want to thank the Bueche Award Selection Committee and the National Academy of Engineering for this tremendous recognition. I would also like to thank my fellow Aerospace Engineering Section members who I suspect were my nominators for this prestigious award. So many of them have been my mentors, my colleagues, and my friends—**Les Lyles**, **Paul Nielsen**, **Wanda Austin**, **John Tracy**, and of course my wingman, **Natalie Crawford**. I would also be remiss if I did not recognize **Hans Mark**, who passed away last year. He viewed life as one great adventure in science and, as my mentor, challenged me to join him in the chase!

It is a tremendous honor to be recognized by the National Academy of Engineering especially because you represent the very best of my profession. I am in awe of our membership, not only because of what you have accomplished but more importantly your dedication to service.

I must admit, I was not familiar with the Bueche Award before **President Anderson** called me to notify me of my selection. After I did my research on Arthur Beuche and the previous award winners, I realized just how special selection for this award is to me because of the focus on promoting technology development and enhancing collaboration between government, industry, and universities. These themes resonate with my lifetime goals.

I have dedicated my life to two goals: first, to bring technology to bear on solving the most difficult challenges. I served for 36 years in the United States Air Force and was blessed to have the opportunity to work on transforming technology into capabilities that made our country more secure while helping bring American soldiers, sailors, marines, airmen, and coast guardsmen home safely.

Along the way, I learned that nothing could be accomplished without teamwork between the Department of Defense, industry, and academia. As a government official, I often had to cut across organizational and contractual bureaucracy to get the job done. I would remind my government teammates that we could not succeed if our contractor partner didn't succeed. Then I would caution our academic researchers that technology doesn't know its application without the user's guidance. And in the end, we all enjoyed the success of seeing a new capability fielded and lives saved. Today, I cherish the sweet reward of pointing to the sky and telling my grandchildren that their grandma helped make that airplane or that rocket ship!

But, as Hans Mark would say, there is so much more to be done. Today's technical challenges call for even better teamwork between government, industry, and academia.

Our continued success also hinges on achieving my second lifelong goal, which is to ensure that the engineering community benefits from talented people regardless of their gender, ethnicity, or economic background.

I grew up with a father who encouraged me to pursue an engineering degree. When I entered college in 1974, I had no idea how unique it was to be a woman studying engineering. And for too many years, I found myself the only woman in the room and in a room with no African Americans. Throughout my career, I tried to change that by encouraging, mentoring, and helping women and minorities grow as engineers.

We have made progress, as witnessed in the diversity of the NAE classes we inducted this weekend. But we are not done. We have overcome many institutional obstacles to diversity but must continue to challenge cultural and economic barriers.

In Macon, Georgia, where I live, there is a grammar school, St. Peter Claver School, where 67 percent of the students live below the poverty line and 90 percent are African American or Hispanic. The school recently received government funding and donations to install a STEM center for their students. It is a small effort in the overall scheme of things, but it has the potential to improve the future for those students and our nation.

In my dreams, I see one of those students sitting beside my granddaughter in this auditorium as new inductees of the National Academy of Engineering. Perhaps then, I can say we have achieved both my goals.

Thank you again for this honor.

NAE Gibbs Brothers Medal Acceptance Remarks by Admiral Frank L. "Skip" Bowman

The 2022 Gibbs Brothers Medal was presented to Admiral Frank L. Bowman, US Navy (retired), "for lifelong marine engineering innovation of nuclear-powered warships and leadership in Navy and commercial maritime safety culture."

2022 Gibbs Brothers Medal Committee chair Geraldine Knatz, NAE president John L. Anderson, Gibbs Brothers Medal recipient Frank L. Bowman, and NAE vice president Wesley L. Harris.

My deepest appreciation to the National Academy of Engineering and specifically to Francis and Frederick Gibbs for endowing this award to encourage innovation and safety in naval architecture and marine engineering.

I stand humbly to accept this award on behalf of the men and women of the US Navy's Nuclear Propulsion Program from its beginning under then-Captain Hyman Rickover to today…and on behalf of the integrated energy company, BP, which readily incorporated much of that Navy nuclear power safety culture into its global shipping and offshore energy segments.

Several marine engineering concepts developed in the late 1990s, which we termed the "four gets," are integral to today's US submarine fleet:

- get connected by developing communications at speed and depth,
- get payload to include offboard sensors and autonomous vehicles,
- get electric by incorporating electric drive, and
- get modular to facilitate new construction through modular development and assembly.

The US Naval Reactors Program, today with over 100 nuclear reactors powering 86 submarines and aircraft carriers, arguably has the world's best safety record of any industry of any kind, with over 5400 reactor-years of accident-free operations while safely traveling over 130 million miles on nuclear energy.

This award recognizes that Navy safety record and the marine engineering innovations since *Nautilus* was launched in 1954 by Mamie Eisenhower…along with the major safety improvements in BP's offshore energy operations.

Again, with humility, I thank you for this recognition.

Highlights from the 2022 Golden Bridge Society Dinner

On October 2, NAE president **John L. Anderson** and his wife Pat hosted the annual Golden Bridge Society dinner in the Great Hall of the National Academy of Sciences Building to celebrate the NAE's most generous members and friends. After two years of virtual events, it was a special occasion for NAE donors, members, and friends to gather in person.

This year we presented 20 recognition awards to our lifetime giving society members, the most ever at the Golden Bridge Society event. A Lincoln medal was presented to Virginia Bugliarello and Curie medals were presented to John and Pat Anderson, **Wesley Harris**, **Al** and Julie **Romig**, **Gordon England**, Mary Kay Friend, **Paul Gray**, **Frances** and **George Ligler**, and **Robert** and Robyn **Wagoner**. Einstein Society statuettes were presented to **Rob** and Lenore **Briskman**, **Cleo** and Eugen **Cabuz**, Yellow Gandhi, **Jennie Hwang**, **Michael** and Diana **King**, **Norman** and Jane **Li**, **Percy** and Olga **Pierre**, **John Samuels**, **Michael** and Ann **Sutton**, **Sridhar Tayur**, and **Hemant** and Suniti **Thapar**. We also welcomed 25 new members into the Golden Bridge Society and one new Heritage Society couple, Robert and Robyn Wagoner.

The Abraham Lincoln Society acknowledges members and friends whose lifetime giving is $1M or more. The Benjamin Franklin Society acknowledges members and friends whose lifetime giving is $500,000 to $999,999. The Marie Curie Society acknowledges members and friends whose lifetime giving is $250,000 to $499,999. The Albert Einstein Society acknowledges members and friends whose lifetime giving is $100,000 to $249,999. The Golden Bridge Society acknowledges NAE members and friends whose cumulative giving is $20,000 to $99,999. The Heritage Society celebrates members and friends who have planned a gift today that provides for the future. Recognition of other giving levels is explained on the

NAE website (https://www.nae.edu/19635/givingtoNAE).

The night included highlights and a video on the newly launched *Campaign for Leadership in a World of Accelerating Change*, emphasizing the excitement of engineering and the importance of philanthropy, which is vital to the work of the NAE. Watch the launch video and learn more about how you can get involved with the campaign at www.nae.edu/acceleratingchange.

If you're interested in joining one of our lifetime giving societies or the *Campaign for Leadership in a World of Accelerating Change*, please contact Radka Nebesky (RNebesky@nae.edu or 202.334.3417) or Stephanie Halperin (SHalperin@nae.edu or 202.334.1842).

Thank you!

NAE president John L. Anderson, Lincoln Medal recipient Wesley L. Harris, and former NAE vice president Corale L. Brierley.

The Grainger Foundation Frontiers of Engineering 2022 Symposium Held in Seattle

This year's US Frontiers of Engineering (FOE) meeting was hosted by Amazon, September 21–23. NAE member **Timothy Lieuwen**, Regents' Professor and David S. Lewis Chair of the Daniel Guggenheim School of Aerospace Engineering at Georgia Tech, served his second year as chair of the organizing committee and the symposium. The sessions were Microbes: The Good, the Bad, and the Ugly; Technology and Racial Justice and Equity; Hydrogen: A New "Universal" Energy Carrier for the Carbon-free Future?; and Conversational AI.

Microbes are everywhere. Some can be harmful to human health, yet our bodies thrive with a healthy microbiome, and engineered microbes can be used to treat disease. Microbes have been harnessed to clean the environment and create products from vaccines to biofuels. This session featured speakers whose work represents the broad potential of microbes. The first speaker, Arthur Prindle (Northwestern University), talked about efforts to understand and engineer collective behaviors that arise from microbial communities. Next, Caitlin Howell (University of Maine) described materials-based approaches to prevent biofilm-associated infections. Aaron Anselmo (VitaKey) pro-

vided an industry perspective on the development of advanced probiotic delivery systems to enhance nutrition. Finally, Kevin Solomon (University of Delaware) spoke about using microbes for materials degradation, plastic upcycling, vaccine production, and biohybrid material development.

Speakers in the Technology and Racial Justice and Equity session explored various themes related to racial equity and engineering—environmental justice, culturally relevant pedagogy, the hidden curriculum of engineering, and engineering identity. Regan Patterson (University of California, Los Angeles) described how racial injustice is perpetuated in engineering practice with regard to the environment, specifically in terms of the transportation sector. James Holly Jr. (University of Michigan) then spoke about the cultural characteristics (e.g., depoliticization, structural racism, romanticized rigor) of engineering education that have established and maintained inequity and the exclusion of certain minority groups. The next speaker, Idalis Villanueva Alarcón (University of Florida), talked about the hidden curriculum in engineering, namely, the ways that values, assumptions, and beliefs about schooling manifest in practice. The last speaker, Monique Ross (Ohio State University), focused on supports and resources that cultivate resilient engineering identities, especially for women of color in computer science.

The third session asked whether hydrogen could be a new *universal* energy carrier for the carbon-free future. Hydrogen is versatile and can be produced from a variety of sources that emit little or no greenhouse gas. Ryan Jones (Evolved Energy Research) started the session with a talk on the critical role of hydrogen as an energy carrier and final fuel in a net-zero emissions energy system. Neha Rustagi (Department of Energy) provided an overview of the DOE's hydrogen R&D, demonstration, and deployment programs and the Hydrogen Earthshot, the DOE's effort to reduce the cost of clean hydrogen by 80 percent and support a clean hydrogen industry. Xiong Peng (Lawrence Berkeley National Laboratory) described cutting-edge innovation efforts to develop cheaper, higher-efficiency electrolyzers for production of hydrogen from carbon-free electricity. The concluding talk by Josh Schaidle (National Renewable Energy Laboratory) covered production of H_2 and sequestered carbon from biomass and waste resources.

The technical portion of the meeting concluded with a session on Conversational AI, where the ultimate goal is to build machines that can interact with humans in a natural, engaging, and helpful manner. Developing systems that both understand users' spoken, textual, and affective signals and learn from users and their environment could bring significant benefits to education, entertainment, automation of everyday tasks, assisted living, and health care. Speakers in this session covered state-of-the-art conversational AI systems as well as the challenges and opportunities for further innovation.

Maryam Fazel-Zarandi (Meta) started the session with an overview on the status, challenges, and future directions of conversational AI systems. Next, Zhou Yu (Columbia University) discussed research efforts toward making communication between humans and machines smoother through realistic dialogues and improved understanding. Alexandros Papangelis (Amazon Alexa AI) reviewed research for building conversational agents that can create the data they need for learning, reducing reliance on costly and manual data collection. Going beyond agents that learn from conversational data alone, Karthik Narasimhan (Princeton University) presented research on building agents that learn through both interaction and language data.

On the first afternoon of the meeting, "meet and connect" breakout sessions provided an opportunity for attendees to share their research and technical work so participants could get to know more about each other relatively early in the program. On the second afternoon, a panel of Amazon scientists and engineers discussed how they work through challenges in supply chain optimization, Alexa shopping, and natural language understanding.

On the second evening, Rohit Prasad, senior vice president and head scientist of Alexa, gave a dinner speech where he described the career path that brought him to Amazon. He imparted three lessons he had learned during his career: Dream big but do all the little things that matter; Don't let anyone come between you and the customer; and Failing is easy, scaling success is much harder.

Many of the presentations are available for public viewing at the 2022 US FOE List of Sessions at www.naefrontiers.org.

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 2023 US FOE will be hosted by the University of Colorado Boulder, September 11–13. The topics are Engineered Quantum Systems, Mining/Resource Extraction/Critical Materials, Combating Disinformation, and Complex Systems in the Context of Health Care.

Funding for The Grainger Foundation Frontiers of Engineering 2022 Symposium was provided by The Grainger Foundation, Amazon, National Science Foundation, Air Force Office of Scientific Research, DOD OUSD(R&E)-Research, Technology & Laboratories, 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 careers, 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 meeting also facilitates 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.

2022 EU-US Frontiers of Engineering Hosted by the Slovenian Academy of Engineering

The EU-US Frontiers of Engineering symposium was held October 19–22 in Bled, Slovenia. The NAE partnered with the European Council of Applied Sciences, Technologies and Engineering (Euro-CASE) to carry out the event, which was hosted by the Slovenian Academy of Engineering (IAS). **Vahid Tarokh**, Rhodes Family Professor in the Department of Electrical and Computer Engineering at Duke University, and Marko Topič, professor and chair of the Department of Electronics at the University of Ljubljana, cochaired the symposium. Euro-CASE secretary-general Patrick Maestro, NAE president **John Anderson**, IAS president Mark Pleško, and Bled mayor Janes Fajfar welcomed the group at the meeting's opening, which was emceed by Stanislav Pejovnik, professor emeritus at the University of Ljubljana and past IAS president.

The 2½-day event brought together approximately 60 early-career engineers from US and European universities, companies, and government labs for presentations on leading-edge developments in four topics: prosthetics and AI, supply chain/logistics, post-Li-ion batteries, and zero-carbon buildings. Participants attended from the United States and nine EU countries: Denmark, Germany, Hungary, Norway, Serbia, Slovenia, Spain, Sweden, and Switzerland.

Interfacing the central nervous system with external devices has revolutionized treatments for people with paralysis from spinal cord injuries and stroke. These advances have been fueled in part by concurrent revolutions in hardware and software such as advanced neurotechnologies that make it possible to measure and manipulate the nervous system with increasing precision and AI that provides powerful tools to leverage data. The first session of the symposium described recent advances at the intersection of AI, neuroscience, and prosthetics: ultraflexible electrodes for long-lasting, large-scale, bidirectional neural interface (Lan Luan, Rice University); machine learning algorithms for neural decoding (Chethan Pandarinath, Georgia Institute of Technology); and robotic hands with soft parts and flexible joints (Cristina Piazza, Technical University Munich).

Supply chains are highly complex global systems, and the Covid-19 pandemic exposed their vulnerabilities. Another growing concern is their environmental and social impacts. This session covered the operations research and engineering logistics elements of supply chain management, from resilience and sustainability to the challenges of electrified transport and digital transformation. Lisa Melander (Chalmers University of Technology) started the session with insights about supply chain resilience in the context of the pandemic, including the impact and management of supply chain disruptions. Next, Veronica Villena (Arizona State University) presented her work on sustainable multitier supply chain networks. The third speaker, Spyros Ntemiris (Business Region Gothenburg), described the city of Gothenburg's public-private initiatives for sustainable transport, particularly related to electrified and autonomous vehicles. Carlos Florensa (Covariant.AI) closed the session with a presentation on the latest technological advances in warehouse automation.

Lithium-ion batteries are well-accepted advanced power sources, from portable devices and electric vehicles to large-scale energy storage. However, concerns over lithium's availability and price, as well as potential geopolitical tensions that impact its distribution, have focused attention on the need for development of concepts based on more sustainable materials that enable improved energy density. This session focused on some of the most promising research directions in post-Li-ion batteries. Matthew McDowell (Georgia Institute of Technology) opened the session with a talk on the development of all-solid-state batteries with metallic lithium as an anode material. Next, Jan Bitenc (National Institute of Chemistry, Slovenia) talked about multivalent batteries, which include magnesium, calcium, and aluminum metal anodes coupled with different types of sustainable cathode materials. The third speaker, Nagore Ortiz Vitoriano (CIC energiGUNE, Spain) described the challenges and benefits of using air as an electrode. The session concluded with a talk by Partha Mukherjee (Purdue University) on how modeling approaches can accelerate the development of novel battery materials and oxidation-reduction (redox) chemistries.

The final session, on zero-carbon buildings, highlighted the multidimensional challenges of achieving a sustainable, carbon-neutral built environment. These challenges include scaling up decarbonization strategies from buildings to communities and cities, considering buildings in the context of an interconnected energy system, and expanding the focus from energy use during building operation to the total energy and environmental impact over a building's lifetime. The speakers explored how cutting-edge building technologies, digital tools, and big data analytics can enable a paradigm shift to create sustainable buildings for a clean energy future. First, Karma Sawyer (Pacific Northwest National Laboratory) provided recommendations to ensure that electrification of space and water heating is an impactful decarbonization tool for buildings in underserved communities. The second speaker, Roderick Jackson (National Renewable Energy Laboratory), discussed smart building and neighborhood technologies that prioritize a sustainable energy future with equitably distributed benefits and costs. Next, Jakob

Photo credit: Marjan Verč.

Strømann-Andersen (Henning Larsen) described the "holis-tech" mindset that integrates smart technology with creative thought and design expertise to support material optimization, energy reduction, and low-carbon solutions to building design. Finally, Catherine De Wolf (ETH Zürich) talked about using digital tools such as building-information modeling, computational design algorithms, LiDAR scanning, digital fabrication, machine learning and AI, and computer vision to connect and coordinate actors across the value chain for materials reuse.

Abstracts of the papers and presentation slides where permission has been granted can be accessed in the List of Sessions for the 2022 EU-US FOE at www.naefrontiers.org.

In addition to the formal sessions, a poster session preceded by flash poster talks was held on the first afternoon. This served as both an icebreaker and an opportunity for all participants to share information about their research and technical work.

Bled is a resort town on Lake Bled near the Julian Alps so attendees were treated to beautiful scenery and views of 11th century Bled Castle outside the meeting venue. On the second afternoon, the group enjoyed a trip to nearby Ljubljana, the capital of Slovenia. They visited the National Institute of Chemistry, where they toured the laboratories housing nuclear magnetic resonance spectroscopy machines and battery research. Afterwards Institute staff treated the group to refreshments on the roof of the building with views of Ljubljana Castle and the mountains. Next, IAS graciously organized a walking tour of the old part of the city of Ljubljana, with a stop at the National and University Library where light streaming through the windows in the main reading room at the top of the main staircase symbolizes this thought: "From the twilight of ignorance to the light of knowledge and enlightenment." Before the attendees returned to Bled for dinner, IAS provided an opportunity for convivial fellowship at an outdoor café.

Financial support for the symposium was provided to the NAE by The Grainger Foundation and the National Science Foundation. We thank the Slovenian Academy of Engineering for its warm hospitality as host and Vahid Tarokh for his service as US cochair for the 2021 and 2022 EU-US Frontiers of Engineering symposia.

The next EU-US FOE will be held October 16–18, 2023, at Nokia Bell Labs in Murray Hill, New Jersey. **Muriel Medard**, Cecil H. Green Professor in the Department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology, will serve as US cochair.

The NAE has been holding Frontiers of Engineering symposia since 1995, and the EU-US FOE since 2010. For more information about the symposium series or to nominate an outstanding engineer to participate in future Frontiers meetings, contact Janet Hunziker at the NAE Program Office at JHunziker@nae.edu. The FOE website is www.naefrontiers.org.

Update on the Ligler-Wagoner Challenge for The Grainger Foundation Frontiers of Engineering

It's been just over one year since the Ligler-Wagoner Challenge for The Grainger Foundation Frontiers of Engineering launched in November of 2021. Since then, nearly 60 past program participants and friends have donated to raise the program's profile and ensure its longevity for future generations. Thank you to all who have donated. We truly appreciate your support.

As of November 4, over $49,000 has been donated, bringing us almost 25% of the way to our $200,000 goal. Every donation is generously matched 1:1 by **Frances and George Ligler** and Robyn and **Robert Wagoner**. Through your support, FOE can continue to:

- enable invitees to attend regardless of their funding situation,
- expand networking opportunities for current and former FOE participants, and
- enhance the cross-disciplinary collaboration that has made it such an effective and esteemed program for the past 28 years.

In October, the NAE publicly launched the *Campaign for Leadership in a World of Accelerating Change*. This $100M fundraising campaign seeks to strengthen the NAE's position as the trusted source for engineering advice, and FOE is a major part of our work. The success of this landmark effort will require the entire NAE community to come together. Learn more about the campaign and how you can get involved at **nae.edu/acceleratingchange**.

Donate today and double the impact of your support, thanks to the Ligler-Wagoner Challenge. Make your donation at **naefrontiers.org**.

NAE Office of Outreach and Communications Welcomes New Staff

SABRINA STEINBERG holds a master's degree in public health from the University of Pennsylvania, where she pursued academic interests in population-based mental health interventions that leverage social media to facilitate outreach of effective messaging to target audiences. As part of her MPH, she completed an internship where she conducted a needs assessment of tobacco cessation continuing education programs to inform the design of a new communication strategy to improve client outreach. As a trained public health professional, she recognizes that the diverse field of engineering is inextricably linked to health and well-being, and she is excited to join the NAE's Outreach and Communications team as a communications/media associate. With the goal of expanding the NAE's outreach to its target audiences, her efforts will focus on assisting in the continued growth of an active social media presence with engaging and current content.

We Stand Ready to Put Landmark Legislation into Action, Say National Academies Presidents

Statement | August 17, 2022

We are pleased that science, engineering, and medicine are at the core of historic legislation recently passed by Congress and signed into law by President Biden. This landmark legislation will boost US competitiveness and national security, strengthen America's infrastructure, spur basic research that drives innovation, and make real progress on decarbonizing our economy and protecting our planet and human health. In addition, the legislation will help lower the cost of prescription drugs for millions of Americans and provide attention to veterans suffering from long-term effects of exposure to toxins while serving overseas.

For decades, the work of the National Academies has helped lay the foundation for many of the actions called for—including our work on strengthening the US economy, combatting climate change, making medicines more affordable, and improving the health and well-being of veterans.

As the nation puts these laws into action, the National Academies stand ready to mobilize the broader science, engineering, and medical and health communities to help inform and implement solutions; in particular, we look forward to providing advice to the National Science Foundation on its new technology directorate, as called for by one of the new acts. We are grateful for the nation's continued investments in science, engineering, and medicine, and we remain dedicated to ensuring that they will benefit all of society.

Marcia McNutt
President, US National Academy of Sciences

John L. Anderson
President, US National Academy of Engineering

Victor J. Dzau
President, US National Academy of Medicine

Calendar of Meetings and Events

October 17	Service Systems Engineering in the Era of Human-Centered AI Virtual
October 24	Workshop: Creating a Sustainable National Electric Infrastructure While Maintaining Reliability and Resiliency of the Grid Invitation only
October 26–27	NAE-ASEE Conference: Weaving Students into Engineering, Not Weeding Them Out Invitation only
November 1–4	Workshop: Noise Around Airports: A Global Perspective Invitation only

2023

February 8–9	Council Meeting Beckman Center, Irvine, California
February 9	NAE National Meeting Beckman Center, Irvine, California
February 16	NAE Regional Meeting San Diego, California
March 1–31	Election of NAE Officers and Councillors (online)
March 22–25	German-American Frontiers of Engineering Jülich, Germany

All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.

In Memoriam

Clyde N. Baker Jr., 92, retired senior principal engineer, AECOM, died August 26, 2022. Mr. Baker was elected in 2004 for advancements in the engineering and construction of deep foundations for safe support of the world's tallest buildings.

Barry W. Boehm, 87, TRW Distinguished Professor of Software Engineering, University of Southern California, died August 20, 2022. Professor Boehm was elected in 1996 for contributions to computer and software architectures and to models of cost, quality, and risk for aerospace systems.

F. Peter Boer, 81, president, Tiger Scientific Inc., died October 3, 2022. Professor Boer was elected in 1993 for leadership in the development of technologies in the areas of specialty chemicals, biomedical devices, and environmental protection.

John J. Cassidy, 92, consultant in hydraulic and hydrologic engineering and retired independent consultant, died July 31, 2022. Dr. Cassidy was elected in 1994 for outstanding energy leadership, and the application of sound judgment to the indefinite aspects of flood hydrology and hydraulic flow.

Thomas W. Eager, 72, professor of materials engineering and engineering management, Massachusetts Institute of Technology, died October 9, 2022. Professor Eager was elected in 1997 for contributions to the theory and practice of welding.

James Economy, 92, emeritus professor, Materials Science and Engineering Department, University of Illinois at Urbana-Champaign, died October 26, 2021. Professor Economy was elected in 1987 for leadership in the engineering of high-performance polymers, and for basic investigations into the mechanism of their formation.

Joseph E. Greene, 77, D.B. Willett Professor of Materials Science and Physics, University of Illinois at Urbana-Champaign, died October 10, 2022. Professor Greene was elected in 2003 for pioneering studies in the synthesis and characterization of epitaxial and highly ordered polycrystalline materials.

Hermann K. Gummel, 99, retired director, Advanced CAD Studies Lab, AT&T Bell Laboratories, died September 5, 2022. Dr. Gummel was elected in 1985 for contributions and leadership in the analysis and computer-aided design of semiconductor devices and circuits.

Robert S. Hahn, 104, retired president, Hahn Engineering Inc., died January 5, 2021. Dr. Hahn was elected in 1984 for inventions and contributions to manufacturing research in grinding and vibrations in precision machining operations.

Juris Hartmanis (NAS), 94, professor emeritus, Cornell University, died August 4, 2022. Professor Hartmanis was elected in 1989 for fundamental contributions to computational complexity theory and to research and education in computing.

Nick Holonyak Jr. (NAS), 93, John Bardeen Chair Emeritus Professor of Electrical and Computer Engineering and Physics, University of Illinois at Urbana-Champaign, died September 18, 2022. Professor Holonyak was elected in 1973 for contributions to development of semiconductor controlled rectifiers, light emitting diodes, and diode lasers.

Kazuo Inamori, 90, founder and chair emeritus, Kyocera Corp., died August 24, 2022. Dr. Inamori was elected a foreign member in 2000 for innovation in ceramic materials and solar cell development/manufacturing, entrepreneurship of advanced technologies, and for being a role model for relating science to society.

Robert B. Jansen, 89, retired independent consultant, died December 14, 2011. Mr. Jansen was elected in 1990 for outstanding international contributions to the design and evaluation of hydraulic structures, especially in the area of dam safety.

Thomas J. Malone, 83, retired executive vice chair, Milliken & Company, died June 5, 2022. Dr. Malone was elected in 1992 for contributions to the state of customer-focused and quality-driven manufacturing and design processes, and production workforce skills.

D. Roger J. Owen, 78, research professor, Swansea University, died January 13, 2020. Professor Owen was elected a foreign member in 2011 for contributions to computational solid mechanics and industrial application of finite and discrete element methods.

Frank L. Parker, 96, distinguished professor emeritus of environmental and water resources engineering and civil engineering, Vanderbilt University, died August 10, 2022. Dr. Parker was elected in 1988 for world leadership in the development of the basic information required for the safe disposal of high-level radioactive wastes.

Zach T. Pate, 86, retired chair, World Association of Nuclear Operators, died September 4, 2022. Dr. Pate was elected in 1997 for promoting and achieving significant improvements in the safe and reliable operation of nuclear power plants worldwide.

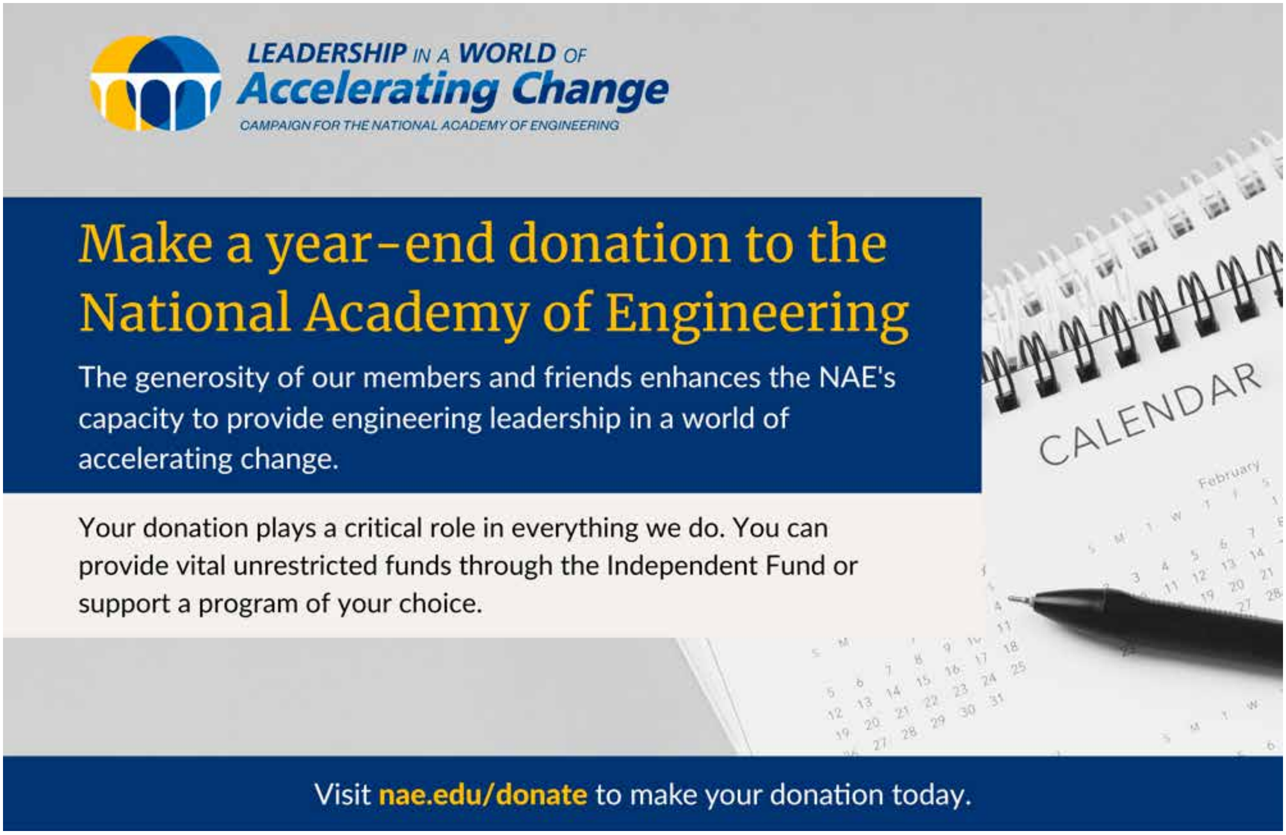
Val P. Peline, 87, retired president, Stanford Telecommunications Inc., died October 21, 2017. Dr. Peline was elected in 1988 for eminent leadership in the development and integration of very large engineering systems for space.

Theodore Stern, 92, Buyers United Inc., died July 29, 2022. Dr. Stern was elected in 1979 for leadership and contributions to the development, project management, and commercialization of pressurized water reactors.

Alvin W. Trivelpiece, 91, director, Oak Ridge National Laboratory, and president, Lockheed Martin Energy Research Corp., died August 7, 2022. Dr. Trivelpiece was elected in 1984 for technical contributions to magnetic fusion energy and for leadership in energy research and development.

David A. Woolhiser, 90, retired research hydraulic engineer, Agricultural Research Service, US Department of Agriculture, died August 19, 2022. Dr. Woolhiser was elected in 1990 for advancing the use of mathematical and statistical techniques to rationalize the description of hydrologic phenomena.

Takeo Yokobori, 99, director, Teikyo University, died October 9, 2017. Professor Yokobori was elected a foreign member in 1981 for being a national and international leader in research on engineering problems of fatigue and fracture and a prime organizer of international cooperative efforts.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