Spring 2023

SUSTAINABLE SMART CITIES

The BRIDGE

LINKING ENGINEERING AND SOCIETY

A Metastructure Approach to Smart and Sustainable Cities
Anne S. Kiremidjian and Michael Lepech

Strategies for Smart Net Zero Carbon Cities
Karen C. Seto

Smart Infrastructure for Smart Cities
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IT for Sustainable Smart Cities: A Framework for Resource Management and a Call for Action
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A Word from the NAE Chair

Infrastructure Here and Abroad

Donald C. Winter

Much of the national political discourse of late has revolved around the topic of infrastructure. As is typically the case for such matters, the political focus has been on the financial aspects of infrastructure investments—how much to spend and where to spend it. Little attention has been paid to questions associated with priorities for investment, options for future infrastructure, and alternative paths for development. These are important considerations that can determine the efficacy of the planned investments and the utility of the future infrastructure.

Unfortunately, infrastructure can be expensive and consequently tied up in the political process. An old saying is that "All politics is local,"[1] and the distribution of funding necessarily plays a critical role in infrastructure investments.

The opportunity to take public credit for such appropriations factors in as well. Some aspects of infrastructure satisfy political needs better than others. We saw this play out in January when multiple (sometimes bipartisan) press conferences were held at bridges that were slated for significant investment in recent congressional action.[2] There is little doubt that such investments are long overdue—but what was not funded?

On January 11 the United States experienced a nationwide ground stop of all air traffic.[3] Such an event had occurred only once before, on September 11, 2001. In the January event, the Federal Aviation Administration (FAA) halted all flight operations because of the failure of the NOTAM system (Notice to Air Missions), which provides safety-related notifications to pilots. While preliminary reports from the FAA indicate that the failure was due to a damaged database,[4] the root cause is still under investigation at the time of this writing.

NOTAM is a vital piece of safety infrastructure that has been the subject of calls for major improvements or replacement for many years.[5] Unfortunately, as with many aspects of increasingly pivotal IT infrastructure, it lacks the visibility of physical infrastructure and its importance is known to few until it fails.

For these reasons, constituent and political support for significant investments in such infrastructure is limited, creating a high barrier to funding. In the case of the NOTAM system outage, it appears that, although it caused major disruption to US air travel, the decision to call for a ground halt ensured that no accidents—or associated potential fatalities—occurred. Hopefully, the publicity surrounding this event will spur the necessary attention and funding to upgrade NOTAM capability.

The question to be addressed is, How can our government identify appropriate priorities for infrastructure investment and ensure that such investments provide the greatest return while minimizing disruptive effects during the transition? This is where the National Academies and, particularly, the National Academy of Engineering can play a very important role. As a trusted advisor to government, we can provide unconflicted and nonpartisan advice on highly technical matters such as these. I am hopeful that Congress and the Executive

[1] O'Neill T, w. Hymel G. 1993. All Politics Is Local: And Other Rules of the Game. Crown Publishing.

[2] Fox News. 2023. Biden's visit to Kentucky bridge highlights infrastructure push, Jan 4 (https://www.foxnews.com/politics/biden-visit-kentucky-bridge-highlights-infrastructure-push).

[3] Diaz J, Schaper D. 2023. Here's the latest on the NOTAM outage that caused flight delays and cancellations. NPR, Jan 12 (https://www.npr.org/2023/01/12/1148480971/faa-notam-outage-ground-stop).

[4] FAA NOTAM statement, https://www.faa.gov/newsroom/faa-notam-statement

[5] https://fixingnotams.org/notam2021-a-global-campaign-on-notam-improvement/

Branch will recognize the value that we can bring to such matters and that NAE members will volunteer their services in support of such critical issues.

While the need for infrastructure investments in the United States is, for the most part, due to long-term effects such as aging and population growth, the same is not true elsewhere. The tragedy of Ukraine is an unfortunate and most poignant circumstance.

Notwithstanding the commitments to Ukrainian territorial integrity that Russia made when it signed the Budapest Memorandum on Security Assurances in 1994, Russia has engaged in military operations in Ukraine since 2014 when it took Crimea.[6] When the current escalation of hostilities—the so-called "special military operation"[7]—was effectively countered by Ukrainian forces, Russia adopted a strategy of terrorism against the civilian population, targeting residential areas and energy infrastructure.[8]

This strategy has not shaken the resolve of the people of Ukraine, but it has destroyed much of their power grid. Actions are underway to provide capabilities to alleviate the damage caused by these attacks, addressing both humanitarian and defense needs.[9] But many of these measures are temporary stopgaps that do not address the country's long-term needs.

Once the conflict with Russia is resolved, extensive rebuilding will be needed to reestablish Ukraine as a self-sufficient country with a modern infrastructure. This will be a massive undertaking, not unlike the Marshall Plan effected to enable the economic recovery of Europe after World War II.[10] It will require both financial support from the United States and European countries and intellectual support—the engagement of individuals with the requisite experience to develop a modern infrastructure tailored to Ukraine's needs.

I am pleased to note that the National Academies' Division on Policy and Global Affairs (PGA) has started to engage on the situation in Ukraine. The initial focus has naturally been on supporting Ukraine's research establishment,[11] but it will soon encompass the broader needs of rebuilding the country, including its infrastructure.

I would like to encourage my fellow NAE members to participate in the PGA activities and/or the efforts of other organizations supporting Ukraine. There is a vast repository of expertise among our members that could greatly assist Ukraine in its redevelopment and I can think of few problems more deserving of our attention and expertise at this time.

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[6] Pifer S. 2014. The Budapest Memorandum and US obligations. Brookings Institution. https://www.brookings.edu/blog/up-front/2014/12/04/the-budapest-memorandum-and-u-s-obligations/

[7] US State Department, https://stories.state.gov/what-is-a-special-military-operation/

[8] Human Rights Watch. 2022. Ukraine: Russian attacks on energy grid threaten civilians. https://www.hrw.org/news/2022/12/06/ukraine-russian-attacks-energy-grid-threaten-civilians

[9] Majkut J, Dawes A. 2022. Responding to Russian attacks on Ukraine's power center. Center for Strategic & International Studies. https://www.csis.org/analysis/responding-russian-attacks-ukraines-power-sector

[10] National Archives. Marshall Plan (1948), https://www.archives.gov/milestone-documents/marshall-plan

[11] NASEM. 2022. Rebuilding Research, Education, and Innovation in Ukraine: Proceedings of a Workshop—in Brief. National Academies Press. http://nap.nationalacademies.org/26795

Guest Editor's Note

Engineering for Sustainable Smart Cities

Chai K. Toh (FREng) is Honor Chair Professor of Electrical Engineering and Computer Sciences, National Tsing Hua University.

The term *smart cities* appears in news and media lately but few clearly understand what it means and what it entails. For example, the word *smart* in this instance does not specifically refer to artificial intelligence. And because sustainability is a rapidly increasing concern around the world, the International Telecommunication Union (ITU) defines a smart sustainable city as "an innovative city that uses information and communication technologies (ICTs) and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social, environmental as well as cultural aspects."[1]

Governments around the world have embarked on smart city projects over the last few years, with investments amounting to millions or billions of dollars, to address concerns such as traffic congestion, air pollution, health hazards, inadequate or outdated infrastructure, and pedestrian safety.

The technologies used to create a smart city include high-speed wireless communications, artificial intelligence (AI), sensors, the Internet of Things, fiber optics, and geospatial engineering, to name just a few. They combine advances in electrical, computer, civil, and environmental engineering, as well as behavioral and geosciences. Thus smart cities require multidisciplinary knowledge, which is rare in the education structure of most universities. There is a need to cultivate more talent with multidisciplinary background; I hope this will be addressed in future research.

Given the growing interest and momentum in smart cities, this issue is timely. The articles describe an "urban metastructure," strategies for a net zero carbon city, smart infrastructure, a supply-demand framework for resource management, the possibilities of humanoid architectural structure, and vehicle-infrastructure cooperative autonomous driving for smart cities.

In the first article, **Anne Kiremidjian**[2] and Michael Lepech of Stanford University present an urban metastructure approach to smart and sustainable cities. Using sensing and data collection, computation, and engagement, the metastructure accounts for physical infrastructures, digital technologies, regulations and policies, financing mechanisms, community engagement, businesses and business models, and partnerships to support a high quality of urban life. Acknowledging challenges to the implementation and deployment of smart cities, the authors cite some successful examples.

"Strategies for Net Zero Carbon Cities" by Karen Seto (Yale University's School of the Environment) reviews high- and low-tech strategies that can be used in combination to achieve a net zero carbon city. In addition to using data, technologies, and systems, cities can reduce energy consumption and carbon emissions by creating bicycle and pedestrian walkways, colocating jobs and housing to reduce commuting traffic, preserving tree canopy, and actively engaging residents in changing their behaviors.

In "Smart Infrastructure for Smart Cities," **Kenichi Soga** of UC Berkeley presents the need for intelligent monitoring, learning, anticipating, and responding to infrastructure threats, whether anticipated or unforeseen. He discusses stakeholder roles in the four layers of smart infrastructure: sensors and data collection, data analysis and interpretation, assets, and systems. Digital twins, machine learning, and AI can greatly help in the design, adaptability, monitoring, operation, and longevity of smart infrastructure.

Next, in "IT for Sustainable Smart Cities: A Framework for Resource Management and a Call for Action,"

[1] Recommendation ITU-T Y.4900

[2] Bold denotes NAE members.

Cullen Bash, Ninad Hogade, and Dejan Milojicic of HP Labs and **Chandrakant Patel** of HP Inc. discuss the integration of information technologies (IT) in city-scale resource management to achieve sustainability through optimal provisioning. They introduce a holistic urban supply-demand framework, breaking down supply-side resources into city-scale verticals such as power, water, waste management, transport, and health care, and considering design, implementation, and management. To assess lifecycle, their framework uses metrics for "net positive impact" and "net positive carbon impact." The authors conclude with actions for government, industry, and academia to jointly address sustainable infrastructures in smart cities.

The concepts and components of a "humanoid architectural structure" (HAS) are explained by Xiangsheng Chen, Changqing Xia, Hongzhi Cui, Chengyu Hong, and Min Zhu of Shenzhen University. They explain the use of HAS to realize smart resilient infrastructures through human characteristics such as a robust, flexible, and self-healing "body," acute "sensory perception," "intelligence" for self-diagnosis and decision making, and self-protection ("immunity"). An important application of HAS is in underground tunnels, where it can detect and instantly set about "healing" threats such as cracks or raised water levels.

"Smart Infrastructure for Autonomous Driving in Urban Areas," by Guyue Zhou, Guobin Shang, and Ya-Qin Zhang of Tsinghua University and Baidu, Inc., addresses the current state of vehicle-infrastructure cooperative autonomous driving (VICAD) in China. The authors explain how VICAD can enhance road safety, reduce vehicle collisions, and minimize traffic delays through enhanced perception, coordinated input from sensors and the cloud, data analytics, AI, and collaborative decision making. The article concludes with challenges to be overcome and next steps toward implementation.

This issue considers important aspects of smart cities, from infrastructure to energy to transportation, and provides insights on their role and strategies for achieving net zero carbon emissions and sustainability. I thank the authors for their thoughtful contributions and their willingness to share their knowledge and insights.

Thanks are also due to the experts enlisted to evaluate the submitted drafts: Yilun Chen, Ian T. Foster, Angel Hsu, Hongwei Huang, **Robert Mair**, **Piotr Moncarz**, Andrzej Nowak, **Thomas D. O'Rourke**, Amip Shah, Bill Solecki, B.F. Spencer, Ertugrul Taciroglu, Feng Zhao, and Kun Zhou. Finally, I greatly appreciate the supportive engagement of the *Bridge* managing editor, Cameron Fletcher.

Smart city implementation involves physical infrastructures, digital IT, policies, financing, community engagement, and partnerships that must be created and sustained in concert with each other.

A Metastructure Approach to Smart and Sustainable Cities


Anne Kiremidjian


Michael Lepech

Anne S. Kiremidjian and Michael Lepech

The smart city concept was born out of a global need to respond to a coupled challenge of ever-growing populations of megacities and significant increases in the demand for limited resources (Bačić et al. 2018). In addition, many of the world's largest cities are coastal, making them particularly vulnerable to climate change and natural disasters such as floods, hurricanes, and earthquakes/tsunamis. Urban communities around the globe are therefore looking to leverage fast-evolving technologies and smart city approaches to mitigate the exposure of populations and infrastructure to these extreme yet increasingly common events, to make them resilient and sustainable for generations to come.

Introduction

In line with technology-infused approaches to meet rising demand, some municipalities have been exploring, and are beginning to implement, many of the ideas put forth in smart city concepts. But cities, and particularly megacities, are complex systems of physical, environmental, social, economic, and financial systems. Each system's functionality depends on

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Anne Kiremidjian (NAE) is the C.L. Peck, Class of 1906 Professor of Engineering and Michael Lepech is professor of civil and environmental engineering, Stanford University. Lepech is also senior fellow, Woods Institute for the Environment.

that of the others, increasing the difficulty of implementation nonlinearly since these systems must work in concert.

To aid city officials in implementation, several models have been proposed for smart city structure (examples are provided in a seminal paper by Harrison and Donnelly 2011, which lays the theoretical foundation for smart cities; Sánchez et al. 2013 and Li et al. 2015 provide details; and Bačić et al. 2018 presents a summary). Some approaches emphasize the technological aspects of smart city developments (e.g., Park et al. 2018), and others take into consideration the social and economic aspects that also need to be addressed (e.g., Baraniewicz-Kotasińska 2022).

A sensing network can be constructed specifically for smart city purposes or leverage the increasing numbers and capabilities of personal smartphones.

Building on that work, in this article we look at the various components of smart cities and cast them in a *smart city metastructure* that is comprehensive in relation to other proposed paradigms. First we discuss the components of this metastructure. Recognizing the difficulties in developing the individual components, we review some successes and failures of smart city implementations, and identify challenges that need to be considered for effective smart city creation.

The Smart City Metastructure

Smart city implementation requires physical infrastructures, digital information technologies, regulations and policies, financing mechanisms, community engagement, businesses and business models, partnerships, and other institutions that must be created, applied, and sustained *in concert with each other*. This set of technologies, policies, and organizations was termed by researchers at Stanford the *urban metastructure*, a transcendent form of city infrastructure that enables the smart city paradigm (Lepech 2017, 2021).

First proposed as a concept for urban transportation systems (Rogers 2016) the urban metastructure can be parsed into three critical elements of smart cities. The foundational element is (1) a dense sensing and data collection network that comprises the physical infrastructures. Such a sensing network can be constructed specifically for smart city purposes (e.g., closed-circuit television [CCTV] cameras, roadway traffic sensors) or leverage the increasing numbers and capabilities of personal smartphones.

Built on this sensing network is (2) a computational layer that translates the growing stream of smart city data into information that can be used by smart city residents, businesses, and visitors. This computational layer, which leverages advanced computational algorithms (e.g., machine learning [ML], reinforcement learning, artificial intelligence) to process incoming data streams efficiently and rapidly, can provide the public with information via smartphone applications or direct alert updates. These two basic layers of smart city metastructure, sensing and computation, are commonly associated with smart city research and implementation.

The final component of smart city metastructure is (3) engagement mechanisms. Engagement is a less studied but critically important component of smart cities. Effective engagement mechanisms are necessary to materially increase the quality of life in cities and provide a lasting value proposition for residents. Without creating long-lasting value for everyone living, working, learning, and playing in a city, and substantially increasing their quality of life, smart city technologies and apps will continue to be novelties, used by early adopters of technology, rather than effective tools of citywide sustainable development and management. These engagement mechanisms comprise the regulations and policies, financing mechanisms, community engagements, businesses and business models, partnerships, and other institutions of the urban metastructure definition.

Figure 1 shows the three major components of the urban metastructure and their interlinking relationships. Each component must be implemented in concert with the others to achieve the goals of smart and sustainable cities.

Physical Infrastructure for Smart Cities

The majority of research and implementation in smart cities has focused on the development of sensing technologies for transportation, power, water, and commu-

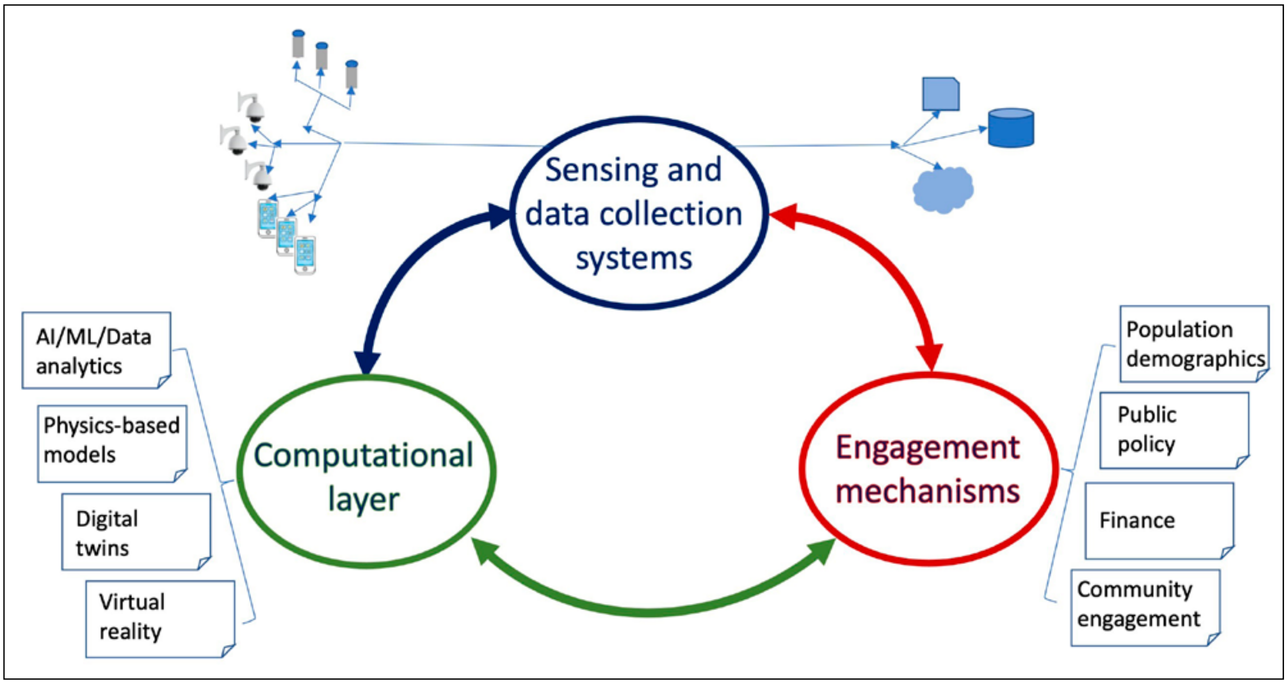

FIGURE 1 Framework of metastructure enabling smart cities. AI = artificial intelligence; ML = machine learning.

nications systems; maintenance and management of infrastructure components and systems; and monitoring of buildings and other structures.

Sensors are a crucial component of any intelligent control system. The performance of an urban system can be improved via control systems that enhance awareness of its environment and operational status through the collection of necessary data from an array of sensors (Bačić et al. 2018). Different types of sensors are typically deployed to collect a variety of data that are then synchronized and analyzed to extract appropriate information that enables robust decision making and control. In situ sensors, embedded on a structure, road, or other infrastructure system components, collect information locally (e.g., at traffic loops); remote sensors (e.g., CCTV camera, satellite sensors) collect data from a distance. Data from human-generated measurements "include subjective observations on the environment, social media posts, mobile phone calls and text messages, and physiological measurements by wearable body sensors" (Bačić et al. 2018, p. 279). Data and information transmission and storage are achieved through wired or wireless communications networks.

For illustration, effective air quality management requires comprehensive data showing spatial distribution of emissions along with combustion and traffic sources (Flaga et al. 2019; Kucharski et al. 2018). Smart city physical infrastructure systems in place to monitor air quality data include dispersed sensors in street lighting for pollution metering (Szarata et al. 2017; Vasiutina et al. 2022). Such systems can be used to understand the nature of air pollution and inform recommendations for remediation through, for example, ventilation towers that generate continuous air streams that supplement natural air flow (Flaga et al. 2019).

Computational Layer

A robust computational layer is key to good decision making and infrastructure management. Data collected from the complex combination of smart city sensors are rather meaningless until information is extracted and used in the management and control of the various urban systems. Computational and data science tools such as advanced statistical analysis, machine learning, and artificial intelligence have been under development for some time, and significantly enhanced over the past decade.

Recent exponential increases in computational power and data storage capabilities have enabled the analysis, storage, and manipulation of large datasets, obtained from myriad sensors, that can be used in smart city applications. Intelligence based on data from sensors is frequently combined with physical models to develop more robust predictive/forecast and control

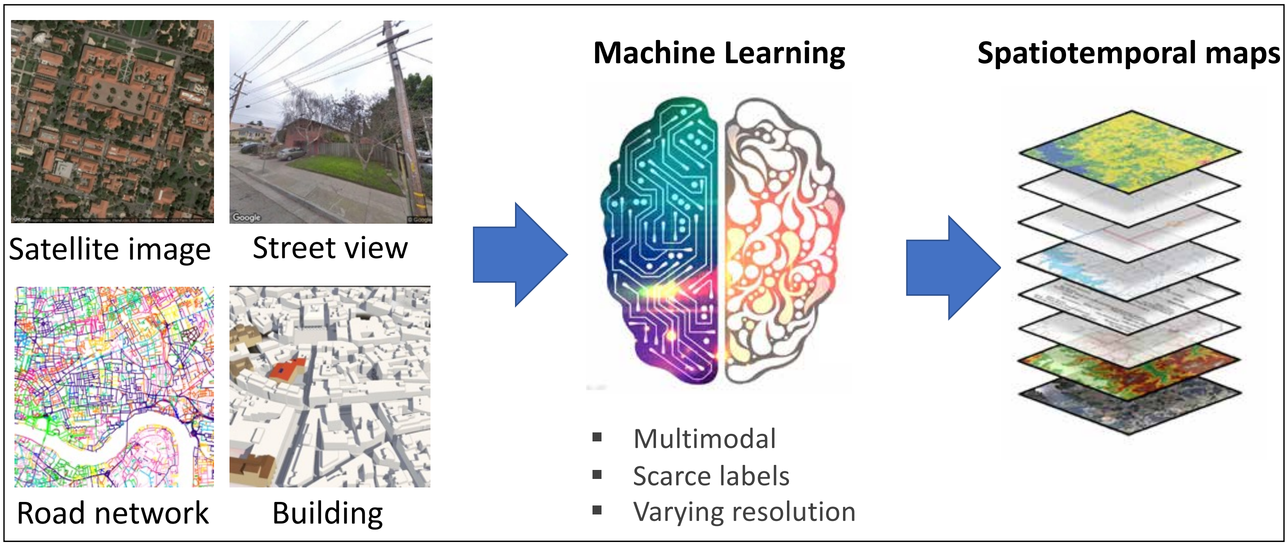

FIGURE 2 Computational engine (shown as the brain that performs the analysis, using multimodal input and incomplete metadata ["scarce labels"] of varying resolution) combined with geospatial data (on the left; from satellite imagery, street view maps, road networks, and building information) for regional smart electrical grid analysis resulting in spatiotemporal maps with optimal power delivery options. Reprinted with permission from Wang (2022).

models. These are powered by hardware and software that greatly increase speeds and storage. Algorithms to support citywide monitoring and management of transportation, power, water, waste, and environmental conditions are continuously being developed, enabling more rapid implementation of the smart city paradigm.

For example, traffic pattern identification and control for optimal traffic management in some major urban areas (e.g., Copenhagen, New York City, San Francisco, Songdo, Stockholm) are effected through the use of data from roadway embedded sensors, CCTV cameras, radiofrequency identification (RFID) technologies, and personal cell phones. The data are used to monitor traffic patterns, control traffic lights, monitor municipal buses and other modes of public transport, detect accidents, identify road damage, control and monitor parking spaces, and spot traffic violations. Foot-traffic patterns are also used to supplement the algorithms to optimize people movement. And management of commercial delivery systems in combination with general traffic patterns reduces wait times and minimizes driving ranges, reducing both fuel consumption and CO_2 emissions.

Making the urban power supply smart and resilient requires hardening the existing grid and supplementing it with alternative power supply modes such as wind, solar, gas, and nuclear power generation facilities. Figure 2 schematically shows an example of a smart grid monitoring system that combines various data that feed into an ML algorithm to produce scenarios for optimal power supply distribution over a region.

Geospatial information about the physical grid, such as location of transmission stations, switching stations, trunk lines, and distribution lines, is obtained by fusing data from satellite imagery, street view maps, road maps, and building distributions. Similarly, satellite and aerial photography is used to show the spatial location, size, and age of rooftop solar panels. These data are then combined with meteorological information to forecast solar power generation over the region. A similar approach is used for wind power generation. The temporal variations of the data are preserved and the overall data are used for robust optimal geospatial power supply allocation over a variety of regions using an algorithm developed by Wang (2022).

Another major effort in computational development focuses on assessing the condition of buildings and other infrastructure components and systems, to enable as-needed rather than regularly scheduled maintenance (e.g., Liao et al. 2019). Such an approach, if done proactively and with the support of a comprehensive decision-support system, leads to lower likelihood of unexpected failures, lower overall lifecycle maintenance costs, greater infrastructure resilience, and a decrease in CO_2 emissions.

Additional examples include environmental monitoring systems that track air and water quality in buildings to identify the distribution of airborne pathogens (e.g., Chew et al. 2022). Systems for tracking footsteps in buildings are being developed to optimize foot traffic flow and, in healthcare and assisted living facilities, monitor elderly occupants to prevent potential falls (e.g., Pan et al. 2017).

Finally, the computational layer embedded in new digital twin technologies is key to the development of smart cities. These technologies can be used in many ways for building and managing critical systems in smart cities (Farsi et al. 2020). It is also important to link digital twins to the physical and functional properties of other systems (Lepech et al. 2016) to map and study system interdependencies and conflicts, thereby enhancing the ability to address intricacies that are often difficult to tackle.

Engagement

Engagement mechanisms are some of the most important components of the smart city metastructure, essential to the effective implementation of smart city systems. They include regulations and policies, financing mechanisms, community engagement, businesses and business models, partnerships, and other institutions. Without the integration of these elements for smart city implementation, the value proposition of smart city technologies can remain ambiguous to residents and fail to achieve long-term goals.

But engagement and decision making are difficult when there is insufficient knowledge among citizens and decision makers, compounded by factors of aversion, bias, and irrational behavior. Information asymmetries may result in city residents not being aware of what constitutes the "best" decision.

Fortunately, there are examples of successful engagement mechanisms around the world: Virtual Singapore provides residents with "a geo-visualization, analytical tools and 3D semantics-embedded information platform to connect and create awareness and services that enrich their community."[1] Digital Dubai now has over 90 government services that are digitalized and accessible to citizens through its DubaiNow App.[2] Songdo, South Korea, has integrated urban mobility management and city operations at a centralized command center that can address transportation challenges in real time and ease urban mobility challenges.[3]

Recognizing the potential of smart cities to reduce environmental impact while improving operational resilience, New York City, in its efforts to reduce its carbon footprint, has adopted smart lighting, water leakage monitoring, smart garbage bins, and traffic monitoring and management (Lai 2022). The installation of smart lighting systems has prevented the emission of over 900 metric tons of greenhouse gases annually since 2013. Smart garbage bins have improved trash collection efficiency over 50 percent while reducing vehicle emissions from city garbage trucks. Finally, New York's automated meter reading system enables faster identification of leaks and other problems in the city's water system, leading to increased ability to operate the system reliably during extreme events such as heatwaves and intense storms.

Engagement and decision making are difficult when there is insufficient knowledge among citizens and decision makers, compounded by aversion, bias, and irrational behavior.

These and other examples illustrate engagement mechanisms implemented both internationally and in other US cities, including Boston and San Francisco.

Challenges to Implementation and Full Deployment

Globally, the concepts associated with smart cities are widely accepted and there is a great deal of enthusiasm to put them into practice. Yet widespread implementation remains elusive.

Several major obstacles prevent municipalities from fully or partially deploying smart technologies to advance their cities to the next generation of more livable and sustainable communities. Obstacles include

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[1] National Research Foundation, Office of the Prime Minister of Singapore, https://www.nrf.gov.sg/programmes/virtual-singapore

[2] Digital Dubai Authority, Apps and Services, https://www.digitaldubai.ae/apps-services

[3] Incheon Free Economic Zone Authority (IFEZA), Global Center, www.ifez.go.kr/global/index

privacy concerns, data security, retrofitting challenges, and costs.

One example of an obstructed effort is the smart city proposed by Sidewalk Lab, the smart urban development arm of Alphabet, which looked to rebuild a 2000-acre waterfront district of Toronto known as Quayside. This new urban district was planned to have affordable apartments, a two-acre forest, a rooftop farm, a new art venue for indigenous culture, and a pledge to be zero carbon (Jacobs 2022). Concerns about privacy and security were cited as the primary reasons the city government and Sidewalk Lab could not reach an agreement. The project was dropped after three years of work.

Privacy concerns, data security, retrofitting challenges, and costs prevent municipalities from fully or partially deploying smart technologies.

Another major impediment to widespread implementation is the difficulty of instrumenting and adopting technologies in cities that have been in use for hundreds of years, with old infrastructure that cannot support the new technology infrastructure. Many major metropolitan areas are struggling with aging water, power, communications, and transportation infrastructure. New digital smart technologies cannot simply be added to these systems.

Key to providing clean water, for example, is a reliable water transmission system. Replacing such a system with smart water pipelines that monitor flow and capture potential contamination or localized failure requires significant capital investment and upgrading. Municipal officials must also confront the dilemma of whether to rebuild existing components using long-proven methods or introduce smart technologies that may have higher initial cost and risk. Similar examples can be cited for power, communications, and transportation systems.

Apart from aging infrastructure systems, there is difficulty in the instrumentation of existing buildings. The installation of sensors for structural and environmental monitoring and for sensing people's movement can be particularly difficult if the sensing network needs to be hardwired. Wireless sensing solutions have been developed for structural monitoring (e.g., Kane et al. 2022; Kiremidjian et al. 2011; Lynch and Loh 2006), but building owners may be resistant to instrumenting their buildings because of privacy and liability concerns.

In California, only a handful of buildings are instrumented for seismic performance evaluation, and they have at most 15 to 20 sensors, an insufficient number for effective condition assessment (Kiremidjian et al. 2011). Dubai's Burj Khalifa, opened in 2010, is perhaps the best-instrumented building for structural health monitoring (Abdelrazak 2012). The instrumentation includes global positioning systems (GPS), Leica high-precision sensors, and clinometers that monitor rotation and displacement of the tower. Data collected from the tower have been used with SmartSync concept (Kijewski-Corea et al. 2013) for continuous monitoring and maintenance decisions.

In light of all these challenges, many major metropolitan areas around the world are still working to introduce smart city solutions to their residents. As noted, New York City has adopted a number of these solutions (Lai 2022). Other US cities that are implementing smart technologies include Seattle, San Francisco, Dallas, Austin, Washington DC, Boulder, and San Jose (Cheung 2021). Around the world, smart technologies are being implemented in Copenhagen, Hong Kong, Stockholm, and cities in South Korea and China, among others.

Successful developments that include multiple smart city aspects have been achieved in cities built from scratch in some cases. Developed jointly by Gale International, Posco, and Morgan Stanley Real Estate, Songdo, South Korea, is an example of a privately funded growing smart city. And Japan is investing in the development of smart cities with funding from private industry; for example, Panasonic Corporation has invested in the development of several such cities, the latest being Suita in central Japan (Hornyak 2022). Features implemented in Suita include solar panels, storage batteries, and home power management systems. In addition, the city's 2000 residents can share bicycles and scooters, and have purchases delivered by bicycles and robots. Sensors monitoring sleep patterns adjust temperature and airflow to provide increased comfort. Many other smart features are being implemented to make this and other cities more sustainable.

Conclusion

The promise of smart cities is exciting. But there remain numerous challenges to achieving implementation over the coming decades. As urban designers, municipal officials, IT specialists, civil engineers, and others come together to deliver on the promise of smart cities, the concept of urban metastructure becomes more important: it presents a transcendent set of physical and social infrastructure systems that must be built in concert with one another to increase the likelihood of smart city success. Smarter, more resilient, more sustainable urban environments will offer higher quality of life to city residents around the globe.

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A combination of high- and low-tech strategies can help cities achieve net zero carbon emissions.

Strategies for Smart Net Zero Carbon Cities

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If the world is to avoid dangerous climate change, immediate, rapid, and large-scale reductions in greenhouse gas (GHG) emissions are needed within the next three decades (IPCC 2018): Global emissions must reach net zero by 2050. This will require major transitions in four systems: energy, industry, land and ecosystems, and urban and other infrastructure.

Cities in particular must transition to net zero carbon as soon as possible given that two-thirds of global GHG emissions are attributed to urban areas (Lwasa et al. 2022). Furthermore, because the urban share of national emissions is large—62 percent in 2015—and growing (Gurney et al. 2022), national or global mitigation strategies that omit urban emissions will be inadequate.

Historical Perspective

In many respects, the idea of transforming cities to make them net zero carbon is the latest manifestation of a recurring theme in history: to make cities more efficient, environmentally safe, and/or economically vibrant. These concepts are embodied in the idea of the smart city.

Smart cities are characterized by the use of technological advances to measure, manage, and improve urban decision making and functioning. Replete with sensors, they run on data and lots of it, with the goal of improving the quality, efficiency, and sustainability of urban life.

The concept of the smart and sustainable city gained ground in the early 2000s, coincident with the rise of the internet and the information revolution, but it had many forerunners. For example, the Sanitary Reform Movement, which started in the 1830s and peaked in the 1880s, was a response to tenement slums and the spread of cholera and other diseases (Ringen 1979). The Eco-City concept grew out of the environmental movement in the 1960s and 1970s and focused on efficiency and minimization of waste (Rapoport 2014).

Seen through this historical lens, the transition to net zero cities can be viewed as an evolution from sustainable and smart cities.

Conceptualizing Net Zero Carbon Cities

Net zero carbon emissions are achieved when anthropogenic carbon emissions and their removal are in balance over a particular period. At the city scale, carbon emissions include those from urban production of goods and services (whether for local consumption or export), transport, and consumption by entities such as households, governments, and commerce.

Cities offer extensive opportunities for deep decarbonization because they concentrate people, infrastructure, and activity.

However, cities are open systems that rely on nearby and distant areas for imported goods and services and waste export. A strictly territorial approach that excludes emissions that occur outside city boundaries (e.g., associated with imported food, energy, transboundary transport) can significantly underestimate urban carbon footprints. For example, a study of 79 cities found that 41 percent of their consumption-based carbon was generated outside city boundaries (Wiedmann et al. 2021). Other studies have shown that upstream emissions that occur throughout the production chain of goods consumed in cities are greater than territorial emissions (Harris et al. 2020; Minx et al. 2013).

Thus how urban carbon emissions are counted will affect the sources of emissions that are balanced under the concept of net zero cities. Territorial emissions should be complemented with accounts of upstream or embodied emissions to get a more complete picture of the emissions associated with urban consumption. With the large discrepancy between territorial and upstream urban emissions, there are increasing calls for cities to account for their supply chains in their commitments to net zero carbon emissions (Ramaswami et al. 2021; Wiedmann et al. 2021).

Given the effects of different carbon accounting systems for urban emissions, it is no surprise that there are varying definitions of what constitutes a net zero carbon city. According to one of the most common definitions, a net zero carbon city is committed to a target of at least 80 percent reduction in GHG emissions or some other decarbonization goal (CNCA 2018). The "net" component of a net zero goal implies that a city's residual GHG emissions are offset by carbon removal.

Net zero is not the same as low carbon. For cities to achieve net zero, they must undergo systemic changes through deep decarbonization.

Urban Deep Decarbonization Strategies

Deep urban decarbonization is the process by which a city significantly reduces GHG emissions to zero or near net zero. Cities offer extensive opportunities for deep decarbonization because they concentrate people, infrastructure, and activity.

Three Strategies

To achieve deep decarbonization, cities need to undertake and integrate three broad strategies:

1. Reduce urban demand for energy and materials.
2. Switch urban energy supply to net zero carbon electricity, fuels, and materials.
3. Enhance carbon sequestration and stocks and reduce emissions in urban supply chains.

Each of these strategies comprises multiple pathways. The first, for example—reducing urban demand for energy and materials—can be achieved by (i) integrating spatial planning to *avoid* the need for motorized transport; (ii) *improving* the efficiencies of individual sectors, such as buildings, transport, and wastewater treatment; and/or (iii) fostering industrial symbiosis, where wastes or byproducts from one industry are used as input for another industrial process, thereby *eliminating* waste and *avoiding* the demand and associated emissions for additional raw materials. Industrial symbiosis requires collaboration and geographic colocation (Chertow 2000).

Switching the urban energy supply would require concurrent development of a net zero carbon electricity grid; electrification of key urban activities such as mobility, heating, and cooking systems; and carbon valorization, which uses captured CO_2 as the chemical feedstock to make consumer products such as plastics, fertilizers, and alcohols.[1]

In terms of mobility, an electric vehicle fleet must be an essential part of the urban mitigation portfolio. However, the planet will add another 2.5 billion residents to cities and towns over the next 30 years. If every one of the 4.5 billion existing and 2.5 billion future urban residents used an electric vehicle, that would amount to around 7 billion vehicles—and significant embodied emissions associated with manufacturing the fleet and the batteries. Therefore, electrification cannot be the only component of urban transport mitigation.

The third strategy, enhancing urban carbon uptake and stocks, can be achieved through (i) carbonation of cement materials, a slow process by which CO_2 is absorbed in solid materials; and (ii) carbon sequestration by vegetation, whereby CO_2 is captured and transformed into biomass through photosynthesis.

The Avoid-Shift-Improve Paradigm

Another way to conceptualize deep urban decarbonization is through the Avoid-Shift-Improve (A-S-I) paradigm. As an example of this approach, emissions may be *avoided* by reducing or eliminating unnecessary demand, demand for energy *shifted* to lower emission modes by switching travel modes from autos to bikes, and the efficiency of energy-consuming technologies and infrastructures *improved* by increasing energy efficiency and reducing the carbon intensity of vehicles.

First developed for the transport sector, the A-S-I approach has been applied to others—such as food, housing, and materials (Creutzig et al. 2022a)—to find potential mitigation pathways. For example, food loss and waste in the United States are estimated to account for 170 million metric tons of CO_2 equivalent of GHG emissions, not including emissions from landfills (EPA 2021). The A-S-I approach can be used to help identify ways to reduce and avoid such loss and waste.

Low-Tech, Low-Cost Mitigation Pathways

Low-tech, comparatively low-cost pathways should be part of every city's strategy to achieve net or near net zero emissions. They are less expensive and often easier to implement, especially in developing countries with rapidly growing cities and high demand for new infrastructure.

Colocate Jobs with Housing

Many studies show that higher population densities in close proximity to higher job densities are strongly correlated with lower GHG emissions (e.g., Lee and Lee 2020; Qin and Han 2013). Locating jobs and housing near each other reduces commuting distances and increases the use of both public transit and nonmotorized transport, in part by making it more convenient to walk and bike to work. The associated increase in physical activity has significant health benefits, such as reductions in obesity (Ewing et al. 2014), cardiovascular and respiratory diseases (Stevenson et al. 2016), and diabetes risk (Saunders et al. 2013).

Because of significant embodied emissions associated with manufacturing the fleet and the batteries, electrification cannot be the only component of urban transport mitigation.

For cities in the early stages of urbanization with low levels of transport infrastructure, the intentional colocation of jobs with housing can help to avoid "locking in" high energy–consuming behaviors and routines that require more effort to change.

Enhance Pedestrian and Biking Infrastructure

Locating jobs near housing is only a first step. This strategy must be supported with efforts to enhance, improve, and expand pedestrian and bicycle infrastructure to make walking and biking more attractive alternatives

[1] For a comprehensive treatment of how cities can achieve net zero carbon, see Seto et al. (2021) or Ramaswami et al. (2021).

to motorized transport. The design of new and redesign of existing cities such that walking, biking, and public transportation can meet the needs of most urban activities is a comparatively low-cost strategy to reduce transport emissions. Bike lanes that are raised and separated from motorized vehicles improve safety and encourage cycling.

More walkable cities are good for climate change mitigation—and also make sense for economic and individual health.

The city of Seville, Spain, built a bike infrastructure network covering 77 km in just two years at a cost of €18 million ($19.6M). In contrast, the city's first metro line cost over €630 million ($684M) to build 18 km (Marqués et al. 2015). Seville also has a bike sharing program, with approximately 2000 bikes, that reports over 8100 trips per day (Faghih-Imani et al. 2017). These types of investments in cycling infrastructure make bicycling a viable and economic form of travel across the city and encourage their use.

Making cities more walkable is good for climate change mitigation and also makes sense for economic and individual health. Reduced traffic from personal vehicle use can reduce air pollution and thus improve health. Furthermore, walkable communities have higher residential (Rauterkus and Miller 2011) and commercial property values (Pivo and Fisher 2011) and are more economically productive (Litman 2003). One study found that among the largest US metropolitan areas, the most walkable produce 49 percent more GDP than the least walkable (Leinberger and Rodriguez 2016).

Make Streets Visually and Commercially Diverse

In addition to enhancing pedestrian and biking infrastructure to improve walkability, cities must have a mix of uses and destinations in close proximity for pedestrians and cyclists. People want to be able to walk or bike to coffee shops, stores, parks, the post office or library, and work. There are two ways to achieve this in existing cities: site commerce near housing or increase housing near areas of commerce.

Improving walkability and colocating jobs and housing will also require a complementary strategy of making streets visually and commercially diverse and geared to the pedestrian. The observation of urbanist Jane Jacobs (1969) more than 50 years ago, that aesthetically diverse street life is an indicator of social and economic vitality, still holds true. Cities with vibrant street life invite people to walk and explore. In contrast, streets devoid of people or visual complexity are likely to discourage walking.

Plant Trees and Preserve Urban Natural Areas

Urban forests and street trees can help mitigate climate change directly through carbon sequestration and storage. Carbon sequestration is the process by which carbon dioxide is removed from the atmosphere and stored in carbon pools, such as the ocean, biomass, rocks, and soils. Carbon can also be stored in bio-based materials used in construction, such as mass timber and bamboo (Churkina et al. 2020).

Globally, urban trees sequester approximately 217 million tonnes of carbon annually and store approximately 7.4 billion tonnes of carbon, although the amounts are highly dependent on canopy structure, composition, extent, and biome (Lwasa et al. 2022). In the United States, annual sequestration of carbon by urban trees is approximately 25.6 million tonnes (Nowak et al. 2013). Forested natural areas in New York City store an estimated average of 263.5 megagrams of carbon per hectare, totaling as much as 1.86 teragrams of carbon citywide (Pregitzer et al. 2021).

Urban tree canopy can also mitigate climate change indirectly by providing shade that lowers surface and air temperatures. This cooling effect can reduce building energy demand for air conditioning.

Associated Costs

None of these strategies require much technology or financing compared to the high-tech solutions, but they do require vision and a strong leader. In many cases, they need supportive policies that combine more than a single objective as well as changes to zoning codes and public financing, including through possible tax incentives. The successful implementation of these strategies is highly dependent on a city's financial and governance capability, and must be addressed simultaneously by various regulatory, management, and market-based instruments. The degree to which these can be implemented will also vary significantly in the Global North versus the Global South.

While these strategies are not expensive, they are also not cost-free. Redesigning existing streets to accommodate bike lanes requires public support and stakeholder engagement. Increasing tree canopy cover is also not without controversy. Trees produce volatile organic compounds (VOCs) that can have negative health effects. Some businesses may not want trees blocking their storefronts, and not all residents want street trees.

In all of the examples, public engagement is critical for uptake, buy-in, and successful design of infrastructure that people use.

Established vs. Rapidly Developing Cities

The opportunities and actions to transition to net zero carbon will depend on the level and stage of urban development.

For new and rapidly growing cities (most of which are in developing countries that are early in their urbanization process), there is an opportunity to design the built environment and infrastructure to avoid higher future GHG emissions. Equally important is that these emerging cities avoid infrastructural, institutional, and behavioral carbon lock-in that creates collective inertia.

In established cities, making them walkable and bikeable is not enough. To achieve deep decarbonization, they need to make systemic changes that include net zero electricity grids and electrification of transport and heating.

Major transformations in the power sector are already taking place. Many cities have incorporated district energy (centralized energy sourcing for multiple buildings in an area) in new infrastructure projects. Such a system achieves economies of scale and can also reduce GHG emissions if the source is renewable energy or waste heat. For example, Tokyo's district energy system uses waste heat and incinerated waste. However, it can be difficult to install new underground networks in cities with established infrastructure.

Social Engagement

Ultimately, achieving deep decarbonization and net or near-net zero emissions will require behavior changes. The most recent IPCC report estimates that reducing demand through shifts in behavior and social norms can reduce global emission by as much as 40–70 percent by 2050 (Creutzig et al. 2022b).

For example, the energy use of a building is determined not only by how the building is designed and constructed but also by the behavior, norms, and culture(s) of its occupants and location. Among other things, the growing global standardization of room temperatures is shaping energy use in buildings (Shove 2003). What used to be a large range of air temperatures considered comfortable and acceptable is now narrowing as people spend more time in temperature-controlled environments such as vehicles, homes, offices, and stores.

Public awareness campaigns can make a difference in changing norms around cooling and comfort.

Public awareness campaigns can make a difference in changing norms around cooling and comfort. The "26 Degree Campaign" launched by environmental NGOs in Beijing during the summers of 2004 and 2005 successfully encouraged the public, especially hotels, restaurants, and business offices, to keep air conditioners set at 26°C (about 79°F) or higher (Xie 2011).

Conclusion

The clock is ticking to transform cities to net zero. To achieve this goal, cities will need to undertake multiple mitigation strategies simultaneously and as quickly as possible. Some of these will be high-tech, others will require significant political will and public engagement more than technological innovation.

The scale of the challenge is daunting. Anything short of transformative change in cities will not bend the emissions curve fast enough to avert disastrous climate consequences.

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How can the built environment be rehabilitated or created so that future generations benefit from smart infrastructure?

Smart Infrastructure for Smart Cities

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Much of the nation's infrastructure is aging and in poor condition, affecting safety, the economy, and quality of life. A variety of emerging technologies can enhance infrastructure to improve safety, resilience, sustainability, and equity.

Challenges to Current Infrastructure Systems

Reactive, damage-based management is ineffective. It takes a long time to build infrastructure, with construction timescales alone stretching from 2 to 10 years. As shown by the first row in figure 1, many infrastructure assets are designed for a service life of 100 years, even with deterioration due to material degradation, extreme temperature, and external loads. But deterioration can accelerate because of poor design or workmanship, construction problems, unforeseen stressors, and inadequate maintenance and repair—it's worth noting that effects of changes in traffic mode, demand, or weather events are not currently considered in maintenance.

Continuous retrofit, renovation, and adaptation are required during an infrastructure's lifetime, and the high cost involved in upgrading and replacing leads to a desire to extend overall life, as illustrated by the second row in figure 1. The American Society of Civil Engineers (ASCE 2021) has estimated that the cumulative needs for US infrastructure—in the form of inspection, maintenance, repair, and replacement expenditures—could reach

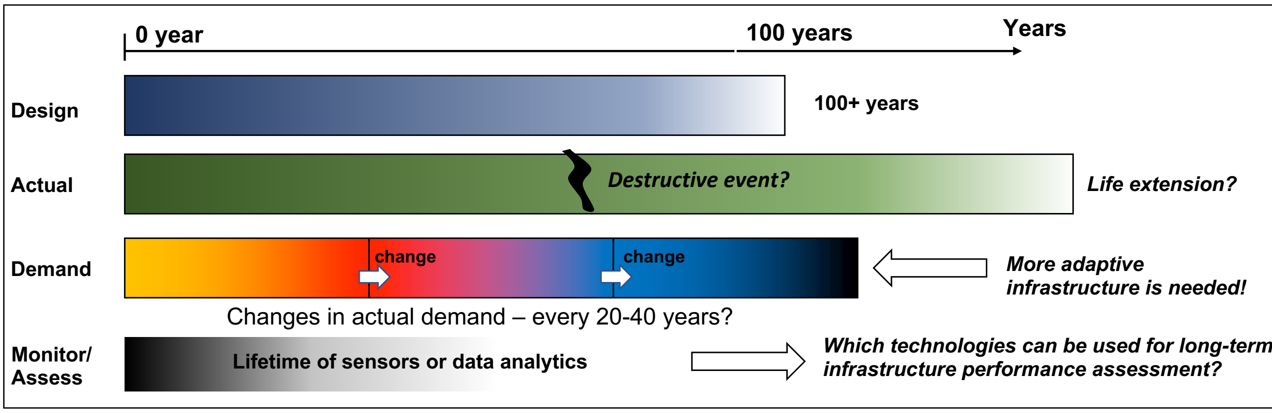


FIGURE 1 Challenges in infrastructure – Differences in time scale.

$5.9 trillion by 2029, but that the estimated available funding is only $2.59 trillion. There is thus a compelling case for extending the useful life of infrastructure.

Assets also face external conditions that deviate from what was known or assumed by the planner or designer, such as population growth/decline, more frequent natural hazards due to climate change, fluctuating energy prices, and shifts in transport modes. These changes often occur several times during the life of infrastructure (the third row in figure 1).

Ideally, infrastructure should be designed to both meet immediate needs *and* be adaptable to future demands throughout its lifetime. Past design philosophy, however, was based on current demand prediction, creating a substantial risk that the infrastructure will be inadequate or obsolete before the end of its expected period of operation. In addition, the covid-19 pandemic changed infrastructure demands as teleworking continues to transform residential and travel patterns. Adopting new mobility platforms and increasing automation and electrification will affect future infrastructure.

Adaptation is no longer a choice but a requirement for sustainable living. Infrastructure must adapt to changes and threats that are here now. The need to improve the capability to predict, design for, and manage the life expectancy of infrastructure calls for smart infrastructure engineering with the sustainability, resilience, and equity of communities at its center. How can the built environment be rehabilitated or created so that future generations benefit from smart infrastructure?

Stakeholders and Layers in Smart Infrastructure

Engineers manage infrastructure safely and economically by dealing with the uncertainties of such assets' life expectancy and performance during hazards. Infrastructure owners, on the other hand, are faced not only with loss of service and lifecycle costs but also uncertainties such as changes in demand, climate, policy, and environment (figure 2). And they must be responsive to stakeholders' expectations.

Engineers provide for infrastructure performance in the future based on understanding and predicting actual performance through sensing and modeling. Infrastructure owners need to know their asset's projected service performance based on information about its anticipated behavior given by engineers. Both need to make decisions for short- and long-term performance based on information obtained from monitoring of the infrastructure. Their judgment is guided by solid evidence, and decisions are made assuming multiple alternatives. The key to realizing smart infrastructure is to verify that the link between asset behavior and service performance is well established.

Figure 2 (right side) illustrates how smart infrastructure can be developed at different scales and layers. Engineers deal with the bottom three layers, and infrastructure owners deal with the top two: both are concerned with the asset layer. The layers—sensors and data collection, data analysis and interpretation, assets, and infrastructure system—are discussed in the following sections, with factors and questions to be considered for each.

Sensors and Data Collection

If sensor technology can be used for an extended period (equal to the infrastructure lifetime) with appropriate maintenance and replacements (as shown by the fourth row in figure 1), it will be possible to introduce

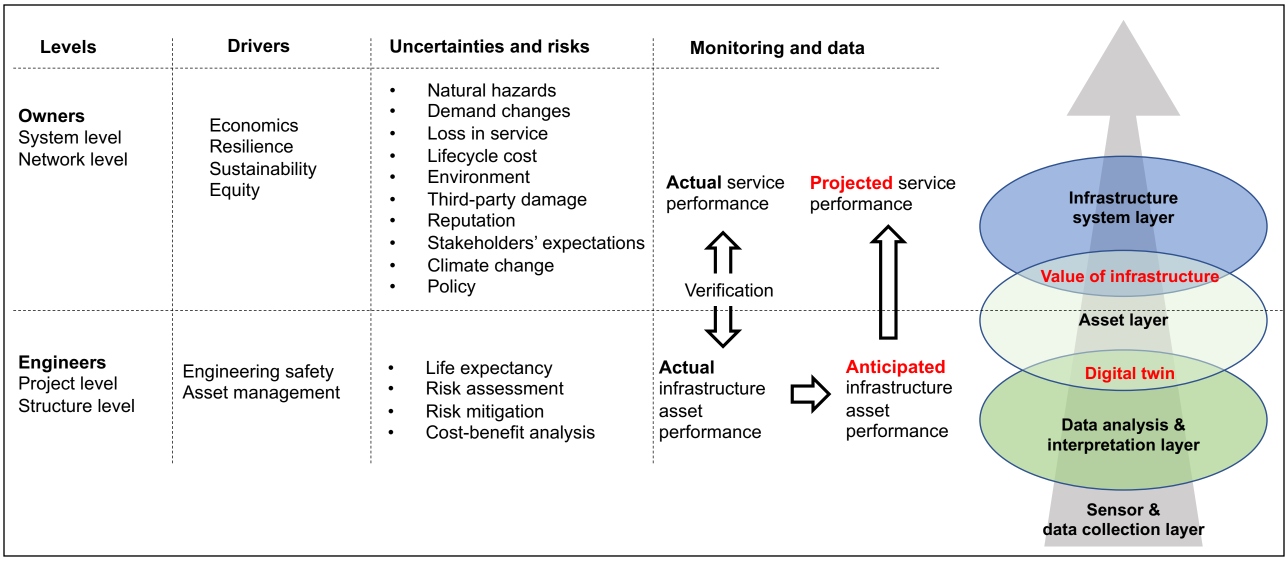


FIGURE 2 Linking asset-level performance to system-level performance.

the lifecycle approach in the civil engineering industry. The information required includes data quality and its degradation over time, survival rates of hardware and software components, and the associated error propagation and cost of component management. Some typical metrics to consider for whole-life sensing are

- the level that can measure the performance of infrastructure to make engineering decisions,
- robustness and reliability of sensors,
- frequency of data collection, and
- replaceability as newer sensors become available.

Data Analysis and Interpretation

Fundamental challenges in this layer lie in creating new models or modifying existing models that drive economic sensing requirements and sensor deployment for specific applications. For example, what resolution and sampling frequency are needed to detect long-term degradation effects, natural hazards, and harmful movements due to adjacent construction or climate change? Answers to this question will require new models that anticipate future stresses on the infrastructure and revision of existing models to correspond to what new sensors can measure. Following are typical questions to answer at this level:

- What data are needed to do this sensor-integrated modeling, and how should it be interpreted?
- Where should sensors be located, and at what time and spatial resolution?
- How can real-time information about physical assets inform usage strategies and future design?
- How can assets and sensor-integrated models be future-proofed against changing requirements and shocks?

Furthermore, the quality of data from sensors and monitoring systems changes with time, and potential error propagation due to aging must be quantified. These questions will be answered by new models that focus on (i) data quality and its degradation over time, (ii) survival rates of hardware and software components and the associated error propagation, and (iii) costs of management and maintenance. Any gaps among the formats need to be identified, and good data transfer links are essential. Data linking may produce errors, which need to be quantified for accurate modeling and assessment of infrastructure performance.

Assets

ISO (2014) 55000 standards on asset management highlight the importance of the lifetime management of physical assets and of realizing value rather than minimizing cost. Asset value needs to be determined from a multistakeholder perspective.

Asset owners face a multiperspective challenge that includes balancing cost and risk with decreasing funding and increasing regulation. Building information modeling (BIM) and digital twin techniques that manage design and construction information in a transparent manner can aid in tackling these challenges. Following are some typical questions to answer at this level:

- How must assets be operated, managed, and maintained to deliver their best whole-life value?
- What decisions are needed to support such operation, management, and maintenance? What information is needed to make those decisions?
- What new engineering design, construction, and maintenance processes need to be developed for an integrated adaptive infrastructure system (i.e., system of systems)?
- What kind of institutional objective utility/optimization is needed for asset owners?

Cities and Infrastructure Systems

Changes in physical infrastructure, transportation, utilities, and communications entail some adaptation for citizens. With the use of sensor data to make infrastructure more adaptable and resilient, this layer can reduce or eliminate inefficiencies in the provision of services while maintaining the integrity of city infrastructure systems.

The ideal is that human behavior and infrastructure evolve together to enhance quality of life while supporting vibrant business, trouble-free transportation, and efficient, sustainable use of resources. Following are typical questions for this layer:

- How does infrastructure best serve its communities?
- How will infrastructure change the current spatial-temporal pattern of cities' transportation networks, energy consumption, commercial activities, lifestyles, and environmental quality?
- What will be the cascading effects after a natural hazard?
- What kinds of policies and planning procedures best incentivize change in infrastructure design, construction, and use?

Emerging Technologies for Smart Infrastructure

Emerging technologies empower decision makers. And many new technologies related to materials, sensing, communication, and computing (Soga and Schooling 2016) may be used for smart infrastructure applications (table 1).

To illustrate the maturity of myriad new technologies relevant to smart infrastructure, their current lifecycles are assessed and mapped using the Gartner (2022) Hype Cycle (figure 3). The Gartner chart illustrates five phases of the technology adoption process: the innovation trigger, peak of inflated expectations, trough of disillusionment, slope of enlightenment, and

TABLE 1 Emerging technologies for smart infrastructure

Emerging technologies	Remarks
Distributed sensors and 5G/IoT network (satellite, fiber optics, wireless sensor network, etc.)	Sensors everywhere, hyperconnected networks
Drones, humanoids, and superlarge robots	In-field autonomy (inspection, construction, and maintenance)
Off-site autonomy at submillimeter resolution	3D printing to self-assembly and operation at submillimeter resolution
Building information modeling (BIM) to sociotechnical digital twin	Infrastructure asset tracking, social behavior monitoring, and modeling for digital reflection and extended reality
High-performance computing in the cloud	Multiscale simulations and data interpretation from submillimeter to tens of kilometer scale using quantum computing
Virtual, augmented, and mixed reality	Creation of an immersive environment linked to digital twins using wearable technologies for training and operation under normal and extreme situations
Artificial intelligence and machine learning	Data analytics and human interpretation under normal conditions and extreme situations, leading to discovery of new materials and processes
Edge computing	Local rather than centralized decision making
Ubiquitous and transparent security	Automating trust by blockchain, digital ethics, and service integration
New materials	Zero or negative carbon, self-healing, sensing, and adaptive
Renewable technologies	Energy generation and storage from micro- to megascale

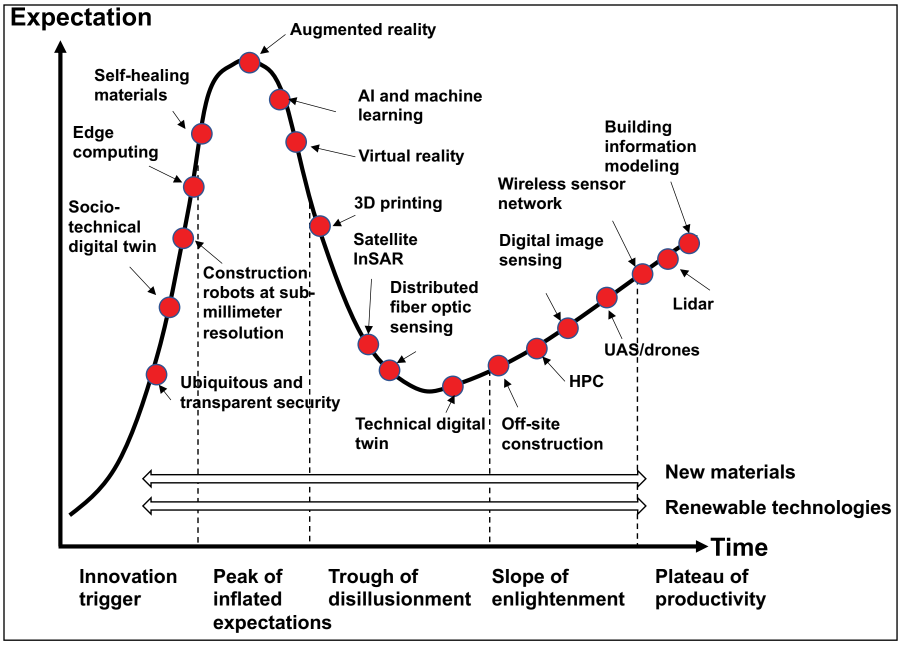


FIGURE 3 Gartner Hype Cycle showing changing expectations of selected emerging technologies over time. AI = artificial intelligence; HPC = high-performance computing; InSAR = interferometric synthetic aperture radar; UAS = unmanned aircraft systems.

plateau of productivity. The vertical axis is a psychological measure of market expectation.

Sensor Systems: Multiple Scales, Autonomy

Integrating structural sensing, environmental sensing, and infrastructure usage can yield significant benefits. For example, the degradation of infrastructure is typically governed by cyclic thermal loading (expansion/contraction), changes in moisture conditions (e.g., humidity, flooding, groundwater pressures), and/or changes in use (e.g., heavier traffic, change in flow volumes and pressures). Integration and communication between long-term value (e.g., structural health, future hazards, degradation) and short-term value (e.g., operation, energy) may provide efficiencies and profoundly shift how infrastructure projects are managed and maintained.

But there is a mismatch between the lifespan of infrastructure and that of sensor and digitized data management systems, which makes the concept of lifecycle-based asset management difficult to realize. Some currently used data may be from older sensors, some sensors may be embedded now but the data will be used in 10, 20, or 50 years. Intelligent sensor and data management systems must be designed for long lifespans or adaptable for replacement.

Smart infrastructure requires a multiscale approach for sensing/monitoring coupled with modeling that uses the data collected. Figure 4 shows the capabilities of satellites, unmanned aerial vehicles (UAVs), and wireless sensors. The point-based wireless sensor networks are hampered by their limited numbers. The risk is that one does not have a sensor where a critical failure occurs.

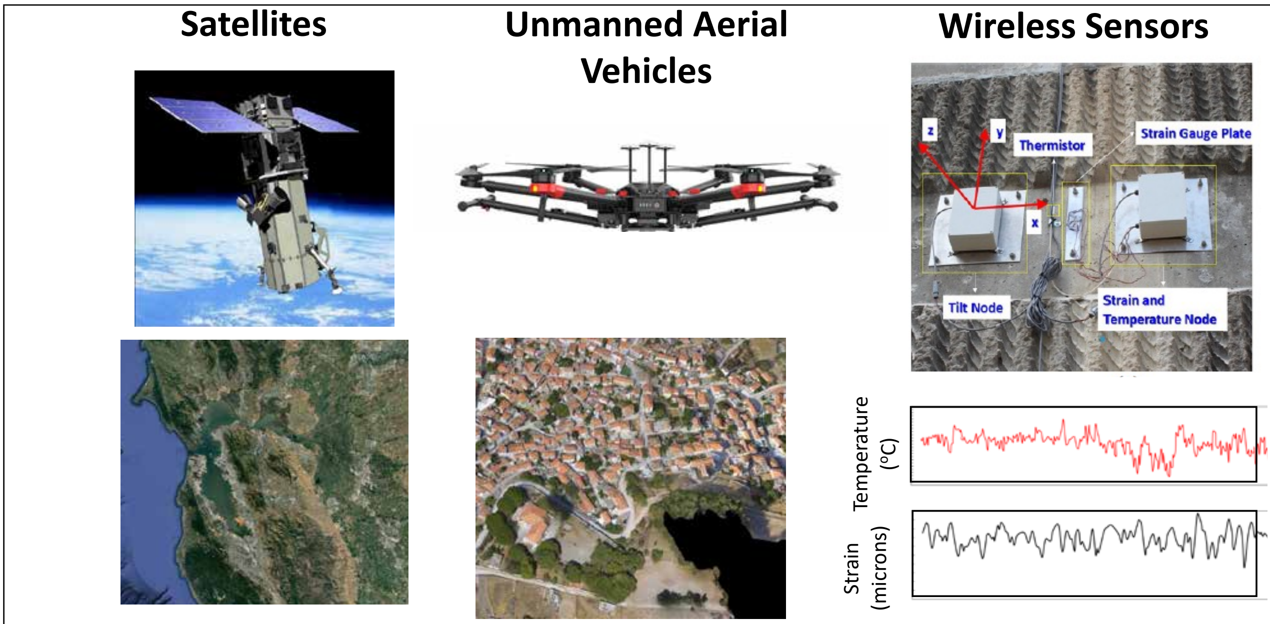
Aerial technologies such as satellite equipment (e.g., optical, InSAR), UAV-based lidar, and photogrammetry are producing point cloud options to measure changes in surface conditions over time, including deformations. The data from these systems can be used to evaluate the performance of an infrastructure system. But these technologies are not yet developed for the simplified user stage and are not commonly integrated with point-based sensors, limiting the value of both.

New larger construction projects often have effective monitoring systems to help manage risks associated with construction, but most of these systems are generally removed or abandoned when construction ends. With guidance for better integration and coordination, some of these large investments could be sustained in lifelong monitoring systems. Automated construction technologies in the framework of a common data environment (CDE) can generate greater amounts of improved (more standardized) data, more economically and without causing extra burden to the limited human resources available.

Autonomy during the operational stage may provide insights into how the built environment is functioning and empower new business models that leverage data to achieve unprecedented efficiencies in infrastructure systems. For example, a traffic analysis service uses in-vehicle navigation apps in smartphones.

Digital Twins: From the Technical to the Sociotechnical

A digital twin (DT) is a digital representation of a physical (infra)structure (Grieves and Vickers 2017). Using simulation, it enables data to be managed and



	Satellites	Unmanned Aerial Vehicles	Wireless Sensors
Coverage	>100 km^2	1-100 km^2	<1 km^2
Data resolution	>0.5 m	>1 cm	local
Data frequency	days	hrs	sec
Sensors	Optical, infrared, radar	Optical, infrared, and more	Wide range

FIGURE 4 Multiscale, multisensing monitoring frameworks for distributed or connected infrastructure systems. Figure prepared by Dimitrios Zekkos of UC Berkeley.

analyzed to, among other things, understand how people interact with infrastructure systems.

Technical Advantages

Digital twins can increase the number of dimensions in BIM beyond 4D (3D + time) with additional performance indicators such as cost, lifecycle and maintenance information, sustainability, and safety (Boje et al. 2020; Ding et al. 2014). They also provide the opportunity for a better understanding of the infrastructure, subsurface, and sensor data through visualization using virtual and augmented reality. And they not only account for both the past performance and present state of the modeled infrastructure, but also are a basis for scenarios to predict likely performance, ensure preparedness, and enhance resiliency.

To advance the ability to simulate natural hazard impacts on structures, lifelines, and communities, the SimCenter,[1] funded by the National Science Foundation and hosted by the University of California, Berkeley, provides next-generation computational modeling and simulation software tools, user support, and educational materials to the natural hazards engineering research community, using a new cloud-enabled open-source framework (Deierlein et al. 2020). Engineering innovation to develop resilient infrastructure was also the focus of the 2019 summer issue of *The Bridge* (O'Rourke 2019).

Sociotechnical Applications

Inequities exist in transportation, housing, urban heat island effects, flooding, energy, and water supply. The transition from existing aging infrastructure to zero-carbon infrastructure must be equitable in the face of growing environmental challenges. These problems cannot be solved without deeply considering the complex socioeconomic and political considerations that impact different communities at different scales.

The definition of infrastructure is expanding, and should include organizational infrastructure (human interactions) and informal infrastructure (unplanned)

[1] https://simcenter.designsafe-ci.org/

in the physical and digital infrastructure framework. The complexity of the social decision processes involved in mobilizing change requires the creative use of DT technologies, such as a sociotechnical digital twin, which integrates models of physical infrastructure systems and virtual networks, including organization, community, and communication networks.

Novel structural designs are required to integrate new materials that can eliminate or capture direct greenhouse gas emissions.

Infrastructure systems need to be examined collectively as an integrated system using theoretical concepts such as system dynamics (Forrester 1969), complex adaptive systems (Holland 1992), and systems of systems (Maier 1998). Collaboration with humanities and social sciences experts is a must.

Artificial Intelligence and Machine Learning

Because the data collected by myriad sensing technologies are extensive, big data approaches are needed to leverage their strength. Machine learning (ML) and artificial intelligence (AI) combined with high-performance computing provide promising techniques to detect trends in high-dimensional data, which was not possible with traditional statistical techniques. This is particularly true for large-scale infrastructure with numerous data channels incorporating multiple measurement parameters, image-based sensing, or other noncontact sensing that generates large datasets. ML/AI can process infrastructure images collected from a drone to find patterns (classification) and anomalies in the surrounding area with relatively high precision. The image dataset can then be combined with other sensing data (e.g., from the structures) to provide a multi-perspective sensing dataset.

Supervised learning is a powerful interpolation tool that can find complex patterns in high-dimensional data without predefined physical laws and assumptions. It may perform poorly, though, in extrapolation problems where the conditions are outside the training boundaries. This constraint may be solved by getting more data and continually expanding the training boundaries. However, this approach is applicable only if there are no catastrophic consequences due to prediction errors—such errors can lead to serious failure and unreliable predictions.

Some models are hampered by overfitting and may perform reliably only within given training boundaries. A model that produces substantial errors due to a lack of generalization (i.e., inability to adapt to new data) or data perturbation (e.g., outliers, noises) cannot be tolerated. This is an important limitation of ML/AI for smart infrastructure applications.

The focus needs to shift from prediction accuracy to prediction reliability by including probabilistic concepts and statistical tools such as bootstrapping and cross-validation.

Materials for Net Zero Carbon Infrastructure

The concept of smart infrastructure should not only include innovations in whole-life sensing and data analytics but also adopt innovations in materials and construction/maintenance processes. Future infrastructure systems must be designed to generate their energy or rely exclusively on renewable energy, realizing a net zero or negative carbon system.

Innovations in self-healing and self-sensing materials have great potential to both extend the life of infrastructure and enhance the resilience of new infrastructure. Novel structural designs are required to integrate the distinct properties of new materials that can eliminate or capture direct greenhouse gas emissions. Methods of modular structural design and construction are needed to enable an adaptable infrastructure that can change with user and technology demands.

With synergistic advances in these areas, future infrastructure systems will not only satisfy immediate needs but also be adaptable to evolving demands throughout their lifetime as part of a circular and net zero carbon economy.

Conclusions

The world is becoming more resource-poor, more connected, and more interdependent. The parameters that affect prosperity are also constantly evolving and spatially variable, contributing to uncertainty about the future. Infrastructure that is adaptable by design must involve the input of communities to enhance understanding of disparities and development of long-term solutions.

Design philosophy has typically focused on current demand prediction, creating a substantial risk that the resulting infrastructure becomes inadequate or obsolete in a few decades (or less). Smart infrastructure can predict, design for, and manage its life expectancy by using emerging technologies such as digital twins, net zero or negative carbon materials, sensors, robotics, and new processes.

Scientific and technological advances make it possible to generate and analyze data about how infrastructure and the environment are used by communities and to develop new ways that are equitable, sustainable, and resilient. Effective engineering service involves listening and responding to the interests and concerns of the people engineers serve. Smart infrastructure in smart cities should embrace this vision and pursue ways to realize it.

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Smart cities represent profound and extensive opportunities to achieve sustainability through IT-enabled supply-demand management of resources.

IT for Sustainable Smart Cities:
A Framework for Resource Management and a Call for Action

Cullen Bash, Ninad Hogade, Dejan Milojicic, and Chandrakant D. Patel

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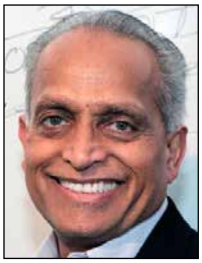

Chandrakant Patel

Sustainability has become a top priority of industry, government, and academia. Efforts to achieve it encompass a range of actions, from reducing energy consumption to mitigating the effects of negative externalities such as climate change (e.g., Smil 2022). Sustainable smart cities are seen as an important opportunity to drive this transformation at scale.

We define smart cities as having automated, to a degree autonomous, infrastructure based on increasing use of data, knowledge discovery, inference, and control (e.g., Founoun and Hayar 2018; Heitlinger et al. 2019; Toh and Milojicic 2021).

Smart cities represent a model for sustainability due to their capacity to continuously adjust to changing factors and optimize parameters to varying

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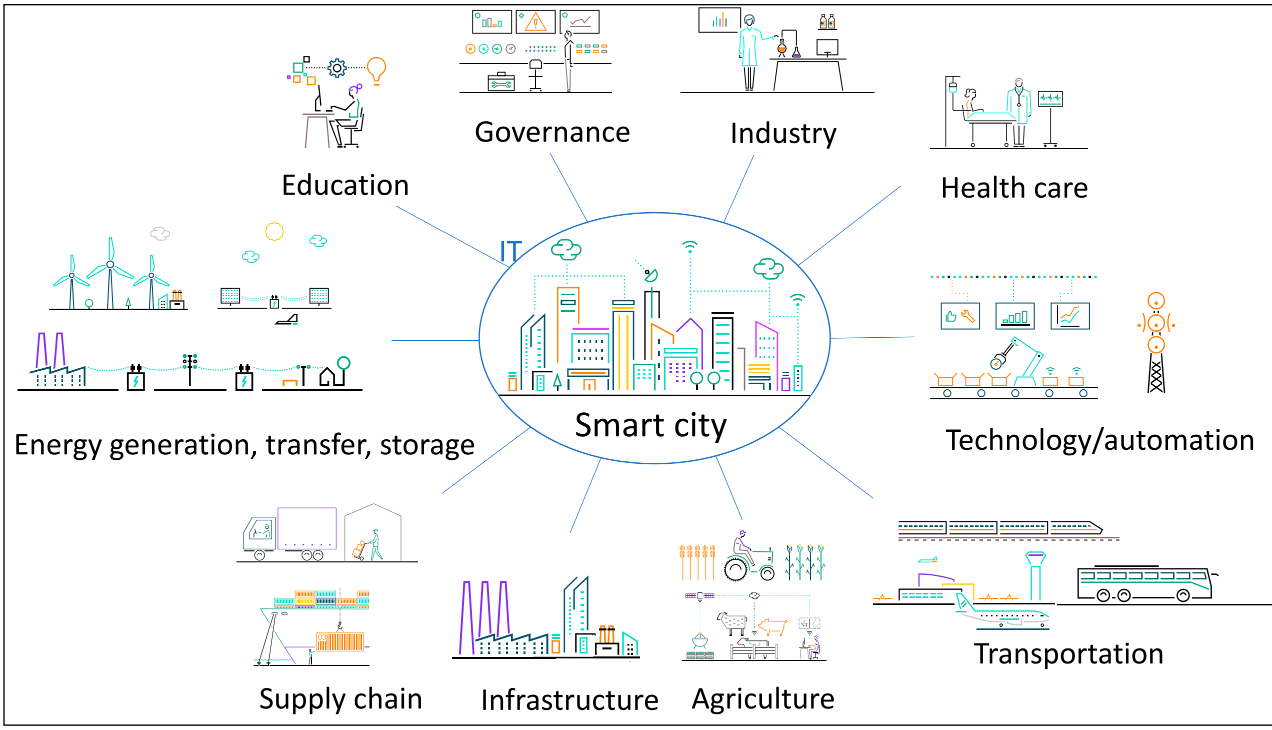

FIGURE 1 Smart city ecosystem.

needs. Integration of information technologies (IT) in city-scale resource management can make cities sustainable through modeling, measuring, and managing to optimally provision resources.

Introduction

Cities have always been at the forefront of technology, and smart cities are the most recent case in point, with IT as the primary enabler.

Cities are centers for goods exchange, typically located near rivers and close to major trade routes for access to critical resources. A city's size drives the supply and demand of all the goods and activities required to keep the city functional: from food and energy to manufacturing and transportation, among other sectors.

Cities also drive advances in the infrastructure around them, by carefully locating agricultural sources for food delivery (e.g., Smil 2019), distributing energy generation for minimizing transfer costs, and building major airports, highways, and ports for goods transfer. Cities are thus part of the much larger ecosystem and value chain (figure 1).

IT has become an integral, ubiquitous part of everyday life (e.g., Santana et al. 2017). What electricity meant in the last century, IT means to humanity today. It drives almost every facet of daily life, spanning the sensors at the edge to cloud computing. High-performance computers play a key role in the analysis and control of city-scale physical infrastructure such as power, water, waste management, and transportation. All these technology solutions require standardized interfaces to enable economical management and interoperability.

In this paper, we focus on how IT makes smart cities sustainable. We list factors influencing smart cities; define the supply-demand framework; present the smart city lifecycle, high-level design, implementation, and management; and conclude with insights and a call for action. We focus primarily on energy and carbon, but similar arguments can be made for other resources.

Factors

Many factors impact the evolution of cities. Some prominent ones are briefly presented here and elaborated in the subsequent sections.

Economic: The availability of resources, especially for energy, and their transportation and supply chains (e.g., Barcelos et al. 2018) are critical for cities, connecting them to global and regional markets. Today such availability entails colocation with electricity resources as well as internet data centers. We focus on sustainability, but a comparable model can be applied to economics, which is an inseparable part of any sustainable solution. Economic underpinnings apply to the whole of this paper.

Ecological: Increasing focus is on the impacts of cities on the Earth, clean energy, water consumption, and global warming. Large data centers such as those required to support smart cities must be evaluated for net zero energy (e.g., Heitlinger et al. 2019).

Technological: The evolution of technology, in particular cyberphysical systems, is core to the very nature of smart cities (e.g., Perera et al. 2017; Santana et al. 2017). Technology solutions incorporate IT advances—for example, in computing, communications, data storage, data management, and data analysis—with physical systems. Technology is the instrument that people can use to achieve sustainable smart cities.

A holistic supply-demand framework can help city planners prioritize the replacement of aging infrastructure with sustainable alternatives.

Sociopolitical: Smart cities are part of their country's political ecosystem (e.g., Poltie et al. 2020). Therefore, regulators are important in enabling technological changes and energy decisions. Sociopolitical implications motivate some of our "calls for action" in the last section of this paper.

In the remaining text, we primarily focus on technological factors, while understanding that they are intrinsically motivated and driven by economic, ecological, and sociopolitical factors.

Urban Supply-Demand Framework

Especially in light of climate change, environmental sustainability is a key driver behind smart cities, and IT is now a key enabler of sustainability. For example, IT services on the demand side include those from both public and private sectors such as ride-sharing, city information delivered through social media, and health and financial services.

We present a holistic supply-demand framework to address sustainability and smart cities. The framework is broad and full implementation may take decades as cities invest on a gradual basis. The call to action is therefore to get started in specific supply-side areas such as power, water, and waste management.

The framework starts with supply-side resources, which we break into city-scale verticals—for power, water, waste management, transport, health care, and recreation, among other areas—overlaid with IT elements to enable supply-demand management. An example of integrated supply-demand is the use of IT to shape power usage by scaling power-consuming devices and by allocating workloads, like manufacturing jobs, to specific devices and turning others off to accommodate supply scarcity.

Lifecycle Metrics

In 2015 the Paris Agreement set the limit on global average temperature rise to 1.5°C from the beginning of the Industrial Revolution, and in 2018 the Intergovernmental Panel on Climate Change set a goal of achieving net zero CO_2eq emissions by 2050 (IPCC 2018; United Nations 2015).

Cities are major users of energy and, as such, are significant sources of carbon emissions. Integrating IT in city infrastructure can improve energy use and carbon emissions, but this integration will necessarily evolve over time through the retrofit of technology in aging infrastructure or the replacement of infrastructure at the end of its useful life.

Decisions about how to prioritize either the retrofit or replacement of infrastructure to improve operational efficiency can be challenging and need to consider embedded resources, like energy and carbon, resulting from the upstream value chain (e.g., manufacturing, transportation) in addition to the use phase of the system. To aid in the decision-making process we propose a metric called *net positive impact* (NPI):

Net positive impact (NPI) =
(Value delivered in energy saved)/
(Available energy consumed over lifetime)

where the numerator quantifies the energy saved through replacement of the existing system and the denominator is the estimated lifetime energy consumed by the replacement system. Note that the numerator includes only use phase energy consumption since the embedded energy is considered a sunk cost.

Leveraging the NPI format, the *net positive carbon impact* (NPI_c) is defined as:

Net positive carbon impact (NPI_c) =
(Value delivered in carbon saved)/
(Carbon emitted over lifetime)

Like NPI, the numerator in NPI_c quantifies the carbon saved from the replacement of legacy infrastructure while the denominator accounts for the projected lifetime carbon emissions of the replacement system. The amount of time it takes for the operation of the replacement system to achieve an NPI_c equal to 1 is termed the *carbon payback period* (CPP).

As an example of how to utilize NPI_c, consider the replacement of a legacy carbon-based energy source with a solar photovoltaic (PV) system. Although no carbon is emitted during the use phase of the PV system, there can be significant embedded carbon from the manufacturing process depending on the energy sources. Depending on the size of the PV system and its operational efficiency, the CPP could be greater than 10 years (Bash et al. 2023). Absent other factors, projects with a shorter CPP coupled with high NPI_c might be prioritized over those with a higher CPP and lower NPI_c. In practice, however, NPI_c and CPP should not be used in isolation. Rather they are part of several deterministic factors that include lifecycle stage (i.e., retrofit vs. replacement), economics, overall environmental benefit and impact (i.e., a net reduction in carbon emissions, environmental damage), and technology readiness.

A variety of energy sources will be necessary for powering the future energy grid. Figure 2 shows the capacity factors (defined as how often a plant runs at full power) for a variety of energy sources. The factors range from 90 percent for nuclear energy generation to 20 percent for solar, accounting for thermodynamic (in-)efficiencies in the various power generation processes (EIA 2022).

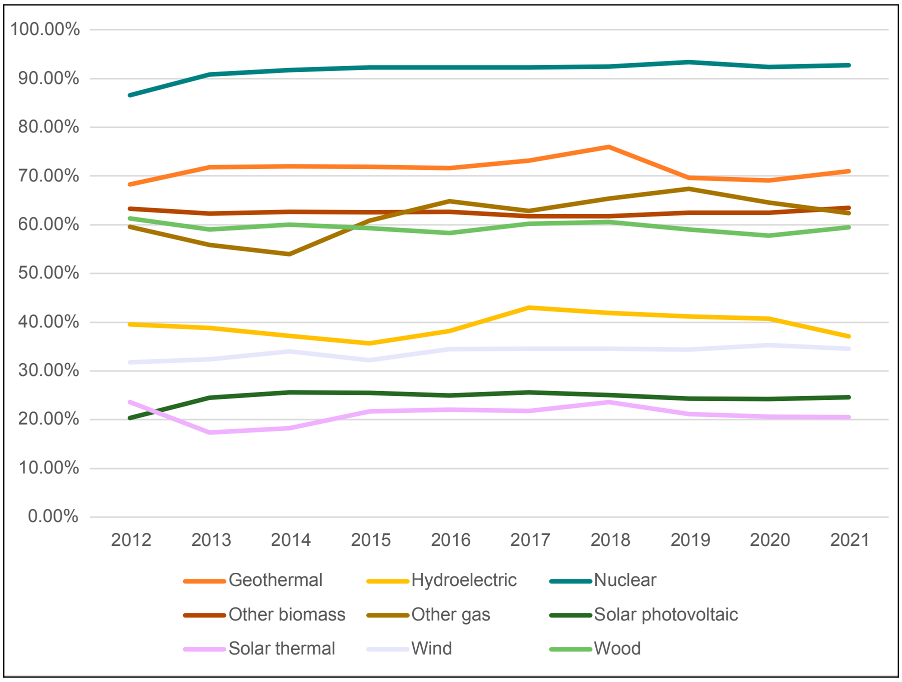

FIGURE 2 Capacity factors (% of fulfillment) for different energy sources (derived from EIA 2022).

These heterogeneous sources present several challenges for their large-scale integration in a city's electric grid. For example, design should integrate the more stable high capacity factor sources like nuclear or natural gas with lower capacity factor renewable sources like PV that are characterized by variable diurnal output. Operational challenges include management to shape the demand given the supply. Demand management is enabled by sensing, communications, and policy.

This is the context in which we see the role of IT and digital technology in accelerating the integration and adoption of sustainable technology and practices at the city scale—achieving high NPI via the addition of sensing management systems to better control resource use in energy systems.

Design and Implementation

Design and implementation must be integrated with management (next section) to form a unified system for an energy-sustainable smart city framework (figure 3).

Lifecycle and Carbon Metrics Analysis

Sustainable cities require a thorough lifecycle analysis to ensure that system design considers the type of energy use (brown vs. green), carbon emissions, and environmental impact. Metrics like NPI and NPI_c can be used

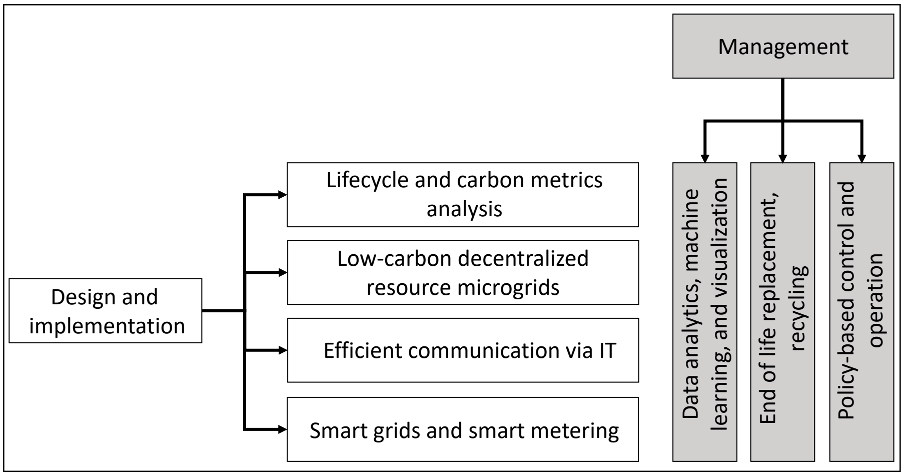

FIGURE 3 Energy-sustainable smart city framework.

to help make retrofit and replacement decisions according to the system's lifecycle stage. As an example, rather than replace an existing system, high NPI_c might be achievable through the addition of sensors and analytics that yield insight into the operation of a system.

Low-Carbon Decentralized Resource Microgrids

Clean or green energy sources such as hydroelectric, PV, solar thermal, biogas, and wind can be an important part of low-carbon energy generation. And zero-energy systems (or buildings), in which the energy both generated and consumed are the same quantity (hence the net consumption can be considered zero) (e.g., Marszal et al. 2011), are made possible through integration with microgrids.

Instead of a centralized production model with large distribution and transmission networks, a more distributed model with local resource microgrids should be considered (e.g., Liu et al. 2018), drawing on multiple local sources, such as rooftop PV cells, hydroelectric power plants, and constructed reservoirs. Such a decentralized resource microgrid model is scalable and modular and makes it possible to configure, upgrade, and add more systems as the city grows.

Efficient Systems Communication via IT

The availability of transmission routes between smart grids, as well as the supply and demand of resources from various geographical regions, can all be determined and managed using an efficient communication infrastructure, which can also provide information such as resource-specific operational characteristics, performance, and sustainability metrics.

The information and communication infrastructure, which gathers data on energy consumption and disseminates information about provider rates, underpins the framework for an energy-sustainable smart city. For smart appliances like dishwashers and water heaters, IT can be used to control operations with the right level of energy consumption. It can also be used to buy energy from a variety of sources, including wind turbines, solar farms, and brown energy generation systems.

Smart Grids and Smart Metering

Smart grids efficiently integrate the actions and behaviors of all connected consumers and generators as well as various energy sources, from fossil fuel–based thermal energy to PV and wind (e.g., Gao et al. 2012). They use IT to assist with demand-response energy management, schedule power generation for various electricity generation plants, and manage dynamic interaction between plug-in electric vehicles and the power grid.

Smart energy metering records electricity consumption at predetermined intervals and transmits the data to the utility for billing and monitoring (e.g., Kabalci 2016). This facilitates accurate reading of use without human involvement.

In these ways smart grids guarantee reliable, cost-effective, and sustainable energy systems with low levels of loss, and improved safety, security, and fault tolerance.

Management

Data Analytics, Machine Learning, and Visualization

To change the operational state of the systems toward least energy operations, sophisticated data analytics and machine learning techniques can be applied to streaming and archival data to identify patterns and predict trends. Data analytics can be used to build models for fault detection, optimization, and control. Data can be visualized and high-level indicators of the health of each energy system can be monitored.

End-of-Life Replacement, Recycling

End-of-life replacement decisions include when to replace older systems to improve NPI or NPI_c. Recycling policies can be proposed to reduce the carbon footprint of a system or product.

Policy-based Control and Operation

Policy-based control and operating systems can be devised to promote efficient energy management, achieve sustainability goals (e.g., selection of green energy resources, increased NPI_c), and maximize the use of power from renewable resources and thus drive to net zero.

As an example, given a sustainability policy, if an onsite PV solar farm at a manufacturing factory generates more energy than required, it can sell the excess energy back to a smart grid (utility company) and help balance the demand and supply of electricity/workload (e.g., Hogade et al. 2018). And the sustainability policy at the same manufacturing plant may allocate certain demand-side fabrication workloads based on local solar power alone.

Insights

The ability to achieve sustainable smart cities requires configurable design and implementation using digital technologies to *integrate supply-demand management* that shapes demand commensurate with supply. For example, in IT-enabled digital factories built with 3D printers, workload allocation and execution profiles can be shaped based on supply-side power from the microgrid (Patel 2020). In all cases, solutions are substantially more manageable when applied to specific city-scale verticals (shown in figure 4).

Next, we advocate that *industrial applications be holistically instrumented* using operational technologies (OT) that interface with cyberphysical systems, are managed and secured through supply chain integration, and are protected using IT that interfaces with digital systems. This would guarantee reliable and regulated supplies from trusted and sustainable (ecologically, economically, politically, and socially) sources. The use of loosely integrated OT/IT workflows will be a basis for automation.

The complexity of our vision will not be possible to realize with traditional management techniques. *AI-based operations will be required to supplement autonomous solutions* to enable anomaly detection and a subtle yet vital combination of full autonomy with just enough human engagement to avoid damaging bugs, attacks, and oversights (e.g., Dang et al. 2019; Laplante et al. 2020; Serebryakov et al. 2021).

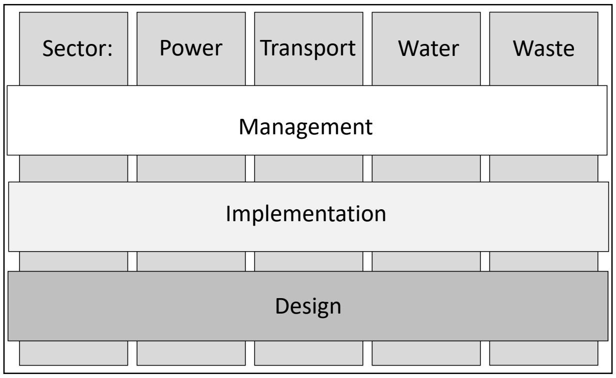

FIGURE 4 Smart city sustainability framework.

To augment our vision and increase confidence in smart cities, *a combination of simulations*—including digital twins (virtual functional representations of physical systems)—will be needed. *Connected with the city's instrumented critical infrastructure and inputs/outputs*, such simulations will enable scenario testing, what-if analysis, planning, and prediction for both regular operations and upgrades to the ecosystem. This is critical for catastrophic situations such as pandemics, earthquakes, tsunamis, wars, and other disasters. IT is a key enabler to make smart cities much more resilient under devastating circumstances, when human attention is diverted to survival.

In a smart city, cybersecurity will become cyber-physical security. *A holistic approach that applies learning from cybersecurity models* will prevent bad actors from harming critical supply-side systems such as pumps, motors, turbines, and other equipment. Crippling attacks on power stations could be at least attenuated if not prevented using cyberphysical security.

Finally, with significantly more automation and autonomy than today's cities, smart cities will require *human capital with expertise spanning IT, sustainability, and the vertical resource domains* shown in figure 5 to operate effectively.

Call for Action

Many revolutionary technologies will directly influence the evolution of sustainable smart cities (figure 5), in layers of devices, interfaces, networks, software, applications, and markets. Each layer can make a huge difference.

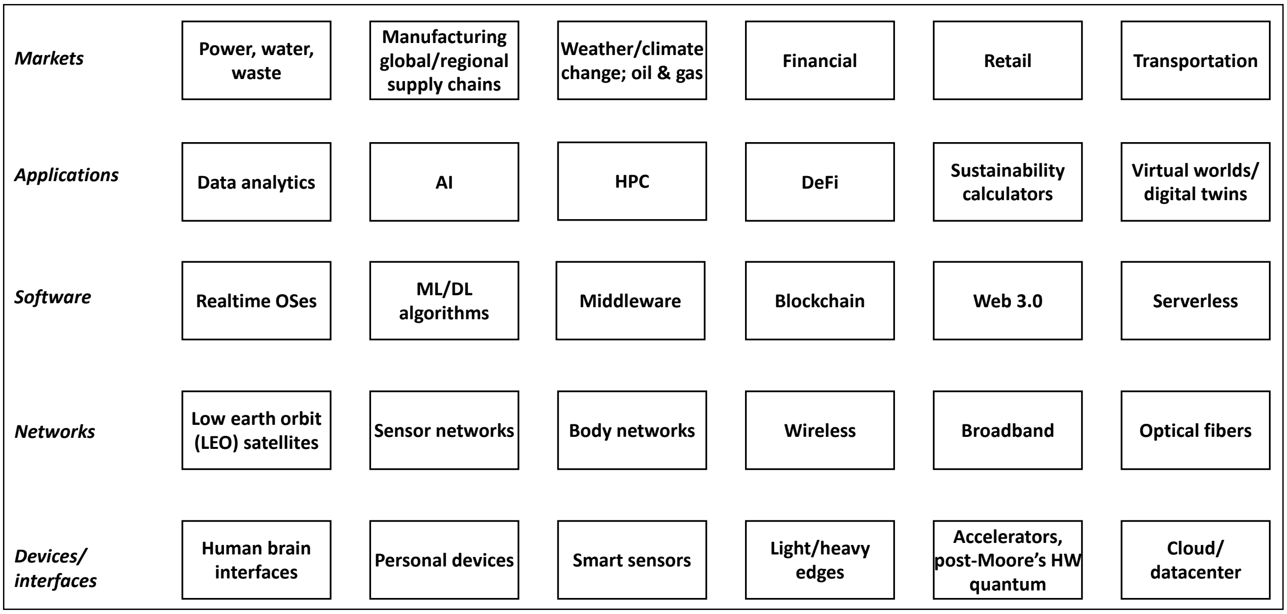

FIGURE 5 Landscape of technologies that will influence smart city evolution. AI = artificial intelligence; DeFi = decentralized finance; DL = deep learning; HPC = high-performance computing; HW = hardware; ML = machine learning; OS = operating system.

But technology alone is not sufficient. For smart cities to be successful, governments, industry, and academia need to take a holistic view that integrates energy, water, climate, carbon emissions, and other critical factors at the city, regional, and global ecosystem levels. To that end, action is needed for the following:

- *Governments:* Distributed energy resources require *regulations* to ensure the safest impacts for climate, carbon emissions, water, energy consumption, and other areas. This needs to be done transparently in attributing and accounting for resources for near- and long-term consumption.
- *Industry:* Smart cities require the introduction and adoption of *standardized and application programming interfaces* to optimize resource management. End-to-end management and regulatory compliance-based rebalancing of resources will require increased automation, analytics, cybersecurity, and the use of AI.
- *Industry:* The lifecycle impact of a city's infrastructure systems needs to be considered when making retrofit or replacement decisions. Metrics like NPI can help guide such decision making as well as effective diversification of systems for risk management. Metrics are also crucial for informing policies for economic, ecological, and social trade-offs and for projections and what-if analysis for long-term resource supply and demand.
- *Academia: Students need to learn about cyberphysical systems* and their integration with IT, OT, and AI. While automation and AI techniques will lead to increased autonomous solutions, engineers will need to profoundly understand the underlying technologies and be able to continuously elevate them to the next levels of efficiency and sustainability.

Smart cities, through the careful integration and management of technology in the overall ecosystem, will enable sustainability. Technological innovations, together with the items in our Call for Action, will make possible this vision, indeed this inevitable evolution.

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Advanced materials and intelligent technologies are enabling urban structures that are as resilient, flexible, aware, and self-healing as the human body.

Developing Humanoid Architectural Structures for a Resilient City

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Min Zhu

Urban resilience has been defined as "the measurable ability of any urban system, with its inhabitants, to maintain continuity through all shocks and stresses, while positively adapting and transforming toward sustainability."[1] The concept aims to ensure a safe environment for city dwellers, with architectural structures that can endure disasters and recover quickly.

A humanoid architectural structure (HAS) synergizes advanced materials, structure, intelligent technology, and real-time holographic sensing and warnings to support such a safe urban environment and contribute to urban resilience. The following "human" characteristics distinguish this new resil-

[1] UN-Habitat, What Is Urban Resilience?, https://unhabitat.org/topic/resilience-and-risk-reduction

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ient construction: a robust and restorable "body" with powerful and flexible capacities for external load resistance, self-healing, and self-resetting; acute "sensory" perception, enabled by ubiquitous and wide-area self-sensing; an "intelligent brain" with the ability to self-diagnose, make decisions, and learn; and strong "immunity" (i.e., self-protective capability) (figure 1).

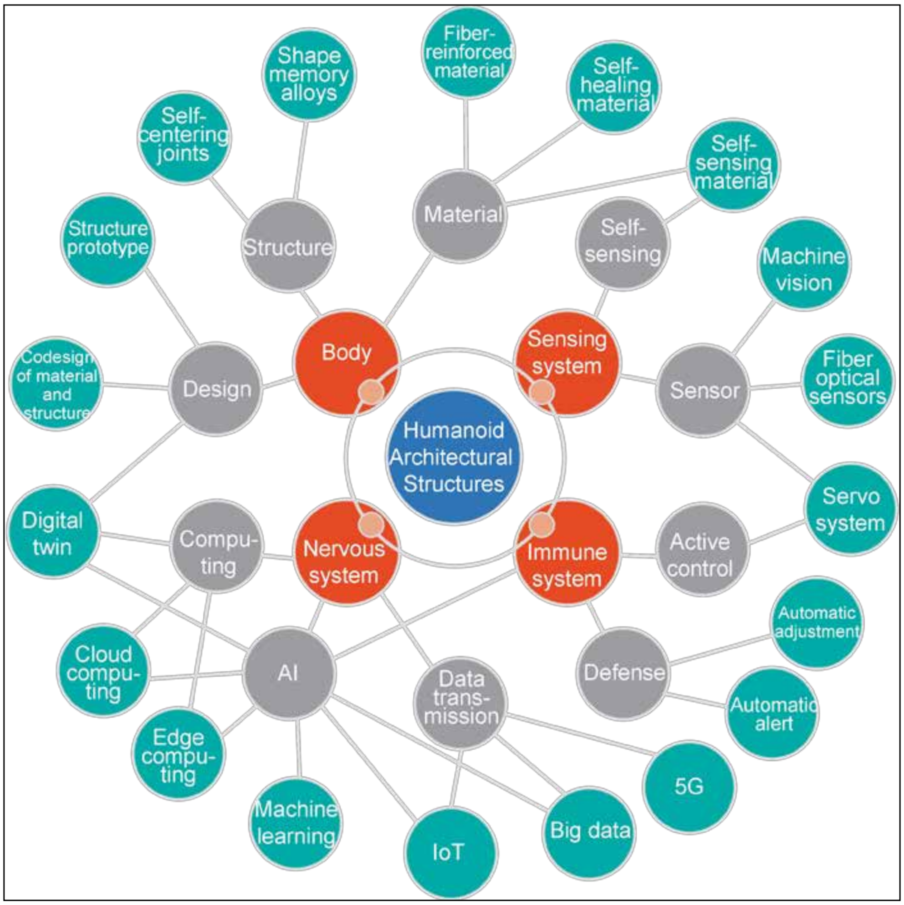

FIGURE 1 Knowledge graph of humanoid architectural structures. AI = artificial intelligence; IoT = Internet of Things.

Robust and Restorable Body

Materials and structural engineering research developments enable a physically robust HAS body, and a novel design paradigm integrating material and structure has economic advantages. High-performance fiber-reinforced cement-based composites—such as steel, carbon, ultrastrong tensile botany (Tang et al. 2021), and two-dimensional polymeric fibers (Zeng et al. 2022)—exhibit superior mechanical properties and aging resistance, and they are gaining traction as potential applications in complex and harsh catastrophic environments.

When using such novel materials for structural design, the evolution of structure modes (e.g., deformation, damage, and destruction) and critical state health threshold values can be determined by developing a digital twin (DT) (Tao et al. 2019). Use of a DT facilitates alteration and optimization of material characteristics (e.g., quantity and kind of fibers in different positions) and/or structural style through scenario simulations and iterative computation. A significant advantage of the digital twin is that designers may quickly assess and forecast the behavior of structures without conducting extensive research.

Another essential feature of the HAS body is its restorative ability. Self-healing technology for concrete is being researched in depth. When tiny cracks or holes in the material occur, self-healing is activated through autonomous or autogenic forms, using either a substance released via internal premade microcapsules or hydration with microorganisms (e.g., bacilli, fungi) that can create calcium carbonate to fill microscopic cracks (Brasileiro et al. 2021).

Several novel and more efficient self-healing techniques have been inspired by some biochemical reactions in cells. For example, the enzyme carbonic anhydrase, which is found in red blood cells, catalyzes the reaction between Ca^{2+} ions and atmospheric CO_2 to create calcium carbonate crystals, healing millimeter-scale cracks within 24 hours (Rosewitz et al. 2021). And shape memory alloys and self-centering joints are being studied to enable conversion of a rigid structure to a flexible one and thus increase seismic performance in terms of both rapid deformation recovery and energy consumption (Movaghati and Abdelnaby 2021).

In cases of extreme damage or destruction, these technologies will help extend the life of an architectural structure. However, they are insufficient for all circumstances, so HAS needs advanced capabilities for sensing, diagnosing, decision making, response, and learning.

Acute Sensing System

The next generation of technology in construction and maintenance is characterized by the fusion technologies of Internet of Things (IoT)–based sensors and terminals, edge computing, cloud computing, and 5G wireless technology (Dai et al. 2020). These technologies, when used, for example, in underground construction equipment (e.g., a shield machine), enable automated operation and the rapid synthesis of smart-monitored information (Armaghani and Azizi 2021). Multielement information—about construction activities, subsurface disturbance, ground movement, water level change, and potential impacts of multisource disasters—is monitored using reliable IoT sensors such as microelectromechanical systems, fiber-optic sensors, and machine vision, all of which are low-power, low-cost, wireless, and autonomous.

Disasters can be efficiently managed by a system's integrated capacity for sensing, diagnosis, decision making, response, and learning.

For operation and maintenance, holographic sensing provides a function comparable to human sensory organs. Ubiquitous wireless sensors embedded in architectural structures can detect stress, strain, cracks, temperature, humidity, and even ionic concentration with high accuracy (Sofi et al. 2022). In addition, materials such as sensing skins (based on electrical capacitance) and self-sensing concrete (based on electrical resistance) are highly anticipated (Bekzhanova et al. 2021). In particular, sensing skins, such as printable conductive polymer and soft elastomeric capacitive sensors, are being studied for 3D printing on the surface of architectural structures (Laflamme and Ubertini 2020). They could convert stress, strain, and cracks into measurable or observable changes via an electric signal.

The Smart Brain and Nervous System

Massive data collected by advanced sensors and actuators in the IoT reveal quantitative variation in structures and circumstances. Data from holographic sensing are used both to construct a knowledge graph in the HAS brain and to analyze and update the DT model.

Cloud computing is a well-established paradigm for the "brain," but colossal data, photos, and videos create a significant transfer and computation burden on the limited-capacity internet and even the cloud. Fifth-generation (5G) wireless technology is a good alternative to improve massive data transfer efficiency (Eid et al. 2021).

The cloud computing platform will be decentralized and replaced by distributed edge computing (near the end of IoT nodes) to reduce information delay (Fraga-Lamas et al. 2021; Ren et al. 2019). Microcomputers at the edge will evaluate structural mode data in real time (Chen 2018) and provide early warning with analysis and diagnosis. In the event of an emergency, the actuators or triggers will receive immediate autonomously generated commands from the microcomputers (Bai and Scholl 2021). Subsequently, big data streams from the edge will aid in dynamic interaction between the cyber and physical worlds at the cloud layer. DT models will be updated to measure bearing capacity, evaluate resilience, predict imminent mode variation, and perform necessary repairs or replacements in the cyber world to serve as a reference for actual repairs (Jiang et al. 2021).

Artificial intelligence (AI) in support of the IoT and big data can be used to enhance decision making about infrastructure maintenance (Zhu et al. 2020). Machine learning (ML) algorithms are critical to AI, whose applications range from robotics and computer vision to autonomous vehicle control and neuroscience research (Jordan and Mitchell 2015). Supervised learning, one type of ML, is used for the detection of infrastructure cracks based on computer vision technology.

Deep learning, part of a broader family of ML algorithms, is normally underpinned by artificial neural networks (ANN). A big data center linked with ANN (through a website, software, and mobile app) is required for effective data processing and analysis. The center should be highly integrated and provide relatively high availability, cost savings, and strong adaptability. Such a center can automatically respond through ANN programmed and assigned to DT model components (Huang et al. 2021).

Machine learning based on optical neural networks (the physical implementation of ANN with optical components) could aid in systematic analysis from multiple perspectives, dimensions, and granularities. It can thus be used to predict variation of structure modes and circumstances, and create knowledge for scenario innovation (Wang et al. 2022).

In summary, AI technologies can enable automated solutions and support decision making and policies for infrastructure maintenance to produce a "nervous system" with the collaborative integration of local and global computing.

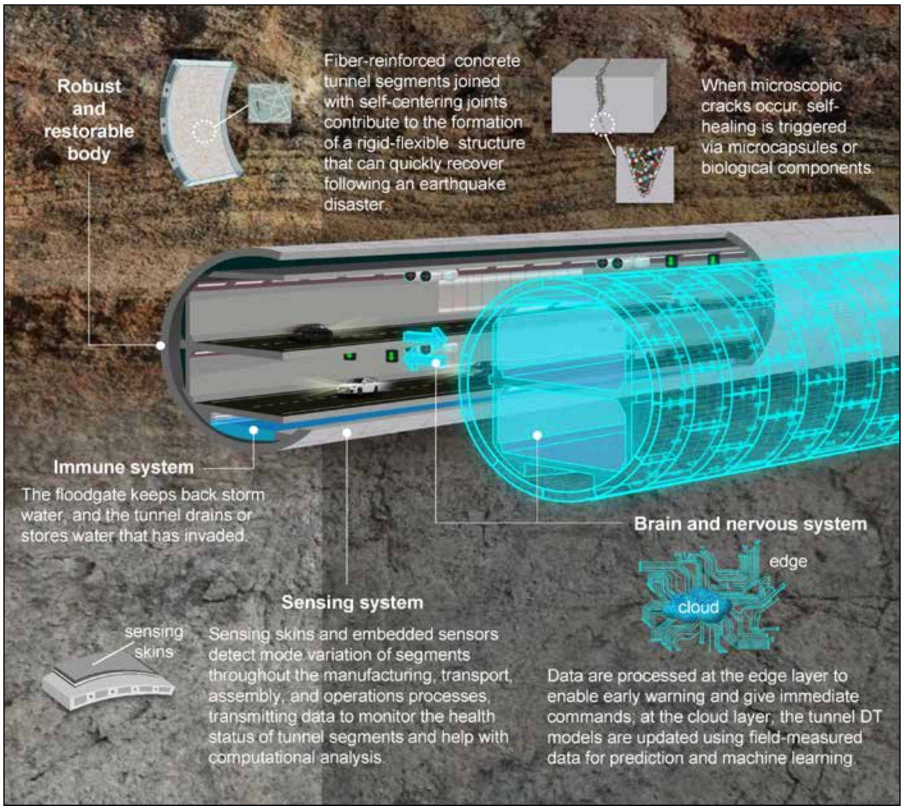

FIGURE 2 Humanoid shield tunnel structure.

Immune System

Humanoid architectural structures have extraordinary self-defense capacities, similar to the human immune system based on the sensing and nervous systems. For example, a servo system has been used to reduce lateral deformation of the retaining structure during foundation pit excavation, and it can be used in architectural structures to control deformation and settlement. Force and displacement are continuously monitored using pressure sensors and ultrasonic displacement sensors. The system compensates automatically as soon as it detects that the force is less than the designed value, and automatically reduces the force if it is higher. An alert is triggered if the monitoring data exceed the warning range.

In the event of a disaster such as a flood, if a sensor detects stagnant water at a certain level, automated floodgates will be activated promptly and water that has entered an underground space will be directed to drainage or storage. Other calamities, such as a poison gas leak, fire, or explosion, can be efficiently managed by the system's integrated capacity for sensing, diagnosis, decision making, response, and learning.

Putting It All Together

Infrastructure construction and operation can benefit from the advanced materials, structure, and HAS intelligent technology. Figure 2 shows an underground shield tunnel with rigid-flexible structures and high-performance, self-healing materials that improve robustness and restorability. With sensing, nervous, and immune systems, the tunnel is capable of self-diagnosis, decision making, response, and learning.

Areas of Needed Progress

Significant efforts are needed in a variety of areas:

- Upgrades: Hardware and software both need to be significantly enhanced, based on research and development of new materials with higher performance, new structural forms, new long-life sensors, an intelligent structural system, and the establishment of design theory.
- Digitization and data flow: These are needed to realize real-time multisource heterogeneous data capture and linkage with physical space to achieve

bidirectional mapping, dynamic blending, and real-time coupling.

- Cognification[2]: Intelligent control and learning evolution rely on explicit knowledge that can provide human-understandable explanations to learning results (Omran et al. 2019), programming and software based on knowledge graphs, and cloud computing and machine learning based on next-generation neural network algorithms.
- Integration: Multiple elements combine with and integrate innovation, during which HAS components are assembled and debugged. Interdisciplinary technologies, such as those spanning civil engineering, next-generation IT, microelectronics, measurement, and control, among others, should be prioritized.

Conclusion

Humanoid architectural structures, endowed with the advanced technologies of digital twins, the IoT, big data, and AI, will be able to monitor themselves, provide early warning of potential risks, and withstand external disturbance using automatic and smart immune systems for risk mitigation. They will enable urban buildings and infrastructure for various systems to sense external disturbances through different smart sensors (like human senses). Information and communication technologies that mimic the human nervous system transmit and integrate all sensor information, while big data centers and AI, acting as the brain, process multisource signals. High-performance materials and the flexible structure of infrastructures (comparable to the human skeleton and muscles) actively protect against infrastructure disasters and failures. The performance of city infrastructures will thus change from passive to reactive and then to proactive.

Although some HAS components, such as the digital twin, are nearing application maturity, the vast majority, including self-sensing materials and optical neural networks, remain in the research stage. With continued development and improvements in materials research and structural design, it will be possible to scale the HAS economically and technically.

We expect that the integration of HAS features in buildings, underground infrastructures, bridges, avenues, and other constructions that serve human habitation can be achieved within one or two decades. Humanoid architectural structure has the potential to revolutionize infrastructure and make a city more resilient and secure during its entire lifespan.

Acknowledgments

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VICAD can enable safer, more comfortable, more energy-efficient, and more environmentally friendly driving in smart cities.

Smart Infrastructure for Autonomous Driving in Urban Areas

Guyue Zhou, Guobin Shang, and Ya-Qin Zhang

Guyue Zhou

Guobin Shang

Ya-Qin Zhang

Autonomous driving (AD) is recognized as a core technology to advance the transportation paradigm shift.[1] Studies have shown that, in the United States, AD may not only reduce up to 94 percent of traffic fatalities by eliminating accidents that are due to human error (NHTSA 2015) but also free up 50 minutes each day per driver (NHTSA 2020). It also has the potential to create a new $1.5 trillion industry by 2030 (Gao et al. 2016).

Recent work in vehicle-infrastructure cooperative autonomous driving (VICAD) significantly augments the capability and effectiveness of AD

[1] We use AD to refer to automated vehicles that do not communicate with pedestrians, other vehicles, roads and traffic, or the cloud.

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through close coordination with pedestrians, other vehicles, roads and traffic, and the cloud (AIR and Baidu 2021).

In this article we discuss VICAD's advantages and challenges to help make autonomous driving a reality with large-scale economic deployment.

Introduction

The automotive and transportation industry will undergo a tectonic shift in the next decade with advances in connectivity, automation, sharing, and electrification. Autonomous driving presents a historic opportunity to transform the academic, technological, and industrial landscape through advanced sensing and actuation, high-definition mapping, new machine learning algorithms, and smart planning and control.

The international Society of Automotive Engineering (SAE 2016) defines levels of autonomy from none (Level 0) to full (Level 5). While significant progress has been made in R&D to support autonomous driving, high-level (Level 4+) AD road testing and commercial trials, led by China and the United States, show that there remain technical challenges and policy issues to expand this capability on urban streets.

Since the US Department of Transportation initiated the Vehicle Infrastructure Integration (VII) program in 2003 (renamed IntelliDrive in 2009) to improve safety, mobility, and convenience (US DOT 2010), other countries and regions—such as Japan (Strategic Headquarters 2013), China (State Council of PRC 2015), and Europe (ERTRAC 2022)—have made remarkable progress on VICAD deployment. As AD decreases its marginal revenue while solving long-tail problems, VICAD will be the most likely scenario in the future.

AD mainly relies on vehicles' on-board sensors, computing power, and drive-by-wire systems for environmental perception, intelligent decision making, and control. VICAD goes a step further, integrating smart vehicles with pedestrians' IoT devices (e.g., smartphones, smartwatches), roadside sensors, cloud-based data and computing, and other connected equipment that provides effective information for autonomous operation. With a much broader array of spatial sensing sources for perception, access to temporal/historical information for decision making, and the capacity to coordinate multiple transportation participants, VICAD is capable of more reliable perception to make smarter decisions in real time and to enable collaborative operation among multimodal transportation participants. VICAD can enable safer, more comfortable, more energy-efficient, and more environmentally friendly driving, playing a significant role in the transportation system for modern smart cities.

In this article we briefly describe the state of VICAD and explain how it improves on AD's capacities in driving safety, operational design domain, and traffic efficiency. We point out challenges to VICAD's continued progress and suggest next steps.

VICAD Stages of Implementation

In 2019 the government of China announced the development of VICAD (CHTS 2019). A subsequent white paper (AIR and Baidu 2021, published by Tsinghua University)[2] summarized VICAD's development in three stages (figure 1), considering technical maturity and passenger understanding of collaborative functions.

In the stage of collaborative information interaction (stage 1), on-board units (OBUs) communicate with roadside units (RSUs) to exchange information (e.g., traffic light status) between vehicles and roads with either dedicated short-range communications or cellular vehicle-to-everything.

As AD decreases its marginal revenue while solving long-tail problems, VICAD will be the most likely scenario in the future.

In the stage of collaborative perception (stage 2), with the rapid growth of roadside perception capability, smart roads can be either a complementary source of information (e.g., for blind spots of on-board sensors) or a redundant source (e.g., for low-height obstacles). For different grades of maturity, collaborative perception is further classified as primary (stage 2-1) or advanced (stage 2-2). The latter is required to support Level 4 AD (i.e., VICAD) with enhanced coverage density, sensor diversity, inspection accuracy, and positioning precision.

In stage 3, collaborative decision and control, the smart road can make some decisions and exercise

[2] The updated Chinese and English version will be published in March 2023.

FIGURE 1 Three stages of vehicle-infrastructure coordinated autonomous driving: (1) collaborative information interaction – sensors manage traffic flow and vehicles show drivers and passengers transmitted data (e.g., waiting time at traffic lights); (2) collaborative perception – vehicles gather sensor data (e.g., from roadway cameras) to enhance awareness and safety; and (3) collaborative decision and control – vehicles execute command data (e.g., to make way for an ambulance) to collaborate with adjacent vehicles. Prepared by AIR and Baidu.

limited control of moving vehicles (e.g., to ensure mandatory yielding to an ambulance) within a defined scope of authority. Before open roads qualify for collaborative decision and control (stage 3-2), a transitional stage (stage 3-1) authorizes designated smart roads with conditional implementation in AD-only (e.g., AD-exclusive lanes) or enclosed (e.g., parking lots) areas.

For real-world deployment, the major development stage of VICAD is upgrading from stage 1 to 2-1. In the United States, industry leaders are taking steps to adapt to VICAD and have articulated roadway needs for AD vehicles. Trials have been conducted in California, Arizona, and other states (Toh et al. 2020), and the Michigan Department of Transportation (MDOT 2020) is working with Cavnue to develop a corridor with smart infrastructure to support driving automation between Detroit and Ann Arbor.

In China several large cities have established VICAD test sites to facilitate R&D, policy formulation, and research (BICMI 2022). In 2020 the Beijing High-level Automated Driving Demonstration Area (BJHAD), built in Yizhuang, became the world's first high-level VICAD-based demonstration area (figure 2). Within BJHAD's 60 km^2, there are 332 intersections fully covered by smart infrastructure and more than 300 high-level autonomous vehicles for taxi service and open road tests.

Driving Safety

According to statistics of the World Health Organization, around 1.3 million people lose their lives each year due to road traffic accidents.[3] A United Nations General Assembly resolution calls for halving the global number of traffic casualties by 2030.[4] Given AD's algorithmic complexity, driving safety tops the research topic list in transportation (Toh et al. 2020) and is the most critical factor hindering AD's large-scale deployment.

To enhance AD safety, the International Organization for Standardization (ISO 2019) proposed a "safety of the intended functionality" (SOTIF) framework to reduce risks from both systemic and random hardware failures for AD vehicles. A SOTIF scenario presents environmental and traffic conditions, including how the AD vehicle responds (e.g., emergency braking

[3] WHO, Road traffic injuries, https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries

[4] UN General Assembly resolution A/RES/74/299 on Improving Global Road Safety, 2020, https://digitallibrary.un.org/record/3879711?ln=en

ahead, traffic lights, a person or animal crossing the road). Scenarios are categorized as known safe, known unsafe, unknown safe, or unknown unsafe.

With stage 2 VICAD, collaborative perception enhances AD in blind spots and sensor failure (e.g., camera-obstructed) conditions. This capacity transforms unknown into known SOTIF scenarios. Moreover, with stage 3 VICAD, collaborative decision making and control can be used to determine the right of way for AD in multivehicle interactions and unexpected road conditions (e.g., road construction, traffic accident). This too may transform unsafe scenarios into safe ones in SOTIF.

For safety reasons, it is not realistic to conduct large-scale real-world experiments to evaluate the safety benefits of different AD strategies. A high-fidelity simulator is therefore essential to analyze SOTIF systematically and quantitatively. Table 1 presents the comparative experimental results of AD and VICAD based on a digital approximation of typical traffic scenarios in BJHAD (AIR and Baidu 2021). The results show that VICAD significantly improves driving safety in high-dynamic scenarios.

Operational Design Domain

The operational design domain (ODD) defines all conceivable individual and overlapping conditions, use cases, restrictions, and scenarios that an AD vehicle might encounter (US DOT 2016). A vehicle's level of automation depends on not only the AD level but also the ODD in which the AD is capable of operating.

VICAD can help expand the AD ODD with additional information acquired from other connected nodes (e.g., pedestrians, roads, cloud servers) and external control commands from authorized remote controllers (e.g., an emergency vehicle, temporary RSU guidance, cloud-based drivers).

We offer an illustration of the effectiveness of VICAD implementation based on the work of Baidu, an enterprise with the largest number of AD test vehicles and the highest AD test mileage annually in Beijing (BICMI 2021). Figure 3 shows typical AD failure cases, which can be easily resolved when VICAD draws from online observations (i.e., based on networked sensors), offline knowledge, and even human intelligence.

From the spatial perspective, VICAD can offer additional information as a vehicle's second viewpoint. Despite rapid progress in AD perception, visibility can still be compromised or reduced in long-range or occluded areas (1st column, figure 3).

FIGURE 2 City-level platform for vehicle-infrastructure coordinated autonomous driving (VICAD) illustrated for the Beijing High-level Automated Driving Demonstration Area (BJHAD).

TABLE 1 Results of safety experiments based on a digital approximation of typical traffic safety risk scenarios in the Beijing High-level Automated Driving Demonstration Area.

Scenario	Vehicle collision rate	
	AD	VICAD
BVLOS following	2.1×10^{-5}	1.3×10^{-5}
Lane change conflict	1.2×10^{-4}	1.8×10^{-5}
Pedestrian from blind spot	3.3×10^{-5}	3.0×10^{-6}
Unprotected left turn	3.1×10^{-5}	1.0×10^{-5}
Abnormal obstacles	5.3×10^{-5}	1.1×10^{-5}

Note: Calculations based on probability distributions of statistically determined scenario parameters. AD = autonomous driving; BVLOS = beyond visual line of sight; VICAD = vehicle-infrastructure coordinated autonomous driving

VICAD can record and transmit historical traffic data, such as the successful strategies of other vehicles, to an autonomous vehicle whose path is blocked (2nd column, figure 3), thereby enhancing AV perception and decision making.

In addition, VICAD can download driving-related data from cloud servers. Thanks to road anomaly information uploaded by either smart roads or human

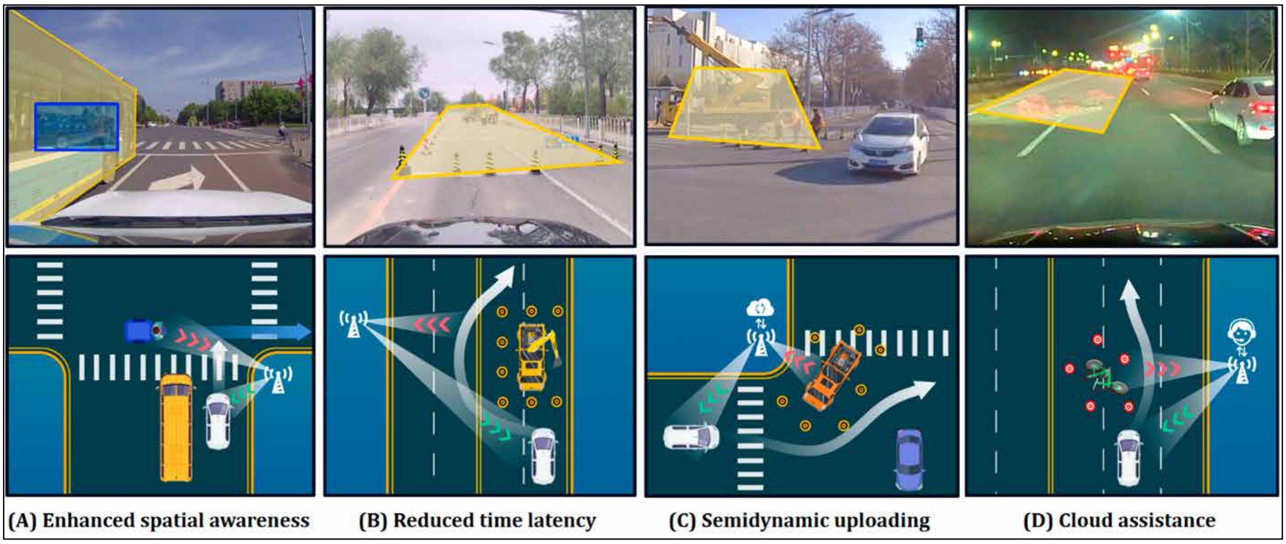

FIGURE 3 Typical autonomous driving failure cases, which can be easily solved with vehicle-infrastructure coordinated autonomous driving (VICAD). Superimposed yellow areas in the top row of images denote unexpected obstructions—a large vehicle blocking view, construction work in the roadway or intersection, an accident—that may interfere with driver awareness and AD sensing and decision making. **(A)** As an unobservable vehicle approaches, hidden by the bus (top), VICAD enhances spatial awareness through a roadside camera. **(B)** Coming upon a temporary detour (top), VICAD reduces time latency by accounting for the trajectories of passing vehicles. **(C)** Upon encountering construction work in an intersection (top), VICAD uploads semidynamic traffic information from the cloud and replans a safe trajectory. **(D)** Destroyed road conditions (top) are abnormal for AI algorithms; VICAD seeks remote human assistance via the cloud to ensure safe passage.

drivers' reports (3rd column, figure 3), AD vehicles can be aware of dynamic traffic conditions in real time to adjust their routes automatically.

Most importantly, VICAD enables the cloud-based driver, which is the requisite to expand ODD for high-level AD. The cloud-based driver provides vehicles with real-time driving assistance for "extreme" conditions (i.e., an unforeseen situation that the vehicle doesn't know how to handle; 4th column, figure 3). VICAD employs an AI-based discriminator in the cloud server to monitor AD status. When the vehicle is not functioning well (e.g., because of an exceeded perception uncertainty threshold), the cloud server will initiate appropriate measures to provide immediate service and assistance.

Traffic Efficiency

Autonomous driving could improve traffic flow by up to 35 percent by coordinating AD vehicles to keep traffic moving smoothly (Hyldmar et al. 2019). In different development stages, VICAD can improve traffic efficiency by coordinating traffic lights, vehicles, and even travel demands.

With stage 1 VICAD, a straightforward way to improve traffic efficiency is through control of traffic lights, an approach that has been widely and globally applied. In BJHAD, Baidu has set up a traffic light control system for 315 adjacent intersections, with 51 trunk road coordinators and 36 controller-deployed single-node adaptive traffic lights. As an optimized result of VICAD, travel time on main roads is decreased by 10.4 percent on average, and the queue length at single-node adaptive intersections is decreased by 19.6 percent on average.

With stage 2 VICAD, collaborative perception among multiple adjacent intersections leads to a better prediction of traffic flow and improved traffic efficiency. With stage 3, collaborative decision and control can jointly control traffic lights and moving vehicles. Additional roadway properties (e.g., variable lanes) and travel demands (e.g., robo-taxi flow control) may further contribute to optimization. A more complex system means greater deployment difficulty, but also better collaborative control and traffic efficiency.

Challenges and Next Steps

VICAD has obvious advantages, but its real-world deployment faces great challenges:

- Time and cost to build large-scale roadside infrastructure, which varies in different countries and cities.

Field tests are of irreplaceable value for VICAD validation and verification, so more large-scale test zones (like BJHAD) are required.

- Difficulty in coordinating different innovation cycles for AD technology and city infrastructure. With increasing large-scale testing and trials, AD's rapid development progress constantly upgrades technical assumptions for roadside infrastructure.
- Ethics and laws not ready for both AD and VICAD in many respects. Two typical concerns are data use for AI algorithms without sufficient attention to data privacy and individual/collaborative decision making to minimize inevitable traffic accidents (as captured in "the trolley problem"; Basl and Behrends 2019).
- Lack of a VICAD platform, including datasets, standards, and other resources. Unlike available public AD datasets and jobs, there are few educational and professional opportunities in VICAD.

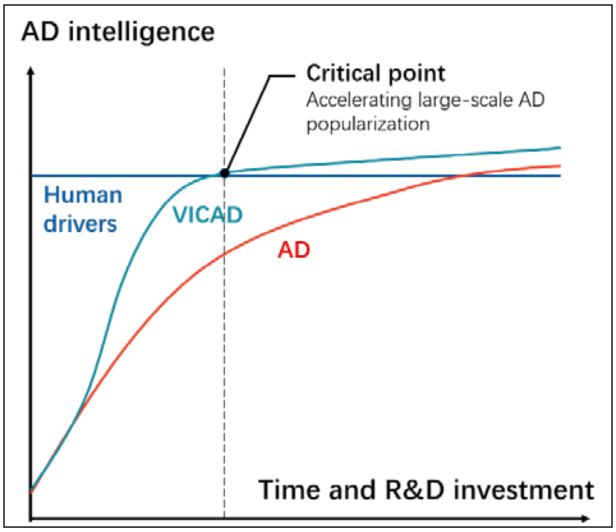

FIGURE 4 Comparison of expected evolution of autonomous driving (AD) and vehicle-infrastructure coordinated autonomous driving (VICAD). Adapted from AIR and Baidu (2021).

Based on public and proprietary statistics of AD intelligence, figure 4 compares the expected evolution of VICAD and AD (AIR and Baidu 2021). VICAD is expected to take the lead in launching high-level AD products, for its advantages in long-tail problem solving. Will VICAD help AD become more publicly acceptable? A positive feedback loop is needed: safer VICAD enables wider commercialization with more customers and more AD data. The feedback data also further improve AD performance.

Communication and coordination among different communities will be essential (Harrington et al. 2018), engaging those involved in AD/VICAD technology, the automotive industry, roadway infrastructure, and government.

- The VICAD technology community should follow industry standards and design a progressive and flexible technical roadmap to fulfill both short-term return on investment and long-term compatibility of new technology in roadside infrastructure planning.
- The automotive communities should adjust designs based on infrastructure planning, allocate resources for VICAD R&D, build VICAD's scientific research infrastructure (e.g., datasets, benchmarks, challenge), and attract talent to this new area.
- The government should lead and carry out or sponsor research, and is also responsible for formulation of policies, regulations, and standards, all of which are key to the development and implementation of VICAD. Research funds should be allocated to encourage long-term university and industry collaboration for VICAD.

BJHAD is a positive government-led example to facilitate collaboration among different players and expedite VICAD innovation. Recent VICAD efforts in Yizhuang are pioneering worldwide R&D to deliver project Apollo Air (AIR and Baidu 2021), which enables high-level AD with roadside sensing capability; a publicly accessible dataset[5] for VICAD (Yu et al. 2022); and an open-source operating system for RSUs.[6]

Conclusion

The development of high-level AD technology is facing great challenges even as massive long-tail problems are being solved. By connecting vehicles with roadway infrastructure, the cloud, and other smart devices, VICAD can help solve critical problems by improving AD safety, surmounting ODD limitations, and optimizing traffic efficiency, environmental perception, decision making, and control execution. There is strong evidence that VICAD can facilitate AD adoption and improve transportation in smart cities.

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[5] https://thudair.baai.ac.cn/index

[6] The AIROS operating system supports Apollo AIR, an AD project based on smart roads only (no dependency on smart vehicles). AIROS source codes and documentation are available in Chinese at https://gitee.com/ZhiluOS (Zhilu means "smart roads" in Chinese).

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Widespread engineering licensure-exemption laws dramatically increase risks to the public and undermine engineering's benefits and commitment to public protection.

Engineering's Grand Bargain vs. Licensure-Exemption Laws

Stuart G. Walesh

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The October 2018 and March 2019 crashes of Boeing 737 MAX 8 airliners killed 346 passengers and crewmembers and grieved many times that number of family members and friends. These disasters share a common characteristic with many engineering tragedies, such as the Ford Pinto fires, space shuttle *Challenger* explosion, GM ignition switch disaster, *Deepwater Horizon* oil rig calamity, amusement ride accidents, Merrimack Valley gas distribution system fires, Gold King Mine wastewater spill, and Volkswagen emissions fraud (Walesh 2021).

The common characteristic? All the engineering organizations responsible for these failures were exempt from placing licensed engineers—Professional Engineers (PEs)—in charge of projects risky to the public. Because of the exemptions, and even though the public was often at risk, engineering work did not need to be directed by competent and accountable PEs, whose paramount ethical and legal responsibility is public protection. Instead, bottom-line-oriented managers and executives drove much of the engineering.

In the interest of public protection, this first of two articles reviews the history of how US engineering practice evolved to the present unnecessarily risky state. The second article offers remedial suggestions for consideration by engineer employers, federal and state government, and the engineering community (Walesh 2023).

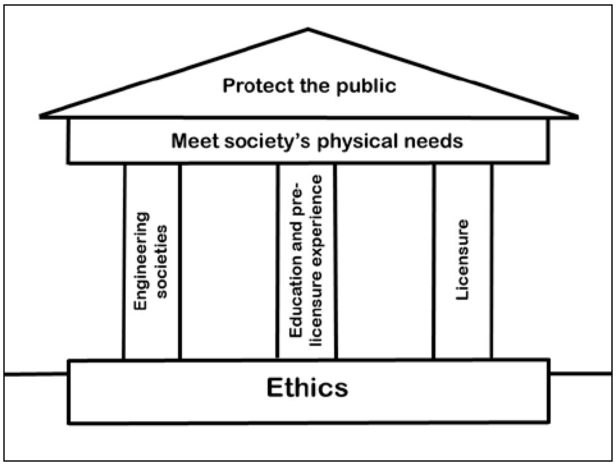

FIGURE 1 After establishing a foundation of ethics, the US engineering community created a superstructure involving engineering societies, education and experience, and licensure to meet society's physical needs while protecting the public.

State Licensing Authority and the Grand Bargain

Dent v. West Virginia, a landmark 1889 US Supreme Court case, gave states essentially unlimited power to regulate professions for public-protection purposes. The case led to others heard by the court, all of which established that a state "has virtually unfettered policy-making power in regulating a profession" (Spinden 2015). That reality caused state legislatures to pass laws requiring licensure for practice in various occupations.

In 1907 Wyoming became the first state to adopt an engineering licensing law. Other jurisdictions, often prompted by engineering disasters, followed suit so that by 1950 all 48 states, the then-territories of Alaska and Hawaii, and the District of Columbia had adopted such laws (Spinden 2015).

To become a PE, today's licensure candidates typically must earn an accredited engineering degree, complete four years of increasingly responsible experience, and pass two examinations. PEs then become participants in what has been called *the grand bargain* between a profession's members and the public (Susskind and Susskind 2015).

Under the terms of the bargain, PEs apply their expertise, experience, and judgment to deliver affordable, current, and reliable services and put the interests of those they serve ahead of their own. Individuals and organizations contracting for services trust PEs to do those things, and grant them exclusivity over a range of services by conferring autonomy in them and paying a fair fee. Licensure formalizes the grand bargain for engineering, as it does for all professions.

The bargain is "grand" for professionals and the public because it offers the former ample latitude in practice and the latter substantial protection.[1]

Engineering Ethics Codes Articulate Engineering's Ideology

Introducing engineering licensure prompts the question, What is engineering's purpose? If the medical profession provides care without doing harm and the legal profession seeks justice within the law, what is engineering's ideology? Engineering's purpose is to meet society's physical needs while keeping public protection paramount.

To further articulate engineering's ideology and licensure's role, the engineering community began to construct, and then build on, a foundation of ethics. The American Institute of Chemical Engineers (AIChE), what became the Institute of Electrical and Electronics Engineers (IEEE), American Society of Mechanical Engineers (ASME), and American Society of Civil Engineers (ASCE) all created and adopted codes in 1912–14 (Hoke 2014). Other engineering groups followed, so that today they all admirably state the following, or something very similar: The engineer will hold paramount the safety, health, and welfare of the public. Most state licensing laws or rules have a similar requirement that is legally binding—except when circumvented by exemptions.

Building on that ethics foundation, the US engineering community constructed a superstructure (figure 1): Engineering societies, education and experience, and licensure would support the work of engineers to meet society's physical needs while protecting the public.

Thus remarkably, by the 1950s US engineering had achieved universal licensing laws plus apparent unanimous commitment, via ethics codes, to hold public protection paramount. But has that commitment led to consistent actions on risky engineering projects?

Licensure-Exemption Laws

Emergence of Licensure-Exemption Laws

Beginning in the early 1940s, three decades after adoption of the first state engineering licensing law and

[1] An article exploring science's place in society uses the term *social contract* to convey the essence of a trust-based relationship (Guston 2000).

during the early part of World War II, many US companies began campaigning to get exemptions for their engineers from mandatory licensing. Exemptions would work like this: Employers would be responsible for their engineers' work and liable for errors and decisions that caused injuries, deaths, and/or destruction—this liability assumption by manufacturers, industries, utilities, and others would "protect" the public. Thus the 346 families who lost parents, spouses, children, and siblings in the two 737 MAX 8 disasters will receive an average of $1.4 million from Boeing (Robison 2021). No individual engineers were held legally accountable.

Engineering disaster victims painfully realize that, while it may provide some justice and financial remuneration, this approach of "closing the barn door after the horses are gone" does not bring back the dead, heal the maimed, or restore what was destroyed. Furthermore, the inevitable negotiation and litigation force survivors to relive tragedies.

Putting profit over public protection, in other than low-risk engineering situations, and accepting unnecessary deaths, injuries, and destruction is flawed public policy. Yet it persists, as DC and all states except Arkansas and Oklahoma have engineering licensure-exemption laws and only about 20 percent of practicing engineers are licensed. Thus most states do not require that competent, ethical, and accountable licensed engineers be in responsible charge of designing airplanes; autonomous and human-driven motor vehicles; amusement park and carnival rides; natural gas distribution systems; oil pipelines; electric power networks; railroads; wind farms; and chemical, construction, and manufacturing processes.

A state-by-state scan of exemptions from licensing laws reveals, depending on the particular licensing jurisdictions, that they collectively exempt industries, manufacturers, mining and petroleum companies, natural gas and electric utilities, railroads, telecommunication companies, government units (federal, state, county, and local), and the armed forces.

How do the laws articulate the licensure exemptions? The Washington state (2020) engineering licensure law exempts "the work of a person rendering engineering… when such services are rendered in carrying on the general business of the corporation and such general business does not consist, either wholly or in part, of the rendering of engineering services to the general public." Boeing and Washington state practices indicate that they interpret aircraft design and manufacturing as not part of "the rendering of engineering services to the general public."

Fortunately, engineering's institutional structure varies around the globe, providing opportunities for the engineering community in one nation to learn from their counterparts in others. For example, 12 of the 13 Canadian provinces and territories restrict the term *engineer* to licensed engineers and, with one minor exception in Ontario, there are no licensure exemptions.[2]

The Resulting Culture

Engineer Stephen C. Armstrong (2005, p. 209) observes that "Culture wields great power over what people consider permissible and appropriate.… The embedded beliefs, values, and behavior patterns carry tremendous weight. The culture sends its energy into every corner of the organization, influencing virtually everything."

> *Sometimes morally or otherwise flawed scripts, written by busy managers and executives, become incorporated as standard operating procedures.*

Culture is also characterized as a collection of scripts written over time in an organization by very busy individuals, especially managers and executives, seeking relief from being bombarded with information and pressed for decisions (Useem 2016). These sometimes morally or otherwise flawed scripts become incorporated, vertically and horizontally, as standard operating procedures. I offer another and consistent definition of culture: "The way things really work around here, especially when the chips are down."

Culture can have positive or negative effects; the engineering licensure-exemption environment exemplifies the latter. Research reveals that manufacturers, industries, utilities, and other organizations that employ engineers to work under licensure-exemption laws tend to develop bottom-line-first cultures, which override public protection.

[2] Engineers Canada, https://engineerscanada.ca/

Consider some examples of the culture created by licensure-exemption laws—in all cases, PEs were not in responsible charge (Walesh 2021).

- Former Boeing engineers reported that licensed engineers were not needed in aircraft design, including the 737 MAX whose two crashes caused 346 fatalities, and that PEs could not display PE on their badge.
- During the design of the Ford Pinto, engineers learned that the explosion risk due to a poorly placed fuel tank could be eliminated for $11 per vehicle, but engineers and management decided that settling accident claims would cost less. Many Pinto occupants were injured or died in gasoline-fueled fires and Ford eventually recalled 1.5 million Pintos.
- A lead Morton-Thiokol engineer urged management to delay the launch of the *Challenger* because of the likely harmful effect of low Kennedy Space Center temperatures on booster rocket gaskets. Managers rejected the advice, telling a high-ranked engineer: "Take off your engineering hat and put on your management hat." Seven astronauts died.
- For a decade, GM engineers brushed off reports that occupants of six car models were being injured or killed around the globe because of a faulty ignition switch. Eventually, GM redesigned the switch and recalled 2.6 million vehicles. Survivors alleged at least 124 deaths and 275 injuries.

A bottom-line-first culture is especially dangerous in engineering organizations because a single engineering failure can injure and kill many.

- A study of two decades of British Petroleum operations leading up to the *Deepwater Horizon* oil rig tragedy concluded that "oil companies…could not be trusted to police themselves and balance the public good against their own profits" (Lustgarten 2012, p. 333). The explosion and fire killed 11, injured 17, and damaged the environment and economy along 1100 miles of coastline in four states.
- The National Transportation Safety Board studied the 2018 Merrimack Valley (Mass.) gas distribution system explosions and fires that caused one fatality and damaged or destroyed 131 structures. The NTSB (2019) recognized the potential for similar disasters in 30 states and recommended that all those states "remove the exemption" that caused the tragedy. A few actions occurred in response, such as Massachusetts removing its exemptions for natural gas systems and an unsuccessful introduction of congressional bills that would have required, across the country, PE approval of plans for natural gas projects (Walesh 2021). There is otherwise no evidence of major action by states in response to NTSB's recommendations.

A bottom-line-first culture is especially dangerous in engineering organizations because a single engineering failure can injure and kill many. In contrast, if a surgeon errs during an operation, the consequences—however dire—are limited to one or a few individuals.

Data vs. Judgment

Interested engineers, as well as other concerned individuals, naturally prefer to see data that prove licensure-exemption laws lead to unnecessary injuries, deaths, and destruction. I believe this could be done by examining a century of engineering tragedies, but that has yet to happen—the effort would be monumental.

Absence of statistical proof does not reduce concerns about public protection. Therefore, some of us apply a powerful "tool" used every day in our engineering work: judgment. It is not necessary to halt engineering projects until all the data needed are available to be 100 percent sure of every decision. Instead, we make judgments.

My professional judgment, for example, draws on examining engineering disasters, empathizing with victims and survivors, understanding human behavior (especially groupthink), contrasting engineering's licensing approach with that of other American professions, and considering the likely priorities of PEs when leading engineering projects.

Engineering's Approach Contrasted with Other US Professions

The common US practice of legally not placing PEs in responsible charge of risky engineering projects would be like

- hospitals not placing licensed physicians in responsible charge of surgery,
- law firms not placing licensed attorneys in responsible charge of legal services, or
- veterinary clinics not placing licensed veterinarians in responsible charge of neutering and spaying.

Of course only licensed physicians, lawyers, and veterinarians lead in risky situations. The same is true for most professions such as audiology, anesthesiology, optometry, ophthalmology, pharmacy, physical therapy, and psychiatry. However, in America, the law frequently and sometimes disastrously explicitly allows risky engineering projects to proceed without state-licensed professionals in charge. That practice conflicts with the grand bargain.

Expected Performance of PEs

Those who defend licensure exemptions often note that tragedies sometimes occur even when PEs are in charge, which is true. But in my judgment, engineering projects led by PEs are much more likely to place public protection paramount than those guided by non-PEs or non-engineer managers.

Revisit the GM ignition switch disaster caused by engineer employees who, for years, brushed off ominous reports about accidents caused by faulty switches. If laws had required a PE to be in responsible charge, he or she would probably have taken action because of ethical and legal expectations, fear of penalties such as loss of license and fines, and a desire to protect GM from legal liability. More specifically, PEs are more likely to

- be *competent*, partly because licensed engineers, when legally challenged, will be held to the standard of care test and because continuing education is a condition of maintaining a license in three-fourths of US licensing jurisdictions;
- be *ethical*, especially as relates to public protection, because they are subject to the ethics codes of the jurisdictions that licensed them and code violations have legal consequences; and
- be *independent*, viewing themselves as members of a profession whose paramount responsibility is public protection, rather than as technical employees answerable mainly to corporate directives and shareholders.

The preceding is not a matter of PEs being "better" than non-PEs. The two have different functions, aspirations, interests, mindsets, and education-experience preparations.[3]

Conclusion

American engineering's approach to public protection is a predicament. The engineering community's widespread claims, via ethics codes, that public protection is paramount contrast sharply with the unfortunate results of equally widespread licensure-exemption laws. The former stress public protection and the latter focus on the bottom line.

Reform is needed so that employers place PEs, who hold public protection paramount, in responsible charge of risky engineering projects.

If this dichotomy stands, engineering will not fully participate in the grand bargain and the public will continue to face unnecessary risks. Reform is needed so that employers place competent and accountable PEs, who hold public protection paramount, in responsible charge of risky engineering projects. It is also important to support and appropriately engage the majority of graduate engineers who choose nonlicensure career paths. The second of the two articles offers many reform suggestions.

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[3] See the second of my two articles for discussion of career options available to degree holders from undergraduate engineering programs (Walesh 2023).

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Engineer employers, the federal and state governments, and the engineering community all have an important role in minimizing the risks of licensure-exemption laws.

Engineering Licensure-Exemption Laws:

Suggested Reforms to Enhance Public Safety

Stuart Walesh is a PE and independent consultant, teacher, and author who previously worked in the business, government, and academic sectors.

Stuart G. Walesh

As explained in the first article in this two-part series (Walesh 2023), engineering ethics codes claim that public protection is paramount. However, widespread exemptions to state engineering licensure laws enable bottom-line-first thinking, which often places the public at unnecessary risk.

If this dichotomy stands, engineering will not fully participate in the grand bargain—engineers enjoy ample latitude in practice in return for protecting the public—and the public will continue to face unnecessary risks. Reform is needed so that employers place competent and ethically and legally accountable licensed engineers (Professional Engineers, PEs), who hold public protection paramount, in responsible charge of risky engineering projects and defending the population from other threats. Support and appropriate engagement are also needed for the majority of graduate engineers who choose nonlicensure career paths.

Reform in three areas could have the most impact on American engineering: engineer employers, the federal and state governments, and the engineering community. I consider reform suggestions for each sector.

Suggestions for Employers Operating Under Licensure-Exemption Laws

Engineering-intensive entities using licensure exemptions should consider a different follow-the-money approach when contemplating their disaster costs. One-time costs are likely to include staff time, attorney fees, expert's fees, victim compensation, customer settlements, and fines. Long-term and repeatable costs may be increased liability insurance premiums, personnel turnover, and damaged reputations. Commenting on the Pinto tragedies, Ford president Lee Iacocca (1984, p. 162) said that "the damage to the company was incalculable."

Consider Boeing's monetary cost for its two 737 MAX 8 crashes. In January 2021 the US government announced that Boeing agreed to pay more than $2.5 billion as part of a legal settlement with the Justice Department. The agreement included a criminal penalty, compensation for customers, and a $500 million fund to compensate the families of the 346 people who died in the crashes (Robison 2021). The preceding does not include the cost of lost or delayed sales.

PEs should lead teams of unlicensed engineers, various specialists, and support personnel to ensure appropriate consideration of public safety—and the bottom line.

What if, a decade ago, Boeing leaders had invested a small fraction of $2.5 billion in studying and implementing a more responsible approach to engineering? The company could have established an engineering structure that strategically identified and recruited PEs and placed them in responsible charge of various aspects of aircraft design and manufacturing.

These competent, ethical, and accountable professionals could have led teams of unlicensed engineers, various specialists, and support personnel to make sure public safety—as well as the bottom line—were appropriately considered. The resulting culture could have prevented the human, financial, and reputational costs caused by the 737 MAX 8 disasters.

Employers could also use other means of creating a public-protection-first culture. For example, require engineers and others to commit to an internal ethics code or appoint individuals empowered to identify troublesome decisions and take them up the chain of command.

Suggestions for State and Federal Governments

All US states (except Oklahoma and Arkansas) plus the District of Columbia have adopted various forms of engineering licensure exemptions. In organizations operating under these laws, bottom-line managers and executives—not licensed engineers—often make major engineering decisions on risky projects.

This practice conflicts with a licensing board's principal responsibility: protecting the public. Boards and state legislatures should proactively provide that protection by removing or reducing exemptions. Use the 1889 *Dent v. West Virginia* US Supreme Court decision, which gives states essentially unlimited power to regulate professions for public-protection purposes. State chapters of national engineering societies could urge licensing boards and legislatures to study the exemption issue, with emphasis on public protection.

The federal government (e.g., the Federal Aviation Administration, the Chemical Safety Board) could require that certain engineering functions, such as aircraft, motor vehicle, and utility design as well as chemical manufacturing processes, be conducted under the guidance of and with engineering approved by PEs, whose paramount responsibility is public protection. This mandate could be articulated in federal regulations that would override contrary state law and be consistent with the US Constitution.[1] For example, the *Deepwater Horizon* oil rig tragedy prompted the federal Bureau of Safety and Environmental Enforcement to require that a PE certify casing and well design before issuing a drill permit (Eiser 2015).

In the interest of a fresh approach, state or federal governments could consider modified or new models for earning a license to practice engineering—a replacement for or modification to the traditional education-examination-experience model. For example (McMeekin 2021),

- A candidate-prepared portfolio, which documents the necessary knowledge and skill, might reduce the content or scope of the PE examination, or completely replace it.

[1] The Constitution's Article VI, Supremacy Clause states that federal laws, made pursuant to the Constitution, take priority over any conflicting state laws.

- The experience requirement could be similarly modified to place more emphasis on quality and less on duration.
- Peer reviews, or interviews by committees, could modify or replace some parts of the three-step model.
- National licensure, administered by state boards with assistance from engineering societies, may be feasible.
- Given emerging technologies and increasing socioeconomic-political complexity, consider placing more emphasis on career-long learning.
- Explore, in the interest of public protection, a non-PE option. For well-defined engineering processes, state or federal governments could require engineering organizations to certify conformance with applicable engineering standards.

Suggestions for the Engineering Community

Consider what members of the engineering community could do to reduce the harmful effects of licensure-exemption laws. This discussion excludes the National Society of Professional Engineers (NSPE) because that pan-engineering organization has been a leader in opposing exemptions.

ABET

ABET accredits engineering bachelor's and master's degree programs. It prescribes criteria for 29 bachelor's programs, but only two—civil engineering and construction—are required to include licensing in their curricula. Furthermore, public protection is never mentioned by ABET as the paramount responsibility of engineers, especially PEs (ABET 2022).

ABET should explore revising its Program Criteria so that they require teaching the purpose of engineering licensure and its educational, examination, and experience requirements. Stress public protection as the engineer's highest duty. If Program Criteria improvements attract widespread attention among engineering disciplines, the changes could instead appear in the General Criteria. Whether or not engineering students eventually select the licensure option, all future engineers should understand that engineering's purpose is to meet society's physical needs while keeping public protection paramount.

National Council of Examiners for Engineering and Surveying

NCEES states that its vision is "to provide leadership in professional licensure of engineers and surveyors through excellence in uniform laws, licensing standards, and professional ethics in order to safeguard the health, safety, and welfare of the public and to shape the future of professional licensure." The Council adopted eight professional policy statements and 37 position statements.[2] Only one of these statements mentions exemptions, and none advocates reducing exemptions "to safeguard public health, safety, and welfare."

All future engineers should understand that engineering's purpose is to meet society's physical needs while keeping public protection paramount.

NCEES should consider adopting a position statement that addresses the potential harmful effects of exemptions and suggests remedial actions.

National Academy of Engineering

The NAE's vision is "to be the trusted source of engineering advice for creating a healthier, more secure, and sustainable world." Its mission is "to advance the welfare and prosperity of the nation by providing independent advice on matters involving engineering and technology," primarily to the federal government.[3] Relative to the content of this article, the Academy's website is virtually silent about licensing, and its use of the term *professional engineer* describes any member of an engineering society, not necessarily a PE.

The NAE should consider

- using the term *professional engineer* to apply only to licensed engineers;
- urging the federal government to reduce licensure exemptions applicable to its engineers; and

[2] See NCEES engineering licensure, https://ncees.org/engineering/.

[3] The NAE vision and mission are posted on its website, https://www.nae.edu.

- studying the effectiveness of US engineering education and the effect of licensure exemptions, and making appropriate recommendations to academic, practitioner, and business communities.

Engineering Societies

These societies provide forums for engineers to continuously improve engineering education, licensure, and practice—and sometimes stimulate reform. Now is the time to help reform engineering licensure.

Reconsider Society Support of Licensure Exemptions

Some engineering societies explicitly support exemptions. For example, ASME recommends "that any person in responsible charge of the practice of engineering be a legally licensed engineer, except where state statutes allow for exemptions" (ASME 2015). The AIChE affirms "its support of an engineering policy known as the industrial exemption, while continuing to strongly encourage individual engineers to pursue licensure" (AIChE 2014a). Looking forward, it also states, "If the overwhelming majority of engineering licensure boards can adopt a streamlined form of reciprocity… AIChE would reconsider its support of the industrial exemption" (AIChE 2014b).

Engineering societies should consider removing their support of licensure-exemption laws and work with states toward streamlining license reciprocity.

Accordingly, the first suggestion, for the sake of public protection, is that some discipline-specific engineering societies consider removing their support of licensure-exemption laws and work with states toward streamlining license reciprocity. Because NSPE has an admirable track record in opposing licensure exemptions, it is a source of strategies and tactics.

Negative Aspects of Employment in Licensure-Exemption Environments

The second suggestion: Engineering societies ought to help prospective and current engineering students understand the negative aspects of employment in licensure-exemption environments. Students and their parents are likely to welcome help in making sound decisions consistent with their values and aspirations.

All engineers tend to do challenging technical work, earn a favorable salary and benefits, and enjoy job security. However, many engineers employed in the licensure-exemption environment, in contrast with other engineers, have to tolerate nonengineer managers making major engineering decisions and a loss of career and business startup flexibility because of the lack of an engineering license. Later, these engineers may regret helping to implement engineering decisions that put the public at risk instead of taking corrective action.

Clarify Career Options for an Undergraduate Engineering Degree

Licensure of some engineers is essential to engineering's ideology of meeting society's physical needs while holding public protection paramount. Licensure enables the grand bargain. However, not all, or even most, graduates of ABET-accredited four-year engineering programs need to become licensed because that degree offers three attractive careers (Walesh 2021). Therefore, the third suggestion for engineering societies is to articulate more effectively the options.

As illustrated in figure 1, three principal career options are PE, engineer with license optional (ELO), and other career (OC). Note the many and varied positions or functions associated with each of the options. While the options are not new, labeling, defining, and proactively publicizing and using them would be. Explanation of the options should begin in high school so potential engineering students, and their parents and teachers, understand the full range of careers available to engineering graduates.

The three options indicate that engineering is like medicine, law, and other professional occupations, in that each offers various points of entry and types of participation. For example, if a high school student expresses interest in medicine or the health field, he or she is likely to learn about nurse practitioners, physicians, emergency medical technicians, physician assistants, physical therapists, and so on. The PE, ELO, and OC options provide a way to introduce young people, and their parents and counselors, to engineering's array of options.

The three options form a large net that can introduce an even more varied group of young people to the highly varied engineering field so that they can consider studying engineering. Frequently remind engineering students about the three options, including their pros and cons, so that they can make wise postbachelor's degree decisions.

Finally, when we engineers of all stripes get into discussions of "how much education," "how much experience," "who must be licensed," "who is liable," and "what does engineering leadership entail," we could first ask: Which of the three graduate engineer options are you referring to?

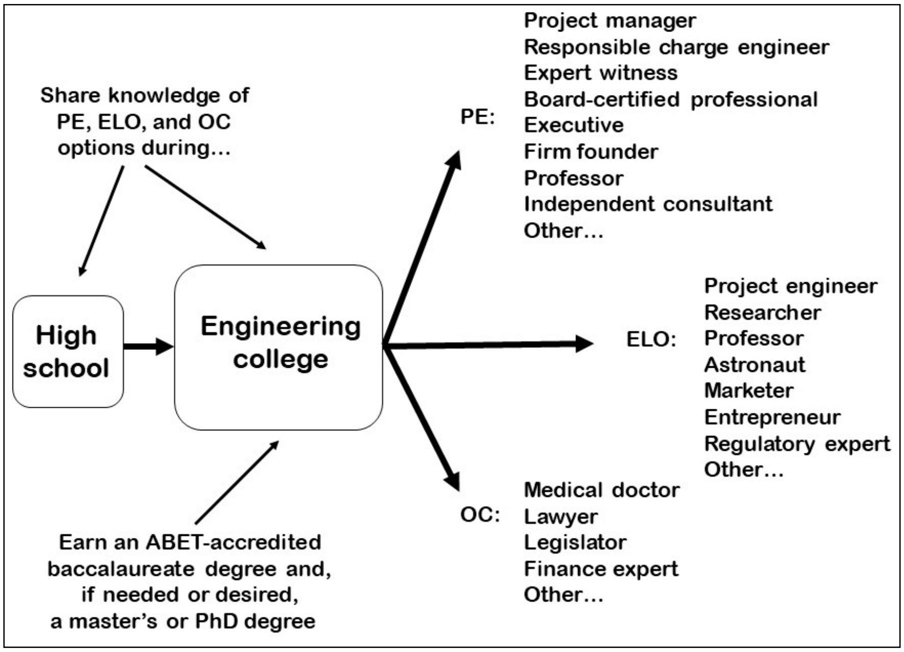

FIGURE 1 Three attractive career options begin with earning an engineering baccalaureate degree. ELO = engineer with license optional; OC = other career; PE = Professional Engineer.

Individual Engineers

We engineers naturally share ideas, experiences, and research results with other engineers. However, talking among ourselves is not enough—we must write to, speak to, and interact with the public.

When doing that, be aware of the prevailing public perception paradox. Surveys and experience reveal that the American public holds engineers in high regard (Nordland 2019). In sharp contrast, the public is unaware of the way omnipresent engineering licensure-exemption laws deny them the protection they deserve. That's where individual engineers should weigh in. Richard Weingardt (1998, p. 75), a PE, said, "The world is run by people who show up." We need to "show up" more in the public arena.

How can engineers "show up"? Weingardt suggested the following broad areas of public sector involvement:

- Civic organizations: Chambers of Commerce, homeowner's associations, planning boards, service clubs, historic preservation boards, and ad hoc task forces
- Educational organizations: School boards, college or university advisory boards, and student and faculty groups
- Public communication: Op-eds, letters to the editor, news releases, talk shows, and blogs
- Politics: Candidate support, candidacy, caucuses, and communication with state and federal legislators.

In communicating with the public, include topics such as engineering's massive impact on societal quality of life, the unnecessary risks imposed by licensure exemptions, and the need to have PEs in charge of projects that put the public at risk.

Individual engineers can help the engineering and broader communities understand the destructive consequences of licensure-exemption laws.

Conclusion

The American engineering community's widespread claim that "public protection is paramount," enshrined in professional and society codes, conflicts with equally widespread state licensure-exemption laws. This dichotomy places the public at unnecessary risk.

Engineer employers, state and federal government entities, and the engineering community should enhance public protection by leading the effort to reduce the exemptions. An engineering community that historically produces amazing individuals and results can, if it so wills, correct this critical weakness and create what could be the greatest profession.

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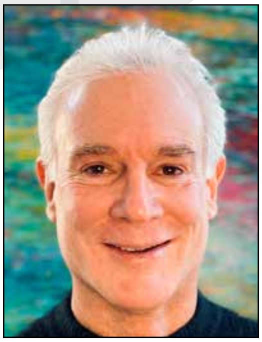
Op-Ed

A Better Way to Validate Autonomous Vehicle Safety



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The National Highway Traffic Safety Administration estimates that in 2022 nearly 32,000 people died in traffic crashes in the first nine months of the year.[1] Autonomous vehicles (AVs) promise to dramatically reduce that number. But, although AV developers have reportedly spent more than $75 billion to bring improved safety and other AV benefits to the public, the vehicles are still not generally available for public use.

Despite the fact that AVs have driven millions of miles on test tracks and public roads, numerous media reports have documented that AV developers have struggled to demonstrate that the vehicles are safe by test driving them on US roads and highways (CBS News 2023; Noyes 2023; NPR 2022; NTSB 2017). In fact, a recent study found that AVs would have to be test driven hundreds of millions—even hundreds of billions—of miles to demonstrate their reliability in terms of fatalities and injuries (Kalra and Paddock 2016).

It is becoming clear that trial-and-error test driving of AVs on public roads and highways may never demonstrate acceptable safety.[2] AV road test failures are creating unacceptable delays for investors. AV start-ups have ceased operations. Failure to achieve acceptable safety levels has become a major obstacle to AV deployment.

The public is concerned because public AV test drives have frightened, injured, and killed people (Noyes 2023; NPR 2022; NTSB 2017). AVs are now considered by some to be more dangerous than vehicles operated by an impaired human driver.

It appears certain that AV deployment will not be successful without public consensus that the vehicles are "safe enough." To that end, a better way than test driving on public roads and highways is needed to determine whether AVs are "safe enough" to be used without restriction in the public domain.

But how safe is "safe enough" for AVs? Since the public already accepts licensed human drivers as "safe enough," I think most people would accept that an AV is safe enough if it demonstrates safety performance at least as safe as that of the average human driver. With that in mind, the next step toward developing consensus that an AV is "safe enough" is to determine the specific criteria and the methods used to validate that level of safety performance.

Fortunately, in the United States (and probably other countries) there is an established acceptable precedent for introducing a new human driver into the public domain: a driving test. Such a test is required for an individual to become, and periodically to remain, a licensed driver.

In a typical driving test a person must demonstrate that they

- can operate a vehicle safely,
- have safe driving habits,
- can apply their knowledge of traffic laws in real-life situations, and
- have the ability to safely compensate, as needed, for any physical condition (e.g., loss of a limb, poor hearing, or the need for vision correction).

An AV driving test could similarly be used to determine whether the vehicle can demonstrate that it

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[1] NHTSA Estimates: Traffic deaths third quarter of 2022, https://www.nhtsa.gov/press-releases/nhtsa-estimates-traffic-deaths-2022-third-quarter

[2] There is no consensus on what constitutes "acceptable safety" for AVs. Each AV developer appears to define "safe" differently. The most widely published metric developers use is miles driven on public roads; the idea seems to be that someday enough miles will be driven to demonstrate a level of safety that the public accepts. This hasn't happened yet.

- follows applicable traffic laws and operates safely under both routine and unforeseen circumstances;
- exhibits safe driving practices—for example, recognizes the differences between bicycles, motorcycles, pedestrians, cars, and trucks, and knows to stop when approaching an emergency vehicle stopped in the road; and
- can safely compensate for any loss of capability (e.g., sensor failure, software problems, safety-critical hardware failure).

The use of the driving test standard in the United States has yielded a large amount of data about human driving safety.[3] An analysis of the data will reveal both the safety performance of the "average human driver" and the causes and circumstances of vehicle accidents that result in damage, injuries, and fatalities. The results can be used to inform AV driving test "safe operation" requirements and corresponding test methods. This approach will produce an AV safety validation process that mirrors human driver competency validation procedures. An additional benefit is that an AV driving test based on human driving behavior can be readily incorporated in existing regulatory processes.

I'm confident that a driving test designed to validate that AVs are as safe as the average human driver will validate AV safety, reduce investor risk, and reduce time to deployment.

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[3] Federal and state departments of transportation track accident reports, and insurance companies quantify driver safety to determine insurance rates. These data, if made available, could be analyzed to develop an appropriate AV safety test that effectively determines whether an AV performs safely when confronted with circumstances associated with accidents involving human drivers.

An Interview with . . .

Lucy Yu, Chemical Engineer and Bookstore Owner

Photo by Chris Deng.

RON LATANISION (RML): Today we're talking with a chemical engineer who has a deep social conscience, I believe, as I look into some of the things she's done. She's a chemical engineer and also now the proprietor of a bookstore, cleverly called Yu & Me Books, in Manhattan. That's a really interesting history.

Let's start at the beginning. Where did you grow up, Lucy, where did you go to school, and how did you end up opening a bookstore in Manhattan?

LUCY YU: I grew up in Los Angeles. My dream was to be a cardiothoracic surgeon, and I was ready to do biochemistry in college. But I applied to UC Berkeley so late in the evening—I think it was 1:00 a.m.—that I selected chemical biology instead of biochemistry and I was accepted into the college of chemistry instead. When I got there I thought, 'This doesn't seem like your normal premed class. It looks a lot heavier in technicality.' And I was told, 'Yeah, you're in the wrong college.' So I started off choosing the wrong major!

But my GPA at that point was too low to transfer to premed. So I decided, I've always loved math, I love solving problems, why not do chemical engineering. One of the best memories of my time at UC Berkeley was when I did research in nuclear magnetic resonance (NMR). That was so fun, because I got to go work in the labs at RWTH University in Aachen, Germany, and I published a paper on NMR—specifically, the diffusion of metal organic frameworks. I finished my undergrad, and there was a moment there that I thought, 'Maybe I'll do a PhD program.' But I'm interested in so many different things, I couldn't see myself being so specific for so many years on just one thing.

Once I graduated, I signed up for a rotational program at MilliporeSigma. Every nine months I would change to a different location and a different job description.

CAMERON FLETCHER (CHF): That sounds perfect for you.

MS. YU: Exactly. I think of myself as a career hobbyist, so it was an ideal situation. But it was difficult in a lot of ways. I think I was the first person of color, female engineer that they hired for the program. I found out things that were said behind my back. For example, I was called "egg roll" behind my back, and some racial terms that really frustrated me, because I thought my work spoke for itself. I realized then that, in the chemical and manufacturing industries, I was always going to have to overcome my identity, and my work couldn't just speak for itself.

I told HR about it, but I ended up pivoting away—I thought maybe engineering isn't really a safe place for someone that looks like me.

I love food, I've always loved food, and I thought, 'Why don't I see if I can solve some problems in food, because there's a ton of food waste—I think people end up wasting about a third of our food because of supply chain inefficiency. That's a big problem. But I am an engineer; maybe I can figure something out.'

On the side, during my rotation at MilliporeSigma, I actually became a line cook as well at a restaurant. I

This interview took place February 2. It has been edited for length and clarity.

shifted my schedule from 6 a.m. to 4 p.m. at my day job, and then from 5 or 6 p.m. to closing, 10 p.m., I worked as a line cook at a vegan restaurant. I was just so curious to see what the process was, where do they get the food….

RML: Let me get the logistics straight here. When you were working at Millipore, this was in Burlington in Massachusetts?

MS. YU: Yes.

RML: So you worked at your day job and then you went to the restaurant.

MS. YU: Yes. The restaurant was called Whole Heart Provisions, a fast-casual vegan restaurant in Boston. Unfortunately it's now closed.

RML: So you were raised in California, you worked as a chemical engineer in Massachusetts, and then how did you come to open a bookstore in Manhattan?

MS. YU: After I realized engineering wasn't for me, I ended up taking a supply chain and logistics job at Splendid Spoon and that moved me to New York City. I worked at the company for about three years.

Engineering taught me to not be afraid of any problems and to break down a big problem into a bunch of small problems.

During that time I went through the loss of one of my close friends who was also a chemical engineer; he passed away and it really shook my world and my idea of time.

I had always wanted to open a bookstore—it was a dream of mine. I figured why not do it now? So I chipped away at it for about a year, a year and a half, and then I got to the point where the last step was to find a retail space—and I opened in December of 2021.

CHF: Wow, what a tough time to open a business, during the pandemic.

MS. YU: It was not easy for sure. A lot of challenges there.

CHF: But you made it work.

MS. YU: Yes. Engineering is about problem solving, and I figured out how to solve some of the problems. It's constant pivoting, constant adjusting. I think anything can be engineered, and I did that in the bookstore.

CHF: Tell us how you've brought your engineering mindset to some of the specific challenges.

MS. YU: I think engineering has taught me to not be afraid of any problems and to break down a big problem into a bunch of small problems. Setting up the bookstore, the whole idea of opening a business, that's a big problem, and I broke it down into 30 different small problems that I slowly worked away at.

When I opened, it was right during the Delta variant of covid. At first it was really exciting, there was a lot of excitement around the bookstore. And then for a couple weeks in January 2022 no one left their house again.

So I pivoted to having an online e-commerce platform. I started scheduling events in the future. I started building out community where I could with the bookstore. I did all this understanding the risks and that there was a potential for it to not work and for the store to close in four months. I always knew that. But I tried everything I could and suddenly everything was better. We launched different events, and they brought so many people into the store because we were representing stories that were never spotlighted before at other bookstores.

RML: Are most of the titles in your bookstore fiction or—?

MS. YU: They're a mix of everything. There's fiction, nonfiction, we have a lot of memoirs, we have cookbooks, but the focus of the bookstore is immigrant stories and books written by writers of color. I used to go into stores and search for stories like mine. Also, I had felt like an outsider during almost all of my engineering days. I felt that because I looked and acted the way I did, my intelligence was always being questioned and put under a microscope, that my skills and work were challenged more than some of my colleagues because I didn't fit into the stereotypical engineering archetype.

I wanted people to come into the space and not have to search so much for stories that represented their own.

RML: What's your demographic in terms of the clients?

MS. YU: It's very diverse—age ranges, gender, race. When you go into another bookstore you see a lot of titles written by white authors, and that's never been questioned. I want someone to come into my space and realize ‘there is so much good written work here and it just happens to be from authors that are immigrants.’

At the baseline, it’s just good fiction or good nonfiction, good books. When people come in, they always ask for recommendations. They note a lot of books that they’ve never seen before, and that’s exciting.

CHF: That is wonderful. Do you find that you’re a resource for certain groups—say, a book group or a cooking club that’s looking for nonwhite authors and resources?

MS. YU: I think the people who come to the store are just looking for good stories. What I have found, though, is that there are a lot of people who have similar experiences to me—of being an engineer and having a lot of interests outside of engineering and not really ever finding a way to fit in even though they had good qualities or did good work or were a good engineer. Being able to share those stories in an actual physical space, and on top of that sharing books with each other, has been really beautiful and fruitful.

RML: I’m fascinated by the thought of your focus on immigrants, because if you look at the history of the United States, we basically all have immigrant roots. My grandparents were from Poland and Russia—they were coal miners, they were poor. My wife’s family was from Ireland and England, and they had similar characteristics.

When you think about immigrants now, do you go back to that stage in immigration in the United States? For example, the immigration history of the Jewish population in New York City is incredible. Are they described in your books, or is the focus more contemporary?

MS. YU: It’s a mix. A book that I’m reading right now that one of my closest friends recommended to me is *The Periodic Table* by Primo Levi. It’s a wonderful memoir in which every chapter describes an element and how that element has impacted the author’s life in his journey being a Jewish resident of Italy during World War II.

RML: Yes, that’s what I’m thinking about. So you do include that kind of history as well.

MS. YU: Yes. We rotate through our inventory since we are such a small space, and we have both new and used books. We have a large range of titles and they change pretty much every week.

Yu & Me bookshelves. Photo by Mel Hong.

RML: Do you have any contemporary engineering writers? I’m thinking of Henry Petroski or Sam Florman. Are those names at all familiar?

MS. YU: I don’t think we have those specific authors in the store. But have you heard of Weike Wang?

RML: I have not.

MS. YU: She got her degree in chemistry and is now a fairly well-known contemporary author. She wrote *Chemistry* and just released *Joan Is Okay*. So she has a somewhat similar background in terms of being a scientist and now she writes novels. That’s integrated in the way she writes, which is hilarious.

I think a lot of people connect with that, because it seems rare for engineers. I think it’s more rare than we realize for engineers to be strictly engineers, and there is so much fluidity in the idea and the description of engineering.

RML: I brought up Henry Petroski and Sam Florman because we’ve interviewed both of them for *The Bridge*. One of Henry’s early books is *To Engineer Is Human*, and it's a remarkable story about what it means to be an engineer, the impact on society. Sam Florman lives in Manhattan and he's written a book called *The Existential Pleasures of Engineering*. These are not titles you would expect to find in many bookstores, but I recommend them to you because they have characteristics that I think are in keeping with where you're headed. They are about engineers and engineering, but with a deep sense of social responsibility. If you haven't seen them I think you would enjoy reading them.

MS. YU: For sure.

RML: You do have a very deep sense of social consciousness or social justice. I applaud that. I think not just engineers but people in general have lost that today in many respects, and it's something to be treasured. We tend to forget as engineers that we are serving a social purpose, and yet, when I look at some of the things that have found their way into the marketplace, I think you have to question whether they're really serving society's interests all that well.

How did your sensitivities develop?

MS. YU: When I was in engineering, I was surrounded by people who didn't have these sensitivities or the priorities to think about 'what does what we're doing mean for the benefit of society? Who are we not including in the conversation when we're engineering this? What group are we excluding from this product or from this invention?'

It's hard to be one person challenging an entire classroom that doesn't look like you.

When you look at engineering classes and the demographics, diversity is lacking. So it's not so surprising that that thinking is missing there. I think there is a huge gap and a huge opportunity for curriculum to integrate that.

I remember arguing with my professors. They were making the argument that being moral from a business and engineering perspective was really being financially responsible or finding a way to make things financially efficient. That isn't what morality is, and when I challenged that, it's hard to be one person challenging an entire classroom that doesn't look like you.

It's not so much that I developed these sensitivities but that I have to live through them. I think being on the margins of a lot of the academic courses and career portions that I've been through, you can't help but develop some of that mindset. I was excluded; who else is excluded?

RML: I appreciate that comment. I really believe that engineering schools should involve social scientists in their curriculum.

For example, the internet was intended to serve as a platform that would provide information globally, and it does that beautifully. We all use it every day. But it has also become a tool of divisiveness, sometimes recruiting people who are antagonistic to their colleagues and the population in a broad sense. I don't think anyone ever intended that, but I'm not sure we thought through the potential or the problems. What people put up on social media is almost unfettered, and some of it is very divisive. I don't think that's socially useful.

Would you agree that social scientists should have a role in an engineering curriculum or a university?

MS. YU: I think that in any technical field, there is a huge lack of social awareness. In terms of engineering, it's an iterative process. When something is developed, potential can never be predicted, because we're only starting at one phase and that phase will continue to iterate to many different phases. Once it's out there, it is kind of out of your control. It's like shipping a package: all I can do is put the book in the bubble mailer, and once I send it out I don't know how it's going to arrive to the customer. I think that that's bound to happen continuously, and all we can do is create the right barriers. For example, face recognition tools are based largely on white male faces. Are we being considerate of the harmful effects of that on populations that are not included in the hypothesis or product development portion? I think a lot of the conversations aren't even being had at the technical level.

RML: I think you're right. A lot of this is unanticipated in many respects, and I think that's another way of expressing what you just said. On the other hand, once you begin to see that these things are happening, doesn't that suggest there should be some response?

I'm concerned that as technologists we should look at both the economic and social risks in rolling out a new engineering system into the marketplace. Often, it seems, once in the marketplace, there is a great resistance to any regulatory attachments. That's what I'm concerned about with the internet, for example, and social media. They seem to be almost unfettered at this point.

CHF: And the more kinds of people are involved directly in engineering—who are present in classrooms and labs and startups and education and companies, the more people who are other than white men—the better will be the consideration of possible effects and ramifications. As you said, Lucy, once something is out there and on the market, it's out of your hands, it's going to evolve the way it evolves, with different iterations. But before it gets to that point, the potential outcomes could be improved with the involvement of more diverse perspectives and input.

RML: I agree, that's exactly what I'm thinking about.

MS. YU: And that's my view as well. I think sometimes engineering happens in a vacuum, and it happens in the vacuum of people who look very similar. To shift that dynamic could add to a lot of potential for good for the future of engineering.

RML: Lucy, are you also a writer?

MS. YU: Casually. And in my opinion, not a very good one.

RML: What have you written?

MS. YU: Other than research papers, I've written some flash fiction—short stories—from time to time.

RML: What's on the horizon? Where do you see yourself in five years with your bookstore? What's your grand vision?

MS. YU: I do get asked that question, but I don't tend to look that far. I used to look far in advance and had five-year plans, but I think the best that we can do is try to look at the next day ahead of us. My hope is that someone feels a little more at home in the store tomorrow and the tomorrow after that. The best I hope for is to expand the community and feel that I am continuing to iterate my nurturing process for developing the bookstore, however that looks. I'm open to pivoting in different ways.

RML: Do you feel comfortable now economically, socially? Do you feel integrated into the culture in New York and Manhattan?

MS. YU: I love New York City and feel very at home here. I think as a business owner, you're never comfortable. I think you're always trying to figure out different ways to expand or change, because times change and the last thing you want to do as a business owner is to be stagnant.

I'm super excited to be past the one-year mark. I think that's a big mark for a small business. I hope it continues that way, but I'm always cautiously hopeful. I think every business owner would say the same.

CHF: It sounds like you're doing cool things with your bookstore, and bookstores have gotten very creative and resourceful as community resources. For example, there are small independent bookstores in this area that host their own reading groups and do wine tastings and other kinds of events. You clearly are also active in outreach. Can you tell us anything you're thinking about in terms of further outreach for your bookstore?

MS. YU: When I first opened, I partnered with an organization called Soar Over Hate. At the time, there was a huge rise in Asian hate crimes in New York City and especially against women. This group distributed free pepper spray at the store, and I think on that day we ended up distributing over 1,000 pepper sprays.

When something is developed, potential can never be predicted, because we're only starting at one phase, which will continue to iterate.

We have a slew of different events at the bookstore. For example, we have a book club every month—people vote on the book and we discuss it for an hour and a half while drinking wine or water. The focus this year is to be a little more engaging with the events, beyond our readings and signings. How can we create an environment where people create their own work, have poetry workshops, and can be more engaged in the events that we host?

There are two kinds of events. There's a somewhat more passive engagement, such as listening to an author

Yu's painting of her bookstore's "Employee of the Month," Odie.

speak, with a moderator; and there's active participation. But the bookstore space is very small, and at our events we sometimes get 50 or 60 people. The space is tiny, so you're just maybe one foot away from the author. It creates a more intimate gathering and experience, less of a performance and more of an engagement with the audience.

RML: How many employees are in your store, aside from you and Odie?

MS. YU: Other than Odie, "the employee of the month," we have seven employees.

CHF: That's a good size staff. What's the square footage of your store?

MS. YU: It's tiny, a bit less than 1,000 square feet. We have kind of bar hours, too, on Thursdays, Fridays, and Saturdays, when we're open until 1 a.m.

CHF: Who are some of the authors at your events?

MS. YU: We just had a signing with Michelle Zauner, who wrote *Crying in H Mart*. We actually had 240 people come, and the line out the door was three blocks long.

In addition to her and Weike Wang, there's Stephanie Foo, Qian Julie Wang, and Cathy Park Hong, who wrote *Minor Feelings*. We've had a mix of debut authors, and local poets as well. We do a poetry night where we have five or six local poets come together and they share their chapbooks. So it's a range of big names and a lot of local authors.

CHF: That makes you a resource for the artists as well.

MS. YU: I sure hope so.

RML: What is Odie's role?

MS. YU: She waits in the corner and steals people's food.

CHF: She's the self-appointed welcoming committee.

MS. YU: Exactly. She's a very good host.

CHF: Your job frankly sounds like fun. How do you go about selecting new titles and authors?

MS. YU: It *is* fun, a lot of fun. The best part is I work with my friends. One of my coworkers is a software engineer. Another was a biologist who did consulting for a couple of years, and now he works as a barista and also at the store. With all of us having similar backgrounds, one of the best parts of our job is sitting down and discovering new titles. There's a plethora of incredible titles out there. We all try to read a lot, which is another fun part of the job. Every title in the store is handpicked by one of our booksellers.

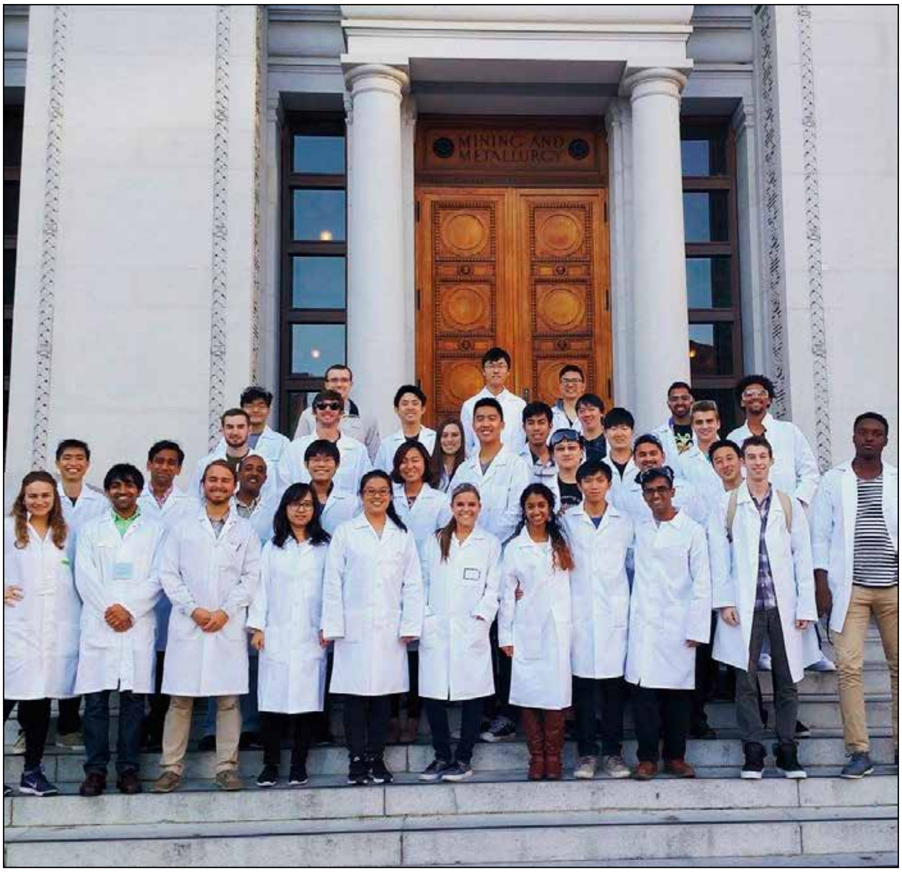
RML: How do you arrange a book signing?

MS. YU: It can happen a couple of different ways. Either we reach out to the author or the author's team, or they reach out to us, through their agent or publisher, or directly.

CHF: That's pretty fabulous that you're well-known enough that they're contacting you. That speaks volumes (no pun intended).

How do you decide on what books you're going to stock? There's such a wealth of riches and possibilities increasingly on the market. Do you ever have to say, 'Hm, we don't have room to order all seven of these titles that sound fabulous. We're going to have to narrow it down to three or four.'

MS. YU: Yes, I think any bookstore has to make that decision. There's only a limited amount of space, but as I mentioned, our inventory moves very fast. We don't keep a ton of safety stock. What we have on our shelves rotates a lot, and because of that we can add in titles that we weren't able to last week, or add them to the list for next week. It's very fluid. We have a mix of new and old titles, which always helps, and people find something new every week at the store.



Yu (second row, 5th from left) with her chemical engineering classmates at UC Berkeley.

CHF: So you can afford to be pretty flexible and nimble.

MS. YU: That's the structure that we've developed. I think we kind of have to do that in the small space that we have. But it allows it to be a different customer experience every time they come in the store.

RML: In the store photos on your website I see a lot of art on the walls. Do you also sell art, or is it on the walls because you like it?

MS. YU: We sell art from local artists in New York City. I'm also a painter, and some of the art I painted myself. We do rotate with different artists that we try to support locally.

RML: What kind of painter are you—what's your medium?

MS. YU: Mostly acrylic.

RML: Am I looking at any of your art in these website pictures? I see a photograph that has your employee of the month front and center.

MS. YU: Yes, that's the one I painted.

RML: Tell me about Odie.

MS. YU: She's a great dog, and a great employee. She sweeps the floors with her ears. Her face naturally looks disappointed, so I think it's really funny to have her as the employee of the month. She's a sweetheart and everyone loves her in the store.

RML: Is she typically in the store with you?

MS. YU: Not all the time, because she does steal all our food. But when she's there, she says hello to anyone and welcomes all the pets in the world.

RML: Do you get back to Berkeley at all, or do you have any communication with people you worked with while you were there?

MS. YU: I'm still very close with the professor I worked with when I did NMR research. We keep in touch. And a lot of the grad students that were in that program, a lot of my colleagues or classmates—I have a close group of friends and they actually all flew to New York to surprise me and support me on my opening day, which was so amazing. And sometimes people from high school or college will come in to the store and say hi.

I've pivoted pretty far from engineering at this point. It was incredibly difficult curriculum, and I really hope they're more inclusive in the way they approach it and the ways professors treat their female students especially. I had some experiences where it was clear that a lot of the female classmates I worked with were experiencing a different treatment than the majority of the class. I hope that has gotten more inclusive and a bit better.

RML: So you don't see yourself engaging in chemical engineering again?

MS. YU: Not at this point, but you never know. That's why I don't make a five-year plan.

RML: Absolutely. As we wind up, I do want to say that I get to Manhattan regularly, so don't be surprised if I pop up, but I will introduce myself.

MS. YU: Please do stop by and say hi.

RML: I will. Thank you very much, Lucy, for joining us today. I continue to be amazed by the things that engineers do that go beyond what people expect of them, and this is another great example.

CHF: Thanks a bunch for taking the time to talk with us, Lucy. What a pleasure.

MS. YU: Thank you so much. Have a wonderful month.

NAE News and Notes

Class of 2023 Elected

The NAE has elected 106 new members and 18 international members, bringing the total US membership to 2,420 and the number of international members to 319.

Election to the National Academy of Engineering is among the highest professional distinctions accorded an engineer. NAE membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature" and to "the pioneering of new and developing fields of technology, making major advances in traditional fields of engineering, or developing/implementing innovative approaches to engineering education." Election of new NAE members is the culmination of a yearlong process. The ballot is set in December and the final vote for membership occurs during January.

Individuals in the newly elected class will be formally inducted October 1, 2023, during the NAE's annual meeting. The list of the new members and international members follows, with their primary affiliation at the time of election and their election citation.

New Members

John E. Abele, owner, Meach Cove Farms, Shelburne, VT. For developing minimally invasive medicine and championing STEM education at all levels.

Ali Abur, professor, Electrical and Computer Engineering, Northeastern University, Boston. For contributions to power system state estimation and power engineering education.

Darius Adamczyk, chair and chief executive officer, Honeywell International Inc., Charlotte, NC. For technical and business leadership in quantum computing, sustainable technologies, and automation, and promoting diversity in STEM careers.

Mark G. Allen, Alfred Fitler Moore Professor and inaugural scientific director, Electrical and Systems Engineering, University of Pennsylvania, Philadelphia. For contributions to the technology and commercialization of microelectromechanical systems (MEMS) for health care.

Andrew George Alleyne, professor and dean, College of Science and Engineering, University of Minnesota, Minneapolis. For contributions to modeling and control of dynamic thermal systems, with applications in aerospace, automotive systems, and buildings.

Daniel Ammon, vice president, R&D, Collagen Matrix Inc., Oakland, NJ. For the invention and development of disruptive technologies, across many disciplines, in the medical device industry.

Shorya Awtar, chief executive officer, Parallel Robotics LLC, Ann Arbor, MI. For inventing and commercializing game-changing surgical products that have made minimally invasive surgery affordable and accessible around the world.

Michael J. Barber, chief diversity officer (retired), General Electric Co., Boston. For contributions and leadership in developing diagnostic imaging and point-of-care devices in the global healthcare sector.

Regina Barzilay, Delta Electronics Professor, Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge. For machine learning models that understand structures in text, molecules, and medical images.

Asmeret Asefaw Berhe, director, Office of Science, US Department of Energy, Washington, DC. For understanding of soil carbon cycling and sequestration as related to land use and climate change.

Vladimir Blasko, senior manager, Sikorsky Aircraft Corp., Lockheed Martin Corp., Stratford, CT. For contributions to the theory and practice of regenerative electrical drives and grid-tied converters.

Jeffery Bricker, senior director, UOP LLC, Honeywell International Inc., Des Plaines, IL. For a fundamental approach to catalysis resulting in environmentally safe technologies used globally in refining and petrochemical industries.

Tory Bruno, president and CEO, United Launch Alliance, Centennial, CO. For creating and leading space launch programs supporting national security missions and expanding future sustained space capabilities.

Markus J. Buehler, Jerry McAfee (1940) Professor in Engineering, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge. For implementing the use of nanomechanics to model and design fracture-resistant bioinspired materials.

Michael Burrows, distinguished engineer, Google LLC, Mountain View, CA. For pioneering work in compression, web search and indexing, operating systems, and security protocols.

Robert D. Caligiuri, corporate vice president and principal engineer, Materials and Corrosion Engineering, Exponent, Menlo Park, CA. For contributions to understanding failure mechanisms in engineering materials, especially in metals at very high strain rates.

J. Richard Capka, chief operating officer, Dawson & Associates, Washington, DC. For engineering leadership in executing complex, nationally significant water resource and transportation projects and fostering innovative public-private-university partnerships.

Shih-Fu Chang, dean and Morris A. and Alma Schapiro Professor, Fu Foundation School of Engineering and Applied Science, Columbia University, New York City. For contributions to multimedia search and retrieval.

Ramalingam Chellappa, Bloomberg Distinguished Professor, Electrical and Computer Engineering, Johns Hopkins University, Baltimore. For contributions to digital image analysis, automatic face recognition, and applications.

Hudong Chen, senior director, Simulia Research and Development Technology, Dassault Systèmes, Waltham, MA. For contributions to lattice Boltzmann simulation of turbulent flows and applications to automotive and aerospace industries.

Leo H. Chiang, senior R&D fellow, Dow Chemical Co., Lake Jackson, TX. For contributions to process data analytics and its applications to process monitoring and for continuous improvement in the chemical industry.

Inderjit Chopra, Alfred Gessow Professor and director of Gessow Rotorcraft Center, Aerospace Engineering, University of Maryland, College Park. For advancing rotorcraft aeromechanics/aeroelastic analysis, enhancing bearingless rotors, active control, and human-powered helicopters.

Dimitris I. Collias, research fellow, Procter & Gamble Co., West Chester, OH. For innovations in sustainable plastics used in consumer products to lower the carbon intensity of high-volume polymers.

Steven M. Cramer, William Weightman Walker Professor, Chemical and Biological Engineering, Rensselaer Polytechnic Institute, Troy, NY. For scientific and technological advances leading to new chromatographic materials, processes, and predictive tools for the purification of biopharmaceuticals.

Peter T. Cummings, John R. Hall Professor of Chemical Engineering (emeritus), Chemical and Biomolecular Engineering, Vanderbilt University, Nashville, TN. For simulation-based solutions to chemical engineering problems, and for innovations and leadership in modeling and computational nanoscience.

Jennifer Sinclair Curtis, distinguished professor, Chemical Engineering, University of California, Davis. For work on particle-laden flows and industrially used algorithms for dilute and dense-phase gas-solid flow.

Christine Mann Darden, director (retired), Strategic Communications Office, NASA Langley Research Center, Hampton, VA. For pioneering research in supersonic flight technologies and leadership in advancing aerodynamics design to produce low-boom sonic effects.

Anir Devgan, president and CEO, Cadence Design Systems, San Jose, CA. For technical and business leadership in the electronic design automation industry.

Kathy Jane Ehrig, superintendent geometallurgy, BHP Olympic Dam, Adelaide, South Australia. For advancement of geometallurgy by linking geology, mineralogy, geochemistry, and metallurgy to optimize metal recovery while minimizing waste.

Elfatih A.B. Eltahir, H.M. King Bhumibol Professor, Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge. For advancing understanding of how climate and land use impact water availability, environmental and human health, and vector-borne diseases.

Benny D. Freeman, William J. (Bill) Murray Jr. Endowed Chair in Engineering, McKetta Department of Chemical Engineering, University of Texas, Austin. For the development of polymeric membranes for gas separation, ion transport, and gas and water purification.

David Alan Friedman, president and CEO (retired), Forell/Elsesser Engineers Inc., San Francisco. For leadership in the development of innovative solutions for the seismic retrofit of historical structures.

David U. Furrer, senior fellow discipline lead, Materials and Processes, Pratt & Whitney, East Hartford, CT. For development and industrial implementation of computational modeling tools enabling efficient material/process/product design of legacy and emerging aerospace alloys.

Patrick Paul Gelsinger, chief executive officer, Intel Corp., Santa Clara, CA. For technical and business leadership in the semiconductor and computing industries.

Neil Gershenfeld, director, Center for Bits and Atoms, Massachusetts Institute of Technology, Cambridge. For eliminating boundaries between digital and physical worlds, from quantum computing to digital materials to the Internet of Things.

Donald Goldfarb, Alexander and Hermine Avanessians Professor, Industrial Engineering and Operations Research, Columbia University, New York City. For the development of widely used algorithms and methodologies for linear, quadratic, and nonlinear optimization.

James Goodnight, cofounder and chief executive officer, SAS Institute Inc., Cary, NC. For creating a leading analytics software and spearheading data science and STEM education globally.

Peter F. Green, deputy laboratory director and chief research officer, Science and Technology, National Renewable Energy Laboratory, Golden, CO. For contributions in the physics of polymer diffusion, glass behavior, and organic electronic devices, and leadership in the energy technologies.

Deborah L. Grubbe, president and owner, Operations and Safety Solutions LLC, Chadds Ford, PA. For contributions and leadership to improve engineering safety practices in the chemical process industries.

Kerrie L. Holley, director, Healthcare and Life Sciences Industry Solutions, Google Cloud, Google LLC, San Rafael, CA. For contributions to the evolution of service-oriented architectures, enabling global businesses to respond more quickly to changing market conditions.

David Huang, associate director and director of research, Casey Eye Institute, Oregon Health & Science University, Portland. For development of multidimensional micron-level optical imaging technologies that revolutionized the diagnosis and treatment of eye diseases.

Xuedong D. Huang, technical fellow and chief technology officer, Azure AI, Microsoft Corp., Redmond, WA. For technical contributions and leadership in speech and language technologies and products including the development of cloud-based intelligent systems.

Lisa Perez Jackson, vice president, Environmental, Policy, and Social Initiatives, Apple Inc., Cupertino, CA. For sustainability leadership in government and business to protect air and water quality and limit greenhouse gas emissions.

Miriam E. John, vice president emerita, Sandia National Laboratories, Livermore, CA. For national-level contributions to systems and technology for nuclear deterrence and homeland security.

Clyde Peter Jupiter, cofounder, AZIsotopes, Salt Lake City. For contributions to nuclear radiation detection and advancing nuclear energy.

Roger D. Kamm, Cecil and Ida Green Distinguished Professor of Biological and Mechanical Engineering, Biological Engineering, Massachusetts Institute of Technology, Cambridge. For contributions to the understanding of mechanics in biology and medicine, and leadership in biomechanics.

Gabriel Katul, Theodore S. Coile Distinguished Professor of Hydrology and Micrometeorology, Civil and Environmental Engineering, Duke University, Durham, NC. For advances in ecohydrology and environmental fluid mechanics.

Christine Mary Keville, president and CEO, Keville Enterprises Inc., Marshfield, MA. For promoting diversity in the engineering profession through business success, mentoring students and businesses, and leadership of national professional societies.

Anthony R. Kovscek, Keleen and Carlton Beal Professor of Petroleum Engineering, Energy Science and Engineering, Stanford University, Stanford, CA. For contributions to pore-scale imaging and understanding of foam flow in porous media.

Kelin J. Kuhn, adjunct professor, Materials Science and Engineering, Cornell University, Ithaca, NY. For technical contributions enabling development and integration of novel transistor devices.

Mark W. LeChevallier, principal and manager, Dr. Water Consulting LLC, Morrison, CO. For advancing knowledge and developing and implementing solutions for control of microbiological contaminants in drinking water.

Eva Lerner-Lam, founder and president, Palisades Consulting Group Inc., Tenafly, NJ. For accelerating adoption of intelligent transportation systems and smart city codes and standards in engineering practice.

Carlos G. Levi, Mehrabian Distinguished Professor, Materials Department, University of California, Santa Barbara. For contributions to understanding and development of high-temperature engineered surfaces and multilayers used in advanced gas turbine engines.

Stephen M. Lewis, vice president, Technology and Innovation, POET LLC, Sioux Falls, SD. For leadership in developing and commercializing bioprocess technologies that established corn ethanol as a cost-competitive, sustainable transportation fuel.

Yaoqi Joe Liu, chief technology officer, James Hardie Industries plc, Chicago. For contributions to the development and commercialization of multilayer polymeric optical film products, and for championing innovation globally.

Laurie E. Locascio, director, National Institute of Standards and Technology, Gaithersburg, MD. For development and commercialization of microfluidics technologies and visionary leadership of NIST for the benefit of US emerging technology.

Karen Lozano, Julia Beecherl Endowed Professor, Mechanical Engineering, University of Texas Rio Grande Valley, Edinburg. For contributions to nanofiber research and commercialization, and mentoring of undergraduate students from underserved populations.

Alan Luo, professor, Materials Science and Engineering, Ohio State University, Columbus. For implementation of lightweight aluminum, magnesium, and titanium materials and advanced manufacturing processes for automotive applications.

Jock Douglas Mackinlay, technical fellow, Tableau Software, Salesforce Inc., Seattle. For contributions to the fields of computational data visualization and information visualization.

Linsey C. Marr, Charles P. Lunsford Professor, Charles E. Via Jr. Department of Civil and Environmental Engineering, Virginia Tech, Blacksburg. For advancing fundamental knowledge of transport, removal, and mitigation of airborne pathogenic viruses.

Fariborz Maseeh, founder and president, Massiah Foundation, Newport Beach, CA. For leadership and advances in efficient design, development, and manufacturing of microelectromechanical systems, and empowering engineering talent through public service.

James G. Maser, senior vice president, Space, Aerojet Rocketdyne, Manhattan Beach, CA. For dedicated work in the space launch industry and leadership of established and emerging companies.

Gerard Guy Medioni, vice president and distinguished scientist, Physical Stores Tech, Amazon Inc., Los Angeles. For contributions to computer vision and its consumer-facing applications.

David F. Merrion, CEO, Merrion Expert Consulting LLC, Novi, MI. For leadership in the development of multiple advanced commercial diesel engines incorporating high-reliability, fuel-efficient, and low-emission technologies.

David W. Miller, Jerome C. Hunsaker Professor, Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge. For contributions in control technology for space-based telescope design, and leadership in cross-agency guidance of space technology.

Thuc-Quyen Nguyen, director, Center for Polymers and Organic Solids, University of California, Santa Barbara. For leadership in education and diversity, and research in organic photovoltaics for energy-efficient buildings and greenhouses.

Larry T. Nitz, executive chief engineer (retired), Electrified Propulsion, General Motors Co., Pontiac, MI. For contributions to and leadership in the development and global implementation of innovative automotive propulsion systems and electrification.

Virginia Norwood, manager (retired), Earth Resources Requirements NASA Systems Division, Hughes Aircraft Co., Topanga, CA. For the original design and implementation of radar multispectral satellite systems forming the basis for Earth-observing Landsat missions.

Christopher Kemper Ober, Francis Norwood Bard Professor of Metallurgical Engineering, Materials Science and Engineering, Cornell University, Ithaca, NY. For the invention of new photoresist families enabling high-resolution lithography in microelectronics manufacturing.

Douglas M. Owen, senior principal, Stantec, Carlsbad, CA. For contributions to drinking water quality, expansion of potable reuse, and integration of sustainability in water treatment plant design.

Karen Ann Panetta, dean of graduate education and professor, School of Engineering, Tufts University, Medford, MA. For leadership empowering females in STEM, and for contributions to computer vision and simulation algorithms.

Panos Y. Papalambros, James B. Angell Distinguished University Professor Emeritus and Donald C. Graham Professor Emeritus, Mechanical Engineering, University of Michigan, Ann Arbor. For contributions to complex systems optimization and leadership in advancing transformative engineering design research and education.

David Parrillo, vice president, Research and Development, Dow Chemical Co., Midland, MI. For development and commercialization of innovative processes and products for consumer and industrial applications.

Christa D. Peters-Lidard, deputy director, Science and Exploration, NASA Goddard Space Flight Center, Greenbelt, MD. For contributions to understanding land-atmosphere interactions, soil moisture monitoring and modeling, and leadership in Earth system modeling.

Martin Gerard Plys, chief technology officer and vice president, Waste Technology and Post-Fukushima Services, Fauske & Associates Inc., Burr Ridge, IL. For contributions to nuclear reactor safety and the science of waste technology for irradiated nuclear fuel.

Mark Prausnitz, Regents' Professor and J. Erskine Love Jr. Chair in Chemical & Biomolecular Engineering, School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, Atlanta. For invention, development, and translation of dissolvable microneedles for painless vaccination and drug delivery.

Thomas Ward Prete, vice president, Military Engineering, Pratt & Whitney, Northford, CT. For engineering leadership in developing and servicing advanced military and commercial aircraft jet engines.

T.S. Ramakrishnan, senior scientific advisor, Schlumberger-Doll Research Center, Cambridge, MA. For contributions to petrophysics, reservoir characterization, abandonment of production wells, and carbon sequestration and storage.

James Edward Rekoske, senior vice president, Global RD&E Industrial, Ecolab, Glenview, IL. For leadership in development and implementation of petrochemicals, renewable fuel, alternative energy, and water conservation technologies.

Anil Sachdev, principal technical fellow and lab group manager, General Motors Co., Warren, MI. For the research, development, and commercialization of lightweight materials to improve vehicle fuel economy.

Adalio T. Sanchez, president, S Group Advisory LLC, Naples, FL. For contributions that improved business processes through the advancement of leading-edge innovations in personal, enterprise server, and supercomputing systems.

William H. Sanders, Dr. William D. and Nancy W. Strecker Dean, College of Engineering, Carnegie Mellon University, Pittsburgh. For technical contributions and interdisciplinary leadership in cybersecurity and resiliency technologies for critical infrastructures.

Stefan Savage, professor, Computer Science and Engineering, University of California, San Diego. For contributions to the security, privacy, and reliability of network systems, transforming approaches to problems in these areas.

Christopher H. Scholz, professor emeritus, Applied Physics and Applied Mathematics, Columbia University, New York City. For developing experimental and theoretical studies on faulting and earthquake mechanics.

David Simchi-Levi, professor, civil and environmental engineering, Massachusetts Institute of Technology, Cambridge. For contributions using optimization and stochastic modeling to enhance supply chain management and operations.

J. Gary Smyth, executive director (retired), Global Research & Development, General Motors Co., Rochester Hills, MI. For leadership and technology innovation in automotive energy efficiency, environmental sustainability, vehicle electrification, and autonomous driving.

Kenichi Soga, Donald H. McLaughlin Chair in Mineral Engineering and Chancellor's Professor, Civil and Environmental Engineering, University of California, Berkeley. For advances in geomechanics and computational modeling, as well as simulation and monitoring of underground infrastructure.

John W. Sutherland, professor and Fehsenfeld Family Head, Environmental and Ecological Engineering, Purdue University, West Lafayette, IN. For research contributions to environmental sustainability in manufacturing and their implementation in industry.

Melody A. Swartz, William B. Ogden Professor, Pritzker School of Molecular Engineering, University of Chicago. For fundamental and translational insights into lymphatic transport, immunobiology, and immunoengineering, leading to novel approaches for cancer immunotherapy and vaccination.

Costas Emmanuel Synolakis, president, Socrates Program, Athens College, Los Angeles. For the development of predictive models and early warning systems of tsunamis, and advising policymakers in hazard management.

Kevin L. Tomsovic, Chancellor's Professor, Min H. Kao Department of Electrical Engineering and Computer Science, University of Tennessee, Knoxville. For contributions to power system computational methods and power engineering education.

Hansel Tookes II, chair and chief executive officer (retired), Raytheon International Inc., Palm Beach Gardens, FL. For leading the design and development of advanced military aircraft engines and systems.

Elias D. Towe, Albert and Ethel Grobstein Professor, Materials Science and Engineering, Carnegie Mellon University, Pittsburgh. For contributions to semiconductor quantum structures and applications in heterogeneous photonic and electronic devices and systems.

Amin Vahdat, fellow and vice president, Google LLC, Mountain View, CA. For contributions to the design and implementation of datacenter and planet-scale networks that power cloud computer systems.

Q. Jane Wang, professor, McCormick School of Engineering, Northwestern University, Evanston, IL. For contributions to computational tribology in industrial applications.

Gregory Nathaniel Washington, president, George Mason University, Fairfax, VA. For the advancement of technology at the interface of electromagnetics and materials, and dedicated leadership and service in engineering education.

Paul Westerhoff, Regents Professor and Fulton Chair of Environmental Engineering, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe. For leadership and pioneering research on emerging contaminants assessment and water purification technologies.

William Woodburn, founding partner and operating partner, Global Infrastructure Partners, Greenwich, CT. For leadership applying engineering principles to improve infrastructure businesses and founding Engineering Tomorrow to advance STEM education.

Dawn Jeannine Wright, chief scientist, Environmental Systems Research Institute, Redlands, CA. For applying geographic information system technology to ocean science and developing GIS models for the oceans.

Vanessa E. Wyche, director, NASA Johnson Space Center, Houston. For leadership of NASA's Johnson Space Center, enabling a commercial space economy and future Moon and Mars missions.

Longya Xu, cofounder and director (retired), Center for High Performance Power Electronics, Ohio State University, Columbus. For contributions to high-performance electric machines and variable-speed drives for aerospace and wind turbines.

Jie Xue, vice president, Technology and Quality, Cisco Systems Inc., San Jose, CA. For engineering and leadership contributions to high-reliability networking product development and manufacturing.

Lily Y. Young, professor and dean of international programs, School of Environmental and Biological Sciences, Rutgers University, New Brunswick, NJ. For implementing work on anaerobic microbial metabolism enabling remediation of organic and metal contaminants in the environment.

Douglas C.H. Yu, vice president, Research and Development, Taiwan Semiconductor Manufacturing Co. Ltd., Hsinchu, Taiwan. For contributions to advanced integrated circuit interconnects and microelectronics packaging technologies.

Linda Zall, environmental scientist (retired), Central Intelligence Agency, Clermont, FL. For leadership in enabling synergistic use of classified reconnaissance satellite imagery for advanced Earth environmental studies through international cooperation.

Ji-Cheng (JC) Zhao, department chair and Minta Martin Professor of Engineering, Materials Science and Engineering, University of Maryland, College Park. For contributions to computational alloy design, integrated computational materials engineering, and high-throughput methods used in industrial products.

New International Members

Claire S. Adjiman, professor, Chemical Engineering, Imperial College London, United Kingdom. For developing the fundamental principles for advanced thermodynamic modeling of complex fluids and improving industrial productivity using these models.

Frank Kenneth Crundwell, director, CM Solutions (Pty) Ltd., Johannesburg, South Africa. For elucidating fundamental reactions and mechanisms of mineral dissolution to optimize metal extraction.

Vikram S. Deshpande, professor, Engineering, University of Cambridge, United Kingdom. For contributions to mechanics of microarchitected solids with applications to structures under extreme dynamic loading.

David B. Dreisinger, professor, Materials Engineering, University of British Columbia, Vancouver, Canada. For contributions to the development of hydrometallurgical processes and their transfer to industry.

Alfonso Farina, consultant, Land and Naval Systems Division, Leonardo SpA, Rome, Italy. For contributions to the development and deployment of advanced radar systems and technology.

Martin A. Green, Scientia Professor, Photovoltaic and Renewable Energy Engineering, University of New South Wales, Sydney, Australia. For technical contributions enabling the proliferation of silicon photovoltaics.

Hakki Polat Gülkan, professor, Civil Engineering, Başkent University, Ankara, Turkey. For improving earthquake safety of buildings and seismic resilience worldwide.

Nicholas J. Higham, Royal Society Research Professor and Richardson Professor of Applied Mathematics, School of Mathematics, University of Manchester, United Kingdom. For design and analysis of matrix algorithms widely used in diverse engineering applications.

Wei Huang, vice chancellor, Frontier Science Center for Flexible Electronics, Northwestern Polytechnical University, Xi'an, China. For innovation and leadership in organic optoelectronics materials and devices.

Innocent Kamwa, professor, Electrical and Computer Engineering, Laval University, Quebec, Canada. For contributions to adaptive power grid control schemes and synchronous generator testing and standards.

Luis M. Liz-Marzán, Ikerbasque Research Professor and group leader, BioNanoplasmonics Lab, CIC biomaGUNE, Donostia–San Sebastián, Spain. For contributions and application of colloid chemistry in the fields of nanoplasmonics, nanoparticles, and nanosensors.

Aniruddha B. Pandit, vice chancellor and UGC Professor, Chemical Engineering, Institute of Chemical Technology, Mumbai, India. For contributions to cavitational reactors from concept to commercialization, and engineering solutions to improve the lives of underserved people.

Dan Peer, director and vice president, Laboratory of Precision NanoMedicine, Tel Aviv University, Israel. For developing strategies for systemic, cell-specific delivery of RNA payloads.

Judit Eva Puskas, distinguished professor, Food, Agricultural, and Biological Engineering, Ohio State University, Wooster. For coinventing an FDA-approved, life-saving coronary stent coating, and fundamental research and scale-up of polymerization processes.

Andreas Seidel-Morgenstern, director, Physical and Chemical Foundations of Process Engineering, Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany. For contributions to adsorption, preparative chromatography, and crystallization processes and to development and theory for resolving enantiomeric mixtures.

Raman Sujith, chair professor, Aerospace Engineering, Indian Institute of Technology, Madras. For applications of dynamical systems theory to the understanding and control of instabilities in engineering systems.

Michel Virlogeux, consultant, Michel Virlogeux Consultant SARL, Bonnelles, France. For achievements in the design and construction of concrete segmental, composite, and long-span cable-supported bridges.

Fan-Gang Zeng, professor and director, Center for Hearing Research, University of California, Irvine. For engineering better treatments for hearing loss and tinnitus, and for fostering inclusiveness in the engineering profession.

NAE Newsmakers

Linda M. Abriola, Joan Wernig & E. Paul Sorensen Professor of Engineering, Brown University, has been **elected a fellow of the American Association for the Advancement of Science**.

Hari Balakrishnan, Fujitsu Professor of Computer Science, Massachusetts Institute of Technology, is the recipient of the 2023 Marconi Prize, often referred to as the "Nobel Prize for Communications." Professor Balakrishnan was cited for "fundamental contributions to wired and wireless networking, mobile sensing, and distributed systems."

Rodolphe Barrangou (NAS), Todd R. Klaenhammer Distinguished Professor in Probiotics Research, North Carolina State University, and **Lynn A. Conway**, professor of electrical engineering and computer science, emerita, University of Michigan, have been **elected to the National Inventors Hall of Fame**. Dr. Barrangou, with Philippe Horvath, discovered that CRISPR (clustered regularly interspaced short palindromic repeats) sequences and associated proteins confer acquired immunity in bacteria, laying the foundation for the burgeoning field of gene editing. Professor Conway is recognized for her role in transforming the global microelectronics industry with the invention of very large-scale integration.

Karl Deisseroth (NAS/NAM), D.H. Chen Professor of Bioengineering and of Psychiatry and Behavioral Sciences, Stanford University and Howard Hughes Medical Institute, is the corecipient, with Gero Miesenböck, of the **2023 Japan Prize** in the field of life science. They are recognized for their development of methods that use genetically addressable light-sensitive membrane proteins to unravel neural circuit function.

Huajian Gao (NAS), Distinguished University Professor, Nanyang Technological University, Singapore, has won the ASCE **2022 Zdeněk P. Bažant Medal for Failure and Damage Prevention**. Dr. Gao was chosen "for his contributions to fracture mechanics and failure prevention in nanostructured materials, including metals, metamaterials, and battery electrodes."

Newly elected member **Martin A. Green**, Scientia Professor, photovoltaic and renewable energy engineering, University of New South Wales, Sydney, Australia, shares the **Queen Elizabeth Prize for Engineering** with Andrew Blakers, Aihua Wang, and Jianhua Zhao for their work developing PERC (passivated emitter and rear cell) solar technology, the highly efficient solar cells that have become central to global efforts to reduce carbon emissions.

Dorota A. Grejner-Brzezinska, Lowber B. Strange Endowed Chair and University Distinguished Professor, Ohio State University, has been **appointed a member of the National Science Board** by President Biden.

Daniel E. Hastings, Cecil and Ida Green Education Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology, has been **named to serve on the National Space Council's Users Advisory Group** by Vice President Kamala Harris, Council chair. According to a White House news release, the UAG "will advise and inform the [NSC] on a broad range of aerospace topics, including the impacts of US and international laws and regulations, national security space priorities relating to the civil and commercial space sectors, scientific and human space exploration priorities, and ways to bolster support for US space priorities and leadership in space."

Freeman A. Hrabowski III, president emeritus, University of Maryland, Baltimore County, will be presented the **2023 Public Welfare Medal** by the National Academy of Sciences on April 30 during the Academy's 160th annual meeting. The medal, the NAS' most prestigious award, honors him for his outstanding leadership in transforming US science education and increasing cultural diversity in the science workforce.

Chennupati Jagadish, president, Australian National University, and Distinguished Professor in ANU's Department of Electronic Materials Engineering, has won the **2023 Pravasi Bharatiya Samman**, India's highest award for overseas Indians.

Robert E. Kahn (NAS), president and CEO, Corporation for National Research Initiatives, has been selected for the **James Madison Medal**, presented each year to a Princeton alum of the Graduate School who has had a distinguished career, advanced the cause of graduate education, or achieved an outstanding record of public service. Dr. Kahn, coinventor of the fundamental communication protocols at the heart of the internet, received the medal February 25.

Ahsan Kareem, Robert M. Moran Professor of Engineering, NatHaz Modeling Laboratory, University of Notre Dame, has won a second **J. James R. Croes Medal** from ASCE. He shares the 2022 honor with Dr. Xihaier Luo for their paper "Dynamic Mode Decomposition of Random Pressure Fields over Bluff Bodies." The Croes medals will be awarded at the ASCE Convention October 23–26 in Anaheim, California.

Cato T. Laurencin (NAS/NAM), University Professor, Van Dusen Distinguished Professor, University of Connecticut Health Center, received the **2023 Shu Chien Achievement Award**, the most prestigious honor bestowed by the Cellular and Molecular Bioengineering Group of the Biomedical Engineering Society. The award recognizes an individual who has made exceptional contributions to the field of cellular and molecular bioengineering.

Khaled B. Letaief, New Bright Professor of Engineering and Chair Professor of Electronic and Computer Engineering, Hong Kong University of Science and Technology, became the first in Hong Kong and one of the first few in Asia to receive the IEEE Communications Society's **Edwin Howard Armstrong Achievement Award** since it was established in 1958. The award is a major career honor given annually to an individual who demonstrates persistent outstanding contributions in the field of communications and networking. Prof. Letaief was recognized for his pioneering and sustained contributions to adaptive OFDMA and wireless system design.

Ming-Jun Li, corporate fellow, Global Research, Corning Research & Development Corporation, is the **2023 John Tyndall Award** recipient, recognized for "seminal contributions to advances in optical fiber technology." The award is presented by Optica (formerly OSA), Advancing Optics and Photonics Worldwide, and the IEEE Photonics Society.

Asad M. Madni, retired president, COO, and CTO, BEI Technologies Inc., and independent consultant, has received the Royal Academy of Engineering's **Prince Philip Medal**. Presented November 8 in London, the award recognizes Dr. Madni's decades-long career developing and commercializing intelligent sensors and systems across the aerospace, manufacturing, and transportation industries.

Krzysztof Matyjaszewski (NAS), J.C. Warner University Professor of Natural Science, Carnegie Mellon University, has been selected to receive the **NAS Award in Chemical Sciences** for trailblazing advances in polymer chemistry. He will be honored in a ceremony April 30 during the NAS annual meeting.

The **2023 King Faisal Prize for Science (Chemistry)** was awarded jointly to **Chad A. Mirkin** (NAS/NAM), director, International Institute for Nanotechnology, Northwestern University, for his work in chemistry that helped define the modern age of nanotechnology, and **Jackie Y. Ying**, senior fellow and director of A*STAR NanoBio Lab, for her work on the synthesis of advanced nanomaterials and systems and their applications in energy conversion and biomedicine.

Sanjit K. Mitra, professor emeritus, electrical and computer engineering, University of California, Santa Barbara, was unanimously elected an **honorary member of the Bilim Akademisi**, the Science Academy of Turkey.

Colin J. Parris, senior vice president and CTO, GE Digital Energy, was named **2023 Black Engineer of the Year** by *US Black Engineer & Information Technology* magazine at the 37th annual Black Engineer of the Year Award STEM Conference held February 9–11. Dr. Parris was recognized for his significant contributions to the fields of science and engineering and his work in digital transformation.

On February 2, during the Regional to Global Conference organized by Global Energy in Uruguay, **Kaushik Rajashekara**, Distinguished Professor of Engineering, University of Houston, was awarded the **2022 Global Energy Prize in the New Ways of Energy Application**. He was chosen for his outstanding contributions to transportation electrification and energy efficiency technologies while reducing power generation emissions.

Junuthula N. Reddy, Distinguished Professor, Regents Professor, and O'Donnell Foundation Chair IV Professor, Texas A&M University, has been elected a **fellow of the Spanish Royal Academy of Engineering**, an **honorary member of the European Academy of Sciences**, and a **member of the European Academy of Sciences and Arts**.

Vijay P. Singh, Distinguished Professor, Regents Professor, and Caroline & William N. Lehrer Distinguished Chair in Water Engineering, Texas A&M University, has been honored with the **2022 Robert G. Wetzel Award for Water Quality** from the American Institute of Hydrology, presented November 9 at the American Water Resources Association annual conference. The award recognizes individuals who have made outstanding contributions in the field of water quality.

Samuel I. Stupp (NAS), Board of Trustees Professor of Materials Science and Engineering, Chemistry, Medicine, and Biomedical Engineering, and director, Simpson Querrey Institute for BioNanotechnology, Northwestern University, has received the **2022 Von Hippel Award**, the highest honor of the Materials Research Society. The prize recognizes "brilliance and originality of intellect, combined with vision that transcends the boundaries of conventional scientific disciplines."

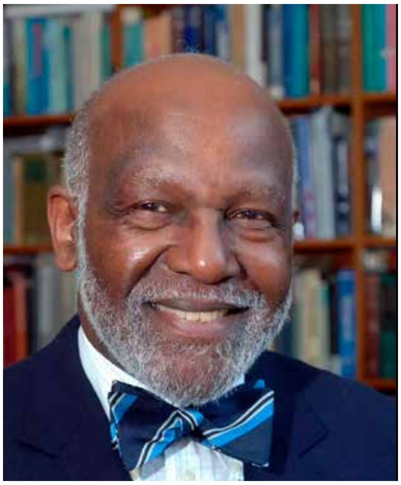
The Franklin Institute has announced its 2023 Laureates. **Deb A. Niemeier**, Clark Distinguished Chair, Energy and Sustainability, University of Maryland, College Park, will receive the **2023 Bower Award and Prize for Achievement in Science**. Dr. Niemeier was selected for "pioneering the advancement and application of knowledge at the intersections among infrastructure, environment, public health, and equity through groundbreaking research on transportation systems and climate-related hazards." **Barbara H. Liskov** (NAS), Institute Professor, Massachusetts Institute of Technology, has been selected for the **2023 Benjamin Franklin Medal in Computer and Cognitive Science** for "seminal contributions to computer programming languages and methodology, enabling the implementation of reliable, reusable programs." Awards will be presented April 27 at the Franklin Institute Awards Ceremony and Dinner.

The National Academy of Inventors has announced the **NAI Class of 2022 Fellows**. Among them are **Rodolphe Barrangou** (NAS), Todd

R. Klaenhammer Distinguished Professor in Probiotics Research, North Carolina State University; **Farshid Guilak** (NAM), Mildred B. Simon Research Professor, Washington University in St. Louis; **Petros A. Ioannou**, A.V. "Bal" Balakrishnan Chair, University of Southern California; and **Roe-Hoan Yoon**, University Distinguished Professor and Nicholas T. Camicia Professor, Virginia Tech.

IEEE has announced its 2023 medal recipients. **Vinton G. Cerf** (NAS), VP and Chief Internet Evangelist, Google LLC, is awarded the **Medal of Honor** for "cocreating the internet architecture and providing sustained leadership in its phenomenal growth in becoming society's critical infrastructure." **Rodney A. Brooks**, Panasonic Professor of Robotics Emeritus, MIT, will receive the **Founders Medal** for "leadership in research and commercialization of autonomous robotics, including mobile, humanoid, service, and manufacturing robots." **Rebecca R. Richards-Kortum** (NAS), Malcolm Gillis University Professor, Rice University, is the recipient of the **Medal for Innovations in Healthcare Technology** for "contributions to optical solutions for cancer detection and leadership in establishing the field of global health engineering." The **Jack S. Kilby Signal Processing Medal** goes to **José M.F. Moura**, Philip & Marsha Dowd University Professor, Carnegie Mellon University, for "contributions to theory and practice of statistical, graph, and distributed signal processing." **Mau-Chung Frank Chang**, Wintek Chair in Electrical Engineering at UCLA, will be presented the **IEEE/RSE James Clerk Maxwell Medal** for "contributions to heterojunction device technology and CMOS system-on-chip realizations with unprecedented reconfigurability and bandwidth." **James J. Truchard**, retired president, CEO, and founder, National Instruments Inc., will receive the **James H. Mulligan Jr. Education Medal** for "the development of LabVIEW and establishing worldwide programs to enhance hands-on learning in laboratories and classrooms." The **Jun-ichi Nishizawa Medal** is awarded to **James S. Harris**, James and Ellenor Chesebrough Professor Emeritus, Stanford University, for "contributions to epitaxial growth and nanofabrication of materials and heterojunction devices." **Luc Van den hove**, president and CEO, Interuniversity Microelectronics Center, Belgium, is selected for the **Robert N. Noyce Medal** for "leadership in creating a worldwide research ecosystem in nanoelectronics technology with applications ranging from high-performance computing to health." **Azad M. Madni**, CEO and CTO, Intelligent Systems Technology Inc., has been chosen to receive the **Simon Ramo Medal** for pioneering contributions to model-based systems engineering, education, and industrial impact using interdisciplinary approaches. **F. Thomson Leighton** (NAS), CEO and cofounder, Akamai Technologies Inc., will receive the **John von Neumann Medal** for "fundamental contributions to algorithm design and their application to content delivery networks."

Message from NAE Vice President Wesley L. Harris



What a year 2022 shaped up to be! I was honored to take on the role of vice president, and I want to take a moment to thank all the members, friends, and partners who donated last year and have supported the NAE in the past. Your support enables the NAE to provide leadership in a world of accelerating change. As vice president, thank you for your continued support.

At last year's NAE annual meeting—the first in-person annual meeting since 2019—we inducted an unprecedented three classes and publicly launched a landmark $100 million comprehensive fundraising campaign to support the NAE. The *Campaign for Leadership in a World of Accelerating Change* seeks to strengthen the NAE's position as the trusted source of engineering advice for creating a healthier, more secure, and more sustainable world.

By drawing on the entire NAE community, the Campaign will support the Academy's core operations and the advisory and actionable outcomes of its programs. You can learn more about the Campaign, watch our inspiring video that makes me proud to be an engineer, and get involved at www.nae.edu/acceleratingchange.

Thanks to your generosity last year, the NAE raised over $4.8 million in new cash, pledges, and planned gifts, including over $2.1 million in flexible, unrestricted funds, 17 six-figure commitments and planned gifts, a $500,000 charitable gift annuity, and three new endowed funds. As of December 31, 2022, we are 54.6% of the way to our $100 million goal for the Campaign. These new funds are critical to the NAE's future and financial health.

You may not think of yourself when you hear the term *philanthropist*. But we all have a part to play, and collectively you genuinely make a difference in the NAE's ability to answer the call whenever it may come.

Your donations sustain approximately 60% of the NAE's operations directly or indirectly. Whether you are providing unrestricted funds to the NAE Independent Fund, donating to a specific program or initiative that is especially meaningful for you, or empowering the longevity of the Academy through endowment support, you are critical to our ongoing work.

The Grainger Foundation Frontiers of Engineering (FOE) continues to forge invaluable cross-disciplinary connections between early-career engineers. The Ligler-Wagoner Challenge for FOE—a $200,000 matching gift challenge launched in late 2021—is now over 47% of the way to its goal. We are grateful to the past participants and friends of the program who have joined this effort by donating. Your generosity is helping to raise and expand the profile of this signature NAE program and ensure its career-changing impacts for future generations. Learn more about the Ligler-Wagoner Challenge for FOE and how you can participate at www.naefrontiers.org.

Lastly, I am pleased to provide updates regarding our annual and lifetime giving societies. The Great Hall Society—the National Academies' leadership annual giving society—saw a 10% increase in membership last year. Members are recognized at two levels: silver, for donors who give $5,000–$9,999, and gold, for donors who give $10,000 or more in a calendar year. And I'm happy to report that as of the end of 2022, the NAE has more Einstein Society members (lifetime giving $100,000–$249,000) than the other two Academies combined with 96 members, 29 Curie Society members (lifetime giving $250,000–$499,999), 13 Franklin Society members (lifetime giving $500,000–$999,999), and 12 Lincoln Society members (lifetime giving of at least $1 million).

Looking Ahead

The start of a new year is a time to reflect, recalibrate, and recommit ourselves to the values we strive toward in our professional and personal lives. This time of reflection is critical to ensure that we are continually growing and learning.

At the NAE, we remain committed to providing engineering leadership and insights for a complex world by focusing on people, systems, and culture. Reinforcing this commitment are our core values of independence, integrity, and dedication to diversity, equity, and inclusion to foster intergenerational collaboration for all people's greater good and well-being.

As vice president of the NAE, I am committed to ensuring that you—our members and friends—understand the impact you make at the Academy through your donations. The success of the NAE's *Campaign for Leadership in a World of Accelerating Change* requires us all to come together and answer the call to ensure the Academy's sustained effectiveness for future engineers.

Thank you, again, for all that you do in support of and service to the NAE every year.

Wesley L. Harris

2022 Honor Roll of Donors

We greatly appreciate the generosity of our donors. Your contributions enhance the impact of the National Academy of Engineering's work and support its vital role as advisor to the nation. The NAE acknowledges contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. The gifts reflected on this list are as of December 31, 2022.

Lifetime Giving Societies

We gratefully acknowledge the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of the Academies as advisor to the nation on matters of science, engineering, and medicine.

The Abraham Lincoln Society

In recognition of members and friends who have made lifetime contributions of $1 million or more to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

Bruce and Betty Alberts
Richard and Rita* Atkinson
Norman R. Augustine
Craig and Barbara **Barrett**
Jordan and Rhoda **Baruch***
Stephen D. Bechtel Jr.*
Arnold and Mabel **Beckman***
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Michael and Sheila Held*
Jane E. Henney and Robert Graham
William R. and Rosemary B. **Hewlett***
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Irwin and Joan **Jacobs**
Robert L.* and Anne K. James
Kenneth A. Jonsson*
Fred Kavli*
Daniel E. Koshland Jr.*
Tillie K. Lubin*
Whitney* and Betty MacMillan
John F. McDonnell
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The Ambrose Monell Foundation
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Bernard and Rhoda Sarnat*
Leonard D. Schaeffer
Sara Lee and Axel Schupf
James H. and Marilyn Simons
John and Janet **Swanson**
Marci and **James J. Truchard**
Anthony J. Yun and Kimberly A. Bazar
Anonymous (1)

The Benjamin Franklin Society

In recognition of members and friends who have made lifetime contributions of $500,000 to $999,999 to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

John and Pat **Anderson**
Rose-Marie and Jack R. Anderson*
John and Elizabeth **Armstrong**
Kenneth E. Behring*
Gordon Bell
Elkan R.* and Gail F. Blout
Russell L. Carson
Charina Endowment Fund
James McConnell Clark*
Barry and Bobbi Coller
Ross and Stephanie **Corotis**
Henry David*
Richard Evans*
Eugene Garfield Foundation
Theodore Geballe*
Penny and **Bill George**, George Family Foundation
Christa and Detlef Gloge
William T.* and Catherine Morrison Golden
Alexander Hollaender*
Thomas V. Jones*
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Ralph and Claire **Landau***
Asta and **William W. Lang***
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Ruben F.* and Donna **Mettler**
Dane* and Mary Louise **Miller**
Oliver E. and Gerda K. Nelson*
Shela and **Kumar Patel**
Henry and Susan **Samueli**
Herbert A. and Dorothea P. Simon*
Raymond and Maria **Stata**
Roy and Diana Vagelos
Andrew and Erna* **Viterbi**
Alan M. Voorhees*
Anonymous (2)

*Deceased

The Marie Curie Society

In recognition of members and friends who have made lifetime contributions of $250,000 to $499,999 to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

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Daniel and Lana Branton
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Rosie and Stirling A. Colgate*
W. Dale and Jeanne C. **Compton***
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James O. Ellis Jr. and **Elisabeth Paté-Cornell**
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Diane E. Griffin
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Wesley L. Harris
John L. Hennessy
Chad and Ann **Holliday**
William R. Jackson*
Anita K. Jones
Mary and **Howard Kehrl***
Kent Kresa
Mark and Becky **Levin**
Frances and **George Ligler**
Stella and **Steve Matson**
William W. McGuire
Janet and **Richard M.*** **Morrow**
Clayton Daniel and Patricia L. **Mote**
Ralph S. O'Connor*
Kenneth H. Olsen*
Larry* and Carol **Papay**
Stephen Quake
Ann and **Michael Ramage**
Simon Ramo*
Richard F. and Terri W. **Rashid**
Anne and **Walt* Robb**
Matthew L. Rogers and Swati Mylavarapu
Julie and **Alton D. Romig Jr.**
Stephen* and Anne Ryan
H.E. Simmons*
Edward C. Stone
Judy Swanson
Ted Turner
Leslie L. Vadasz
Martha Vaughan*
Charles M.* and Rebecca M. **Vest**
Robert and Robyn **Wagoner**
Susan R. Wessler
Wm. A. Wulf
Anonymous (2)

The Einstein Society

In recognition of members and friends who have made lifetime contributions of $100,000 to $249,999 to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

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Holt Ashley*
Nadine Aubry and John L. Batton
Francisco J. and Hana Ayala
William F. Ballhaus Sr.*
David Baltimore
Thomas D.* and Janice H. **Barrow**
H.H. and Eleanor F. Barschall*
Sunanda Basu
Donald and Joan Beall
Daniel and Frances **Berg**
Diane and Norman Bernstein*
Bharati and **Murty Bhavaraju**
Chip and Belinda **Blankenship**
Erich Bloch*
Barry W. Boehm*
Gopa and **Arindam Bose**
Paul F. Boulos
David G. Bradley
Lewis M. Branscomb
John and Sharon Brauman
Sydney Brenner*
Lenore and **Rob Briskman**
Malin Burnham
Ursula Burns and Lloyd Bean*
Eugen and **Cleopatra Cabuz**
Christine Cassel and Michael McCally
Josephine Cheng
Priscilla and **Sunlin* Chou**
John and Assia **Cioffi**
Paul Citron and Margaret Carlson Citron
A. James Clark*
Ellen Wright Clayton and Jay Clayton
G. Wayne Clough
John D. Corbett*
Pedro M. Cuatrecasas
Roy Curtiss and Josephine Clark-Curtiss
Ruth David and Stan Dains
Jeffrey Dean and Heidi Hopper
Zhonghan John Deng
Roman W. DeSanctis
Julie H. and Robert J. Desnick
Robert* and Florence **Deutsch**
Paul M. Doty*
Charles W. Duncan Jr.*
George and Maggie Eads
Robert and Cornelia **Eaton**
The Eleftheria Foundation
Emanuel and Peggy Epstein*
Thomas E. Everhart
Peter Farrell
Michiko So* and Lawrence Finegold
Tobie and **Daniel J.* Fink**

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*Deceased

Delbert A. and Beverly C. Fisher
George and Ann **Fisher**
Robert C.* and Marilyn G. **Forney**
Harold K.* and Betty **Forsen**
Edward H. Frank and Sarah G. Ratchye
Yellow H. Gandhi
Elsa M. Garmire and Robert H. Russell
Melinda F. Gates
William H. Gates III
Louis V. Gerstner Jr.
Nan and **Chuck* Geschke**
Jack and Linda Gill
Sid Gilman and Carol Barbour
Martin E. and Lucinda **Glicksman**
Avram Goldstein*
Robert W. Gore*
Robert K. Grasselli* and Eva-Maria Hauck-Grasselli
Diane Greene and **Mendel Rosenblum**
Corbin Gwaltney*
Carol K. Hall
Margaret A. Hamburg and Peter F. Brown
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Catherine Adams Hutt and Peter Barton Hutt
Jennie S. Hwang
M. Blakeman Ingle
Trina and Michael Johns
Richard B. Johnston Jr.
Trevor O. Jones
Robert E. Kahn and Patrice A. Lyons
Thomas Kailath
Paul and Julie **Kaminski**
Yuet Wai and Alvera Kan
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Casey Gibson Joins Program Office

We welcome Casey Gibson as an associate program officer, initially working on projects related to the Cultural, Ethical, Social, and Environmental Responsibility in Engineering (CESER) program. Casey recently completed her MS degree as part of the inaugural cohort of the Humanitarian Engineering & Science program at the Colorado School of Mines. Her dissertation focused on integrating environmental engineering principles, community-based research methods, and anthropological tools to conduct a qualitative environmental risk assessment in Colombian gold mining/coffee farming communities. Before that, she was an English teaching assistant through the Fulbright Program in Mexico. Casey holds dual undergraduate degrees in Spanish and biological/agricultural engineering from the University of Arkansas and is looking forward to bringing these transdisciplinary skills and passions to the National Academies. In her free time, she enjoys international travel, playing with her dog Elote, going to live music events, being out in nature, and watching stand-up comedy.

Calendar of Meetings and Events

February 24	Underrepresented Minorities NAE
March 1–31	Election of NAE Officers and Councillors (online)
March 22–25	German-American Frontiers of Engineering Jülich, Germany
April 4–5	NAE Regional Meeting: The Mobility Electrification Revolution University of Illinois at Urbana-Champaign
April 12	NAE Regional Meeting University of Central Florida
April 25	NAE Regional Meeting Lincoln Laboratory, Massachusetts Institute of Technology
May 2	2023 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education presentation University of Southern California (by invitation only)
May 9	Council Meeting (virtual)

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

New Volume of *Memorial Tributes* Available

The 25th volume in the NAE's *Memorial Tributes* series, commemorating the lives and contributions of members and international members, is now available both in print and online. The personal remembrances, often penned by colleagues and friends, are intended to be not only an enduring record of engineering and technical accomplishments but also an effective portrait of each subject. We are grateful to the NAE members and others who take the time to craft these thoughtful, inspiring, and engaging accounts.

This volume includes the following tributes:

Jan D. Achenbach
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Clarence R. Allen
Arthur G. Anderson
Stephen D. Bechtel Jr.

David T. Blackstock
Ned H. Burns
Max W. Carbon
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In Memoriam

H. Norman Abramson, 96, retired executive vice president, Southwest Research Institute, died December 19, 2022. Dr. Abramson was elected in 1976 for research in engineering dynamics, research management, and contributions to professional engineering society affairs.

John C. Angus, 88, Kent H. Smith Professor Emeritus of Engineering, Case Western Reserve University, died February 20, 2023. Dr. Angus was elected in 1995 for research in the growth of diamond and diamond-like films by low-pressure chemical vapor deposition.

James R. Biard, 91, independent consultant, died September 23, 2022. Dr. Biard was elected in 1991 for contributions to semiconductor light-emitting diodes and lasers, Schotky-clamped logic, and read-only memories.

Kenneth A. Blenkarn, 93, retired research director, Offshore Technology, Amoco Production Company, died December 5, 2022. Dr. Blenkarn was elected in 1987 for major contributions in technology leading to safe and practical systems for drilling in ice-laden and very deep waters.

John D. Bredehoeft, 89, consultant, The Hydrodynamics Group, LLC, died January 1, 2023. Dr. Bredehoeft was elected in 1994 for fundamental and applied contributions to subsurface fluid engineering and science concerning water management nuclear waste disposal and seismic hazards.

Frederick P. Brooks Jr. (NAS), 91, Kenan Professor of Computer Science Emeritus, University of North Carolina at Chapel Hill, died November 17, 2022. Professor Brooks was elected in 1975 for contributions to computer system design and the development of academic programs in computer sciences.

Herbert S. Cheng, 92, Walter P. Murphy Professor of Mechanical Engineering Emeritus, Northwestern University, died October 24, 2022. Dr. Cheng was elected in 1987 for pioneering contributions to the tribology of gas, elastohydrodynamic, plastohydrodynamic, and mixed lubrication, and for leadership in developing collaborative university and industrial research in tribology.

Welko E. Gasich, 99, executive vice president, programs, Northrop Corporation (retired), died January 14, 2022. Mr. Gasich was elected in 1979 for the conception and development of advanced supersonic trainer and international lightweight lowcost fighter aircraft.

C. William Gear, 87, senior scientist of chemical biological engineering, Princeton University, died March 15, 2022. Dr. Gear was elected in 1992 for seminal work in methods and software for solving classes of differential equations and differential-algebraic equations of significance in applications.

Niels Hansen, 87, Department of Wind Energy, Materials Research, and Advanced Characterization Section, Technical University of Denmark, died August 19, 2021. Dr. Hansen was elected a foreign associate in 1995 for development of the science and technology of the strengthening of polycrystalline materials and for leadership of metallurgical research in Denmark.

David A. Hodges, 85, Daniel M. Tellep Professor, University of California, Berkeley (retired), died November 13, 2022. Professor Hodges was elected in 1983 for innovative contributions to integrated circuit design techniques and their application to data and signal processing.

Stanley H. Horowitz, 97, retired consultant, died November 24, 2022. Mr. Horowitz was elected in 1995 for contributions to electric power systems reliability and integrity through advanced protective relaying concepts.

Jack L. Koenig, 88, professor emeritus, Case Western Reserve University, died January 25, 2022. Professor Koenig was elected in 2000 for applications of spectroscopic methods of polymeric materials.

James N. Krebs, 98, retired vice president, GE Aircraft Engines, died July 20, 2022. Mr. Krebs was elected in 1982 for preliminary design and concept development of aircraft engines, and cycle and mechanical innovations on high-temperature, high-bypass, and variable-cycle engine components.

James L. Lammie, 91, chair (retired), Parsons Brinckerhoff Inc., died November 9, 2022. Mr. Lammie was elected in 1993 for contributions to the organization, direction, and control of large transportation design and construction projects in the urban environment.

Alexander I. Leontiev, 95, professor, Bauman Moscow State Technical University, died November 30, 2022. Professor Leontiev was elected a foreign associate in 2008 for contributions to the fundamental understanding of convective heat transfer, and for furthering international scientific cooperation.

Philip M. Neches, 70, venture partner, Entrepreneurs Roundtable Accelerator, died September 25, 2022. Dr. Neches was elected in 2012 for the architecture and software of parallel database appliances.

John W. Palmour, 62, chief technology officer, Wolfspeed Inc., died November 13, 2022. Dr. Palmour was elected in 2022 for development of silicon carbide (SiC)–based advanced electronic devices.

Frank D. Robinson, 92, retired president, Robinson Helicopter Company, died November 12, 2022. Mr. Robinson was elected in 2011 for the conception, design, and manufacture of low-noise, low life-cycle cost, and high-reliability helicopters.

Ignacio Rodríguez-Iturbe (NAS), 80, Distinguished University Professor & Wofford Cain Chair I, Texas A&M University–College Station, died September 28, 2022. Professor Rodríguez-Iturbe was elected in 1988 for innovations in the analysis, synthesis, and sampling of hydrologic signals, and for inspirational leadership in hydrologic research and education.

Peter W. Sauer, 76, Grainger Chair Professor Emeritus of Electrical Engineering, University of Illinois at Urbana-Champaign, died December 27, 2022. Dr. Sauer was elected in 2003 for technical contributions to the modeling, simulation, and dynamic analysis of power systems and for leadership in power engineering education and research.

Ronald V. Schmidt, 78, independent consultant, died September 22, 2022. Dr. Schmidt was elected in 1994 for contributions to electronic and optical communications and for entrepreneurial leadership.

G. Paul Willhite, 83, Ross H. Forney Distinguished Professor Emeritus, University of Kansas, died December 15, 2022. Professor Willhite was elected in 2006 for research, technology, and education outreach in tertiary oil-recovery processes.

Adrian Zaccaria, 77, retired vice chair, Bechtel Group Inc., died September 7, 2022. Mr. Zaccaria was elected in 2007 for leadership in the design, construction, and maintenance of power plants and other types of engineering facilities all over the world.

Invisible Bridges

(Un)intended Consequences

Beth Cady is a senior program officer and director of the NAE program on Practices for Engineering Education and Research (PEER).

Engineering has contributed to many positive things, such as the supply and distribution of clean water, the automobile and airplane, and communications technologies from the telephone to the internet. But a deeper look at the Greatest Engineering Achievements of the 20th Century (www.greatachievements.org/) illuminates not only inequitable distribution of those achievements but also negative consequences for some communities. For example,

- Highways were intentionally built in ways that destroyed Black neighborhoods and overpasses were constructed to prevent public buses from reaching the suburbs on Long Island.
- Air conditioning and refrigeration benefit primarily those in high-income countries, but the climate changes associated with the chemicals used to cool ourselves and our food affect low- and middle-income countries far more than ours.
- Electronics and appliances are eventually discarded in landfills, and many of the other technologies listed also require disposal of byproducts. The United States has a history of siting landfills, chemical plants, and other properties likely to result in negative health effects in low-income communities. And a 1987 study showed that, although "socioeconomic status was implicated in siting hazardous waste facilities, race was the most significant variable"[1]—approximately 60 percent of Black or Hispanic/Latine Americans and about half of Asian Americans, Pacific Islanders, and Native Americans live near toxic waste sites.
- Nuclear technologies require uranium mining, which often occurs on reservations, poisoning Native communities and water supplies. It's been pointed out that "collapsing environmental discrimination against people of color into one monolithic group elided the experience of Indigenous people who had been undergoing environmental devastation of a particular, genocidal kind."[1]

While these consequences are often framed as "unintended," they frequently are not. To paraphrase a joke about science, engineers can design a method for cloning a *Tyrannosaurus rex*, but humanities can tell us why that might be a bad idea. In other words, to avoid (un)intended consequences, engineers must work with other disciplines, incorporate other ways of knowing (e.g., Indigenous knowledge, non-Western traditions), and practice "*epistemic humility*—recognition that our way of knowing is not the only way of knowing."[2] This recognition is critical, for "only by recognizing and being comfortable with the limits of their expertise can engineers actually help the people and the planet thrive, not just some people, on some parts of the planet."[3]

Unfortunately, usual practice doesn't follow this advice, which is why an "activist engineer" has been defined "as someone who not only can provide specific engineered solutions, but who also steps back from their work and tackles the question, What is the real problem and does this problem 'require' an engineering

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

[1] Gilio-Whitaker D. 2019. As Long As Grass Grows: The Indigenous Fight for Environmental Justice from Colonization to Standing Rock (pp. 16, 18). Beacon Press.

[2] Riley DM. 2018. Foreword. In: Transforming Engineering Education and Practice, eds Leydens JA, Lucena JC (pp. xvii–xxi). Wiley–IEEE Press.

[3] Cech E. 2012. Great problems of Grand Challenges: Problematizing engineering's understandings of its role in society. International Journal of Engineering, Social Justice, and Peace 1(2):85–94.

intervention?"[4] Not all problems require a technological solution. As made clear in the Law of the Instrument, a cognitive bias affecting all humans, "if the only tool you have is a hammer, it is tempting to treat everything as if it were a nail."[5]

Framing the problem correctly requires reflection on these two questions, as well as consultation and/or collaboration with all communities who are or might be affected. Problem framing can lead to (un)intended consequences when the community that is affected is not involved in that framing and Indigenous, non-Western, and other disciplinary knowledge and ways of knowing are ignored. This is especially critical given the "intersectional privilege" of White, nondisabled, cisgender, heterosexual men in STEM fields,[6] because that privilege can lead to minimizing or overlooking the lived experiences of those with intersecting marginalized identities.[7]

Several guiding questions can frame problems in a way that will avoid (un)intended consequences and lead to engineering justice[8]: "What is placed into the problem? What and who is left out? Who draws the borders of what stays in and is left out and based on what assumptions and values? And whose perspectives (interests, values, knowledge, desires) are emphasized, de-emphasized, or ignored?"

When men dominate design teams and are assumed to be the end user for those designs—what has been called "one-size-fits-men"[9]—women suffer. For example, because many masks, boots, gloves, and other items of personal protective equipment (PPE) are designed solely using the "average man" specifications despite the need for women to use them, women experience more injuries and even death resulting from ill-fitting PPE than men do.[5] It is well known that the first automobile airbags injured women; less well known is the fact that crash test dummies used for safety testing of cars have since the 1950s been based on the "average" male. Although an "average" female crash dummy was finally developed in 2011, it did not account for differences in muscle mass and distribution between men and women *and* was used only in the passenger seat, apparently assuming that women rarely drive.

To avoid (un)intended consequences, engineers must practice "epistemic humility—*recognition that our way of knowing is not the only way of knowing.*"

Ideally, engineers would follow the rule of "nothing about us without us," which became part of disability activism in the 1990s.[10] Of course, most if not all engineered solutions affect a wide variety of users and stakeholders whose opinions about how the solutions would affect them are informed by their intersectional identities. Consulting with every possible end user would be time consuming and would also lead to conflicting information. However, it is critical for engineers to cast as wide a net as possible to inform solutions.

Diverse design teams are only part of the path forward, especially because many individuals do not feel they can bring their authentic selves to engineering.[11] For example, many LGBTQ+ individuals in STEM education and the workforce "struggle to be visible, to be heard, and to be recognized."[12] Every engineered solution, policy, or cultural practice must strive for equi-

4 Karwat DMA, Eagle WE, Wooldridge MS, Princen TE. 2014. Activist engineering: Changing engineering practice by deploying praxis. Science and Engineering Ethics 21:227–39.

5 Maslow AH. 1966. The Psychology of Science: A Reconnaissance (p. 16). Harper & Row.

6 Cech EA. 2022. The intersectional privilege of white able-bodied heterosexual men in STEM. Science Advances 8(24):eabo1558.

7 Intersectionality recognizes that individual identities are a function of the intersection of characteristics such as gender, race, ethnicity, socioeconomic status, religion, sexuality, appearance, and disability, among others. For example, a straight White man is likely to experience life and perceive the world differently from a Latina lesbian or a disabled African American veteran—or even a straight White woman.

8 Leydens JA, Lucena JC. 2018. Engineering Justice: Transforming Engineering Education and Practice (p. 20). Wiley–IEEE Press.

9 Criado Perez C. 2019. Invisible Women: Data Bias in a World Designed for Men (p. 157). Abrams Press.

10 See, e.g., NDI's page "From 'nothing about us without us' to 'nothing without us,'" Mar 28, 2022.

11 For example, see the interview with Lucy Yu in this issue (pp. 65–72).

12 Cross KJ, Farrell S, Hughes B. 2022. Queering STEM Culture in Higher Education: Navigating Experiences of Exclusion in the Academy (pp. 268, 278). Routledge.

table outcomes, and "inequitable outcomes should be identified and characterized by [those]…that experience them."[8]

Engineers would also do well to follow recent guidance issued by the White House on the use of Indigenous knowledge in federal decision making: "Since Indigenous Knowledge is often unique and specific to a Tribe or Indigenous People, and may exist in a variety of forms, Agencies often lack the expertise to appropriately consider and apply Indigenous Knowledge. As a result, consultation and collaboration with Tribal Nations and Indigenous Peoples is critical to ensuring that Indigenous Knowledge is considered and applied in a manner that respects Tribal sovereignty and achieves mutually beneficial outcomes for Tribal and Indigenous communities."[13]

Humanitarian engineering, peace engineering, and other relatively new efforts address (un)intended consequences head-on. Hopefully these programs will eventually just be called "engineering" and not need a modifier that expresses work toward justice, because all engineering work and education will incorporate these ideas.

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[13] Prabhakar A, Mallory B. 2022. Guidance for federal departments and agencies on Indigenous knowledge (p. 2). White House, Nov 30.

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