The BRIDGE

LINKING ENGINEERING AND SOCIETY

50th ANNIVERSARY ISSUE

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Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7,000 including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/Publications/Bridge.aspx.*

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The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The National Academy of Engineering was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The National Academy of Medicine (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the National Academies of Sciences, Engineering, and Medicine to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at www.nationalacademies.org.

Editors' Note

Bridges to the Future

Ronald Latanision

Cameron Fletcher

Ronald M. Latanision (NAE) is a senior fellow at Exponent.
Cameron H. Fletcher is managing editor of *The Bridge*.

We are delighted to celebrate the 50th year of publication of the NAE's flagship quarterly with this special issue featuring 50 essays looking forward to the next 50 years of innovation in engineering.

From its early days as a 4-page member newsletter, *The Bridge* has evolved to a thematic quarterly with a distribution of some 7000 individuals around the country and the world. Focus areas are suggested by both members and nonmembers, and guest editors for each issue line up topics and experts to provide effective coverage of the selected subject. In addition, when possible we accommodate unsolicited submissions, which lately have come from engineering students, a welcome voice in our pages.

Recognizing that our lives today are profoundly affected by technology—much of which was not even envisioned 50 years ago—for this issue we call on the curiosity and imagination of engineers and others to express their vision of our technological future. We lead off with a keynote essay, "Temptations of Technocracy in the Century of Engineering" by Sheila Jasanoff, calling for emphasis on both innovation and responsibility as we look forward to the next 50 years. Engineering and technology will continue to serve social purposes, and everyone will benefit from more inclusion and deliberation as new technologies are introduced into daily life and the social fabric.

The following invited papers explore technical, philosophical, regulatory, historical, and societal aspects and impacts of engineering efforts to contribute to quality of life. They consider achievements, possibilities, and challenges in engineering "writ large"—from space exploration, artificial intelligence, cybersecurity, plastics, and quantum computing to fashion, finance, equity, and peace. Topics also include a number of the NAE's 14 Grand Challenges for Engineering, such as efforts to engineer the tools of scientific discovery, make solar energy economical, develop carbon sequestration methods, and provide access to clean water, among others. In the absence of an organizing theme, the papers are presented in alphabetical order by author.

At times innovations have yielded unintended consequences, and we are very pleased that NAE president **John Anderson** addresses this perennial concern in his column. It is a crucial consideration as technology increasingly pervades daily life, living spaces—and even, as projected here, the human body.

In identifying contributors, we sought to enlist a variety of voices to represent the exquisite diversity of perspectives that will ensure a robust future for engineering. The authors are men and women of all races and range in age from 30 to 95; they are in business, academia, and government; from all parts of the country and a few other countries besides; and they include elected members of all three academies.

Finally, we are enormously grateful to **Asad Madni** and **Ming Hsieh** for their generous funding of this issue, which would not exist without their support.

We hope you enjoy and learn from this collection of eye-opening, thoughtful, and thought-provoking essays, and we welcome your feedback.

Foreword

A Special 50th Anniversary Issue

Asad Madni

Ming Hsieh

Asad M. Madni (NAE) is retired president, chief operating officer, and CTO of BEI Technologies, Inc. Ming Hsieh (NAE) is CEO and chair of Fulgent Therapeutics.

At a lunch table during the 2019 NAE annual meeting in Washington, we joined Editor in Chief **Ron Latanision**, Managing Editor Cameron Fletcher, and NAE Director of Programs Guru Madhavan in a conversation about the upcoming 50th anniversary of the publication of *The Bridge*. They were considering a suitable commemorative issue, but mindful that resources would be necessary to pull it together. As enthusiastic supporters and dedicated readers of *The Bridge*, we offered that we would be very glad to provide the funding for this anniversary issue.

We are both members of the NAE's Section 7: Electronics, Communications, and Information Systems Engineering, but we appreciate that this quarterly makes a point of appealing to engineers in every area. Recent issues, for example, have explored nuclear energy, aeronautics, climate change, cybersecurity, and disaster resilience. And the articles are written to be accessible to all readers regardless of expertise.

This issue is no different, except that it spans an exceptional variety of engineering areas within its pages instead of exploring one theme in depth. With the diversity of subjects, it is sure to engage readers and prompt thoughtful reflection on engineering advances and innovations that can truly benefit everyone.

We applaud Ron and Cameron for their resourcefulness and dedication in planning this issue and engaging contributors to examine opportunities in so many different fields. These essays give us all much to think about as we plan for the future!

President's Perspective

Unintended Consequences

John L. Anderson, President, NAE

In theory there is no difference between theory and practice, while in practice there is.[1]

The intention to "do good" is not always realized in the engineering of artifacts, processes, and systems. Innovations have led to many improvements in health, security, and quality of life, but in some cases there have been serious unintended consequences.

A current example of the double-edged sword of technology is social media. While global society has benefited from connectedness and instantaneous communication, malevolent activities such as terrorism and cyberbullying have proliferated. With any new technology there is a potential for both good and bad uses, and sometimes there is collateral damage that is difficult to predict.

One source of unintended consequences lies in design flaws. As **Henry Petroski** notes, "Everything designed by human beings is potentially flawed."[2] This is especially relevant to designs involving human-machine interactions or the way the designed artifact interacts with the environment. As an example of the latter problem, Petroski cites the unintended consequences of buildings designed with polished stainless-steel façades, which reflect sunlight in a harmful way into adjacent buildings. While such flaws can usually be corrected after the fact, they result in lost time, money, and often credibility.

Some unintended consequences have lasting effects. Thomas Midgley is credited with the development of two important innovations in the first half of the 20th century that were initially beneficial to society but later proved detrimental to human health and the planet's sustainability.[3,4] The first was tetraethyl lead (TEL), a compound he and colleagues discovered that greatly reduces "engine knock" and improves fuel efficiency. TEL was so successful commercially that it spawned a new company, Ethyl. Although it was known that lead is toxic to animals, the US Bureau of Mines concluded that the product could be manufactured in a way safe for the workers. Unfortunately, little thought was given to the build-up of lead in the environment resulting from vehicle exhaust fumes. Most Americans who were tested showed elevated levels of lead in their blood after the introduction of TEL, and by the 1980s leaded gasoline was phased out of production.[4]

Midgley's second invention was dichlordifluoromethane (Freon), the first commercial CFC, which replaced other refrigerants such as ammonia. The chemical inertness and lack of toxicity made Freon

[1] Brewster B. 1881. Quoted in the Yale Literary Magazine 47(416):202.

[2] Petroski H. 2019. Overlooked or ignored modes of failure. American Scientist 107(2):90–93.

[3] Leslie SW. 1980. Thomas Midgley and the politics of industrial research. Business History Review 54(4):480–503.

[4] McNeill JR. 2000. Something New Under the Sun: An Environmental History of the Twentieth-Century World. New York: W.W. Norton & Company.

an ideal substitute for other, corrosive and toxic refrigerants, and it also found use as a gas carrier in spray cans. At a meeting of the American Chemical Society in 1930, Midgley made a dramatic demonstration of the safety of Freon by inhaling the gas and then exhaling over a lighted candle to extinguish the flame, thus demonstrating its inertness (noncombustibility) and lack of toxicity (Midgley lived).[4] Freon looked like a win-win for all, until CFCs were implicated in thinning the planet's ozone layer.[5]

These and other examples demonstrate that engineers should seriously consider potential impacts of a design or invention on individuals, society, and nature. The connection between engineering and society should be tighter than it is. Could a new technology cause harm to segments of the population and widen the gap between the haves and have-nots? Is there racial or ethnic bias in the algorithms we are developing for artificial intelligence and automated systems? Could a new product damage the environment, or negatively affect the way humans interact?

Some unintended consequences are foreseeable. In retrospect, it should have taken little imagination to realize that curved, reflective surfaces concentrate light and heat. Yet the famed architect Rafael Viñoly designed two buildings that created what some called "death rays" across public spaces under certain conditions, resulting in costly remediations.[6]

As we look to the future, engineers should accept responsibility for incorporating the consideration of possible unintended consequences into their work and seeking to minimize the possibility of their occurrence. The National Academy of Engineering will contribute in at least two ways. The NAE Program Office has a new initiative on Cultural, Ethical, Social, and Environmental Responsibility in engineering (CESER); one of its goals is to focus on avoiding the unintended consequences of engineering innovation. And the NAE annual meeting will feature a special lecture on engineering and society.

Because engineers want to improve society through technology, we must first understand both the needs and the vulnerabilities of society, including the sustainability of our planet.

It is not enough to state the obvious: any new technology can result in harmful effects or be put to bad uses. Our responsibility as engineers is to anticipate and minimize these unintended consequences.

[5] Molina MJ, Rowland FS. 1974. Stratospheric sink for chlorofluoromethanes: Chlorine atom-catalysed destruction of ozone. Nature 249:810–12.

[6] Taylor-Foster J. 2013. Seven architectural sins committed around the world. ArchDaily, Sep 13.

Keynote

Temptations of Technocracy in the Century of Engineering

Sheila Jasanoff is Pforzheimer Professor of Science and Technology Studies at Harvard University's John F. Kennedy School of Government.

Sheila Jasanoff

Chemistry, physics, and biology took turns shaping the frontiers of industrial development from the mid-19th century onward, but this century's future belongs squarely to engineering.

This is an era of unprecedented convergence across multiple fields, propelled by breakthroughs in nano-, bio-, information, and cognitive sciences and technologies (Roco and Bainbridge 2003). In all of these areas, knowledge is moving with lightning speed from bench to applications, blurring familiar distinctions between science and technology.

To illustrate, DDT languished on the shelves of synthetic chemistry for 70 years before its rediscovery as an insecticide in 1939 won patents and in 1948 a Nobel Prize. Knowledge of its harmful environmental effects came decades later (Carson 1962). In contrast, for CRISPR-Cas9 and genome editing, the transit from lab to applications to a Nobel took only a tenth as long (2012–20), and already scientists are talking about using gene editing to redirect evolution (Doudna and Sternberg 2017).

The Age of Engineering: Evidence and Implications

Science, more than ever, is attuned to meeting human needs, and that shift also favors engineering. Where else should one look for solutions to grand planetary challenges such as the existential threats of climate change, pandemics, famine and food insecurity? The age of pure science, if there ever was one, is past; the age of engineering lies enticingly ahead.

In America, a country wedded to pragmatism and problem solving, the rise of engineering should bode well. The world is awash in problems, and if technological ingenuity holds answers, then America's fix-it, entrepreneurial spirit should be enjoying a field day. And indeed,

- College students today seem more keen on starting new businesses based on technological innovation than pursuing careers in basic research.
- Visions like the Fourth Industrial Revolution promise to create engineering-based commodities, services, and therapies to improve billions of lives and create wealth for all.
- Silicon Valley remains the epicenter of these starry-eyed dreams.
- The Chan Zuckerberg Initiative says it supports "science and technology that will make it possible to cure, prevent, or manage *all* diseases by the end of this century." (Emphasis added here and in the next two items.)
- Google wants to "organize the world's information and make it *universally* accessible and useful."
- The Singularity University wishes to leverage "exponential technologies … to solve humanity's *biggest* challenges."

But if engineering has emerged as the powerhouse of progress in the 21st century, with power comes responsibility. Speed, scale, and pervasiveness create untold opportunities for human advancement, but they also open the door to making big mistakes with little or no accountability. The world does not need heedless technocracy, bringing more Bhopals, more Fukushimas, or misguided one-child policies based on physical science models that did not consider human behavior (Greenhalgh 2008).

Will engineering rise to the challenges of responsible innovation? That depends on how it avoids three great temptations that come with the prospect of remaking the world as we know it.

Temptation: Technology Leads Society

The first temptation is to assume that technology leads society, while ethics and law lag behind, timid handmaidens that hold back progress or arrive too late to the project of making lives better. This belief encourages an unthinking and unreflective extension of the power of engineering. It assumes that the new is good in itself and disruption the path of virtue.

Among engineers, it is common to think that unwillingness to embrace novelty is a problem of bias and ignorance. Reluctance and ambivalence then become barriers to overcome, so that society falls in line with the next big thing, recognizing its merits.

Speed, scale, and pervasiveness create opportunities for human advancement, but also open the door to big mistakes with little or no accountability.

But there may be good reasons for holding back.

We are learning the hard way that the internet was not the instrument of democratization and personal liberation that its pioneers imagined in the 1990s. If law and ethics, and ordinary people's values, had been insistently at the table when the internet's designers first went to work, would there be more intelligent forms of connectivity than in today's world of shredded privacy, rampant misinformation, destructive bullying, silos of extremism, and vast wealth concentrated in the hands of very few? It is hard to know for certain, but giving information technology free rein clearly did not realize the designers' early utopian fantasies.

Temptation: The Mt. Everest Syndrome

The second temptation is the Mt. Everest syndrome: if engineers can do something, then, as with climbing the highest mountain ("because it's there"), they should do it. This way of thinking may yield short-term benefits for some, but it does not ensure that innovation will serve the needs of the wider human community.

Deeply problematic uses are already coupled with technologies of tracking and identification, such as facial recognition software. The introduction of the gig economy, enabled by information technologies, has put workers at risk and threatens grave destabilization in the labor market. Even wildly popular technologies, such as blockbuster drugs, Microsoft Word, and smartphones, are seen today as possible hindrances to further innovation, their very success having produced the conditions for premature lock-ins. Engineering, as these cases show, rules lives, and like any instrument of power it needs to be governed.

Engineering should be a slow process of inclusion and deliberation, not like an extreme sport, where the one with the best equipment and most financial backing invariably wins.

As an object of governance, engineering should be seen as more like constitution making, a slow process that calls for inclusion and deliberation, and less like extreme sports, where the race is to the swiftest and the one with the best equipment and most financial backing invariably wins.

Temptation: "Value-Free" Engineering

The third temptation is to insist that engineering design is value-free and merely a tool for solving problems. This conviction avoids reflection on how and why engineers choose the problems they wish to solve. It marches hand in hand with the perception that technological failures are due to misuse or abuse.

According to this way of thinking,

- There was nothing wrong with nuclear power. It was mismanagement and human error that led to events like Chernobyl and Fukushima.
- There is nothing the matter with chemicals or plastics. It's only unfortunate that humans overuse them.
- Genetic engineering and editing are merely means of correcting nature's errors. Regulation can ensure that they will be safely used.

These simple but widely cited examples ensure that mistakes and disasters are seen as unintended consequences. Whatever went wrong, it was not the designers' fault. The problems arose downstream.

Even more perniciously, some mistakes are seen as inevitable: the few must suffer for the greater good. Never mind that the burden of error often falls disproportionately on the most vulnerable, nor that some projects of progress, such as the search for immortality, chiefly reflect the imaginations of the rich.

Resisting Temptation

2020 is a metaphor for perfect vision, and a bridge between two half-centuries of this publication. For rapidly converging technologies to fulfill the dream of serving humanity well, one hopes the next 50 years will see more serious engagement between engineering and its ethical, legal, and social analysts.

Which of us would not wish to design a better world? To realize that vision in the decades ahead, engineers will have to resist the temptations of mistaking innovation for progress, equating *can* with *should*, and treating responsibility as if it's someone else's business.

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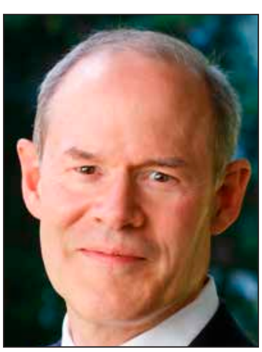
Healthy Buildings in 2070


Joseph Allen


John Macomber

Joseph G. Allen and
John D. Macomber

Fifty years seems a very long time in the future for most industries. Not so in buildings and real estate; built structures routinely last decades if not hundreds of years, as long as they are economically competitive. Any discussion of the 50-year future has to consider existing stock as well as what's being built new.

New Public Awareness

Some things do change. Four factors have recently emerged in the public awareness and will shape how the public and the industry consider healthy buildings:

- People now have a vivid idea of what "public health" means in light of the covid-19 pandemic—the impacts of which are both more obvious and more immediately deadly than those of particulates or plastics.
- Indoor air quality is clearly part of this equation. Until now, for the most part when people talked about air pollution they were referring to smog or other contaminants in outdoor air. But most people spend 90 percent of their time indoors (Allen and Macomber 2020a). Indoor air quality

Joseph Allen is an associate professor and director of the Healthy Buildings program at Harvard's T.H. Chan of School of Public Health. John Macomber is a senior lecturer in finance at Harvard Business School.

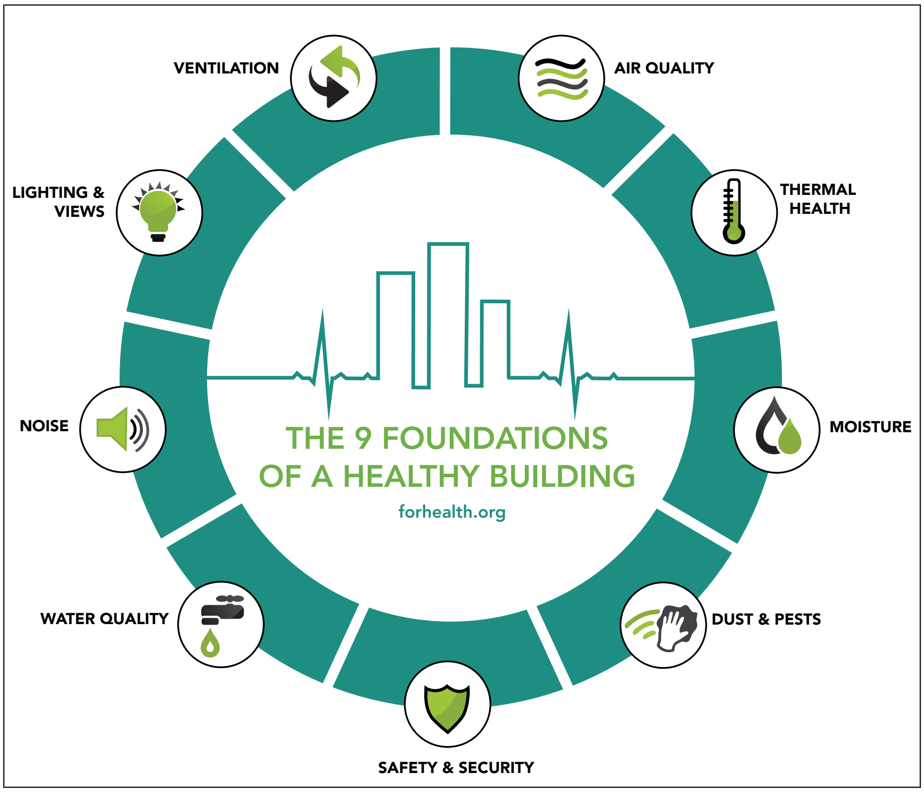


FIGURE 1 Nine foundations of a healthy building.

robustness of timbers, beams, and roofing. Our research indicates that there are nine foundations to a healthy building (figure 1; Allen et al. 2018).

Most of these are easy to detect. Although indoor air quality is the least well understood, most readers know they have spent unhappy time in stuffy hotel rooms, stale conference rooms, or stultifying classrooms. In the coming decades, as people are increasingly aware of the effects of bad indoor air and are equipped with personal air quality monitors, they will not tolerate it. This means that both new and existing buildings will need to invest in adaptations to be "more healthy"—and prove that the claim is true.

matters for health in general—as became clear during the pandemic—and levels of CO_2, particulates, and volatile organic compounds directly affect human cognition as well (Allen et al. 2016).

- Sensors and big data are personal and ubiquitous. A few years ago, a specialty hygienist had to be consulted to measure a few representative samples of air quality. Now dozens of inexpensive personal air quality monitors are available to give homeowners, renters, factory workers, or theatergoers real-time continuous readouts of air quality. These can be shared online and aggregated into reports that the public and others can use (Allen and Macomber 2020a).
- Numerous physical perils threaten buildings, power grids, subways, and roads, such as riverine flooding, drought, sea level rise, wildfire … and pandemic. Every one of these makes it harder to keep a building and its occupants healthy.

These trends mean that engineers and designers will increasingly be asked to define a healthy building based on the health prospects of the occupants, not on the

Measures and Controls

How can building health be measured and documented? Indicators of health performance (Allen and Macomber 2020a) can refer to the building's engineering (ventilation) and to objectively measurable conditions (temperature, humidity, CO_2, particulates). Others refer to the human users. Real-time indicators include biometric screening or subjective comfort surveys; lagging indicators include sick days for individuals and, increasingly important, retrospective healthcare costs for employers.

As we have advised building owners and managers about returning to work in the context of the covid-19 pandemic, benefit and cost should be balanced across a hierarchy of controls that also effectively balances risk (figure 2; Allen and Macomber 2020b).

The widest, most effective layer of the inverted pyramid is social isolation and quarantine. But it's also the most costly in terms of disruption to business and society. Next is substitution of activities, in which only workers deemed essential return to the physical workplace, while many jobs are performed remotely or by proxies like personal grocery shoppers or even robots. Personal protective equipment, the cheapest approach in terms of capital cost, is the smallest component because it's also less effective than the others (although often the most frequently deployed).

Two of the three middle "slices" will have the most impact both in coping with or recovering from the pandemic and in the buildings of the future. Administrative controls are what the office manager, landlord, or facilities manager decides about when or whether people come to work. Decisions about office density, how elevators are used, whether there is a salad bar, and management of queues and flows of people in and around a building arrived with covid-19 and will likely continue.

Engineering controls involve the physical infrastructure, things like air changes per hour, filtration efficiency, water quality, humidity, conveyances, windows. Because of the pandemic, they may now also include ultraviolet germicidal irradiation (UVGI) lights in ductwork or new HEPA-based filtration systems.

Engineering controls come at highly varying cost. It's one thing to build a new house in the suburbs with stronger exhaust fans. It's quite another to retrofit a high-rise downtown office with operable windows and associated HVAC upgrades when the structure was built to deliver a fixed minimum level of ventilation (that inadvertently compromised air circulation and quality).

Strategies

This means that there are likely to be quite different strategies over the next 50 years that vary by both building type and location. Single-family homes are the most numerous building type in the world, whether custom made by a specialty builder or self-built in a slum or favela, and they are where people spend most of their time (in fact, people spend a full third of their life in one room, the bedroom). These dwellings may have multiple problems, so getting health right is critical in the residential sector.

In new buildings, it's easier to engineer health into the core of the structure. Older cities in developed economies, however, may find that hundreds or thousands of existing structures need improvements that can't be made simply by starting over.

Going Forward

The ideal is to design buildings to be healthy. This is driven by the current heightened awareness that buildings can spread disease—or help protect their occupants.

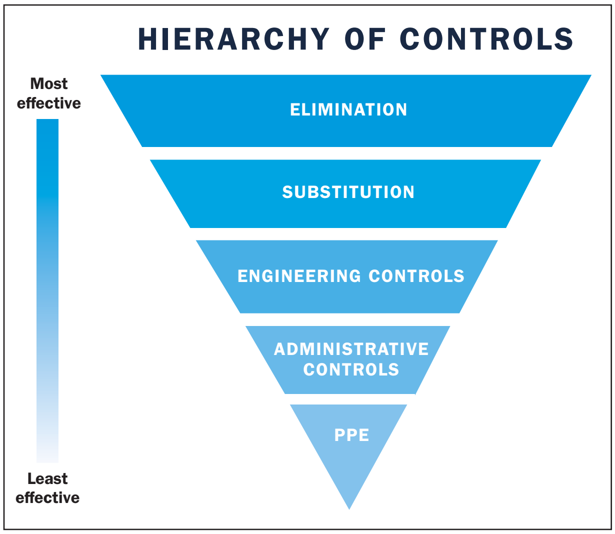


FIGURE 2 Hierarchy of controls to minimize risk in the workplace. PPE = personal protective equipment. Adapted from NIOSH (2015).

Market signals already indicate that companies are reevaluating their offices around health considerations, and some people are fleeing dense city apartments for more space in the suburbs. For apartment renters or condo buyers who have freedom of choice, for office tenants who are informed and thoughtful about the impact of indoor air quality on productivity, and for hotels, schools, conference centers, and hospitals, the ability to provide a healthy building will be a clear business differentiator, particularly in cities and regions of the world where the outside air is unhealthy.

Landlords, tenants, homeowners, renters, office workers, and students can all measure and share information about a building's health performance in real time today. This democratization of information will lead to healthy building changes as revolutionary in this industry as mutual fund rankings were for the investment industry or user ratings for travel and restaurants.

Healthy buildings of 2070 will be assessed by the health of the people first, and the condition of the structure second. Good, healthy buildings will do well economically. Bad ones will decline in value or be abandoned.

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Bringing Space Down to Earth

Norman Augustine (NAE, NAS) was chair and CEO of Lockheed Martin and chaired reviews of the US space program for Presidents George H.W. Bush and Barack Obama.

Norman R. Augustine

Mark Twain is reputed to have said that history does not repeat itself but it often rhymes. Such is likely to be the relationship of commercial airline travel and commercial spaceline travel.

Advances in space travel are also likely to be a microcosm of whatever advances occur in engineering as an overall field, but the latter is not without formidable challenges. There is, for example, a vast difference between what engineers *can* do and what actually gets *done*. Recall the US supersonic airliner, the superconducting supercollider, the US high-speed "bullet" train, and various other projects.

Looking back 50 years to when humans first set foot on the moon, optimism for human space exploration was rampant. Travel to Mars seemed to be just around the corner. But in the 50 years since, no human has been more than about 250 miles from Earth—roughly the distance from New York to Washington, DC.

Impediments to Progress

What are major impediments that could inhibit engineering accomplishments over the next 50 years? Four hurdles seem to stand out and, ironically, none has to do with technology itself.

Call the first of these "the Return of the Luddites." Concern over job losses due to the introduction of automation (e.g., to replace car and truck drivers) and artificial intelligence (e.g., to handle clerical work and retail functions) is very real and deep when one ventures outside the sometimes insular engineering community. In the past, technological advances, while not infrequently destroying jobs, generally created more and better jobs. But there is no law of nature that says this must be true in the future.

Second, a substantial portion of the public is concerned about the loss of privacy, whether to government or to malevolent individuals exploiting fast-paced developments in information and communications technology.

Third, even before the federal spending explosion that was triggered by the coronavirus pandemic, the United States was only about 22 years from when the curve for federal revenues was projected to be passed by the curve for "nondiscretionary" spending (e.g., social security and health care, as set under existing law, and interest on the debt). At that point there will be *no* money for research, national defense, homeland security, infrastructure, or any other such endeavors except through additional borrowing or increased taxes.

"You could no more do that than fly to the moon." Engineering is good at doing the seemingly impossible.

Finally, there is the troubling state of the educational system that the nation relies on to produce future engineers and scientists. The US public pre-K–12 system produces students who, as 15-year-olds, rank 19th among the 35 OECD nations in science and 31st in mathematics.[1] Interest in careers in engineering among America's youth is such that the fraction of baccalaureate degrees awarded in the field of engineering ranks the United States 76th among nations—just ahead of Mozambique (AAAS 2020).

Add to this the 25 percent median disinvestment (in constant dollars) of the 50 states in higher education in recent years, along with the threat that Congress will make it increasingly difficult for foreign students to study in this country (and remain here to work), and a serious science and engineering talent shortage seems to lurk in America's future (AAAS 2020). This will, of course, be the case unless the financial debt weighs so heavily that investment in science and technology is significantly curtailed.

Reasons for Optimism

If these and other roadblocks are somehow overcome, the fundamental scientific and technological capacity for engineering achievement seems immense. Advances in machine learning, artificial intelligence, quantum computing and communications, genomics, nanotechnology, robotics, and many other fields seem to provide the basis for a new Golden Era of Technology.

One example of such developments over the next 50 years will be widespread commercial space tourism, not just brief suborbital excursions like today but 2- or 3-day orbital flights, with brief lunar visits for more wealthy adventurers.

While some observers dismiss such predictions as far-fetched, it is useful to imagine what people in Orville and Wilbur Wright's era would have said if told that on an average day, 44,000 US flights would carry 2.8 million passengers (who would complain about the food and that they had already seen the movie!). What would Robert Scott and Roald Amundsen have said if told in 1911 that by the end of the century, over 10,000 tourists would follow them into Antarctica each year? What might Sir Edmund Hillary have said in 1953 if told that less than 50 years later 40 people would stand on the summit of Mt. Everest in a single morning? And 20 years after that, adventurers would stand in long lines for their turn to reach the summit? Having traveled in 129 countries and stood on both the North and South Poles of the Earth, I believe there will be no shortage of such individuals in the future.

Early air- and spaceline travel face the same fundamental challenges: safety…and cost. With advancing technology and, importantly, increasing use, there is little doubt that space travel to Earth orbit will be made much safer than today's roughly 98 percent success rate, albeit perhaps not approaching the remarkable safety standards set by the commercial airlines over the years. With regard to cost, the first commercial passenger on a scheduled airline paid $400 in 1914 dollars for a 23-minute flight (worthy of note, the passengers who followed each paid $5). A round-trip on Pan Am's first trans-Pacific commercial flight in 1936 cost $27,000 in today's money.

[1] Based on results of the OECD's standardized test of the Program for International Student Assessment (PISA), available at https://www.oecd.org/pisa/publications/pisa-2018-results.htm.

The great breakthrough in air travel came in 1925 when Congress competitively awarded contracts to struggling commercial airlines to carry mail for the US Postal Service. With this new reliable source of income, and greatly increased flight volume, prices dropped to the point that more people could afford to fly—and the cycle then began all over again … and again.

In 2009 a committee established by President Obama to conduct a review of human spaceflight plans proposed that the federal government competitively award contracts to commercial aerospace firms to transport cargo to the Space Station, with the eventual goal of also carrying humans. Much as was the case with the early airlines, this opened the field to new entrants that, along with existing firms, are already establishing the foundation for orbital tourism. And, of course, humans will have walked on Mars within the next 50 years—the only question is what language(s) they will be speaking.

When I was born LXXXV years ago (that sounds better than the Arabic form!), a common expression for something deemed altogether impossible was, "You could no more do that than fly to the moon." It turns out that engineering is good at doing the seemingly impossible.

Please stand by for Commercial Flight 001 into near Earth orbit, departing from Pad 23.

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What Are We Waiting For? Lessons from Covid-19 about Climate Change

Sally M. Benson

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In the grips of a global pandemic that knocked everyone off their feet, what can be learned about responding to the growing threat of climate change?

Parallels between the Covid-19 Pandemic and Climate Change

Scientific experts had been warning that another global pandemic was a virtual certainty and that the "world is ill prepared to respond to a severe influenza pandemic or to any similarly global, sustained, and threatening public-health emergency" (WHO 2011, p. 20).

It should not have been a surprise that as covid-19 spread around the world, it escalated into a devastating event, causing more than 1 million deaths and "negatively affecting global economic growth beyond anything experienced in nearly a century" (CRS 2020, p. i). No country has been spared. Entire industries have been brought to their knees. At the peak, 17 percent of the US workforce was unemployed (CRS 2020). The global economy is expected to contract by 5.2 percent in 2020 (World Bank 2020).

If only countries had been better prepared, and if only they had acted more quickly and more decisively, covid-19 could have been contained and its effects much less severe.

Similarly, scientific experts have warned about the effects of climate change—rising temperatures, changing precipitation patterns, and sea level rise—since the 1970s (NRC 1979; Revelle 1982; Weart 2008). Since that time there have been progressively more urgent calls for decisive action to cut emissions. But actions have been too slow and indecisive. And unlike covid-19, for which it is reasonable to expect suppression within a relatively short period, dealing with climate change is a decades- to century-long marathon.

Which brings the discussion to my point. What are we—individuals, society, government—waiting for? Why aren't we using everything in our arsenal to reduce greenhouse gas emissions? For example, why aren't we accelerating deployment of carbon capture and storage (CCS) technology?

CCS: A Ready Tool to Reduce Greenhouse Gas Emissions

The concept of CCS emerged in the 1970s (Marchetti 1977) and was implemented for the first time about 20 years later, by the Norwegian oil company Statoil (Kaarstad 1992). CCS uses chemical scrubbers to capture CO_2 (Boot-Handford et al. 2014), which is then compressed and pumped deep underground into rock formations where it is permanently trapped—much like oil and gas are naturally trapped for millions of years (Benson and Cole 2008).

CCS reduces emissions by 90 percent or more from a wide variety of sources—electricity from gas or coal, cement manufacturing, steel mills, hydrogen from reforming of natural gas, chemical production, and pulp and paper production (Metz et al. 2005). In optimized technology portfolios, CCS contributes about 13 percent, or ~90 gigatons (GT), of needed global emission reductions to 2060 (IEA 2019). Portfolios that exclude CCS are more expensive, relying on more costly and nascent technologies. Moreover, the need is clear for GT-scale CO_2 removal from the atmosphere to compensate for overshooting the CO_2 emission budget (IPCC 2018). Two of the most promising approaches for such removal are bioenergy with CCS and direct air capture with CCS (NASEM 2019).

CCS deployments have grown at a rate of 8.6 percent annually since the mid-1990s and now 19 projects are capturing 39 MT/year (GCCSI 2020; Zahasky and Krevor 2020). But sustaining this growth rate to 2050 will result in only a tenfold increase in emission reductions through CCS, far short of the required contributions. Doubling growth to 17 percent/year would enable 4.5 GT/year by midcentury—or about 11 percent of current emissions from fossil fuel use and industry, in line with the contributions needed.

Understanding CCS Costs

The slow growth of CCS is often explained by "it costs too much." However, CCS is not more expensive than the costs of many policy measures used to increase renewable power generation and electrify cars.

Costs for renewable portfolio standards in the United States have been estimated at about \$130/tonne of CO_2 emission reductions (Greenstone and Nath 2019). In California costs for rooftop solar deployments are estimated at \$150–\$200/tonne and utility-scale projects at \$60–\$70/tonne (CA-LAO 2020). Even with these costs, about 5 GW of solar rooftop generation and 12 GW of utility-scale photovoltaic (PV) projects have been deployed in California. In Germany, with aggressive incentives for scaling up renewable generation, wind energy is estimated at €44/tonne CO_2 and solar at €537/tonne CO_2 (roughly \$52 and \$633, respectively), and from 2001 to 2010 a total of 21 GW of wind was deployed and 27 GW of solar PV (Marcantonini and Ellerman 2013).

Dealing with climate change is a decades- to century-long marathon. So what are we waiting for?

Costs for switching to electric and hydrogen vehicles are also significant, in the range of \$100s/tonne (CA-LAO 2018; Felgenhauer et al. 2016a,b). The Low Carbon Fuel Standard, a cap-and-trade program to decarbonize fossil fuels, has been about \$200/tonne (CARB 2020).

Costs for CCS compare favorably with what is being spent for other technologies and policies. CCS costs range from about \$40/tonne for high-purity sources such as ethanol plants to \$110/tonne for a natural gas combined cycle plant (NPC 2019).

In 2017 Congress passed the 45Q legislation, a tax credit for CCS of \$35/tonne if the CO_2 is used for enhanced oil recovery and \$50/tonne if it is pumped underground into saline formations for permanent storage. While 45Q is a big step forward, the price support for CCS is not large enough to justify the higher costs for the vast majority of CO_2 emission sources that are dilute (containing less than 15 percent CO_2), such as natural gas and coal power plants. Additional incentives, at the levels used to support renewable generation, electric vehicles, and battery storage, are required to provide certainty for investors and project developers.

Conclusion

There are other factors to address for the scale-up of CCS, such as reducing capture costs, increasing confidence in underground storage, sorting out who owns the underground pore space, and long-term liability. Every technology has its growing pains. But none of these issues are insurmountable. To limit global warming, all solutions are needed: aggressive energy efficiency, renewable energy, electrification of heating and transportation, energy storage, H_2 for a wide range of applications, nuclear power, and CCS.

The challenge is not that CCS is too expensive, too immature, or too risky, but that it has not benefited from the same level of policy and public support as renewable power, electric vehicles, and more recently grid-scale energy storage.

Let's heed the lessons from covid-19. Let's listen to the experts. Let's get prepared and take decisive action. What are we waiting for?

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Imperatives for the Web: Broad Societal Needs


Judy Brewer


Jeffrey Jaffe

Judy Brewer and
Jeffrey M. Jaffe

The World Wide Web has evolved into a complex mechanism for building dynamic applications that are used all over the globe for commerce, education, social networking, entertainment, and information sharing. Innovations to create the roadmap for future functions—immersive environments, privacy-protected advertising, seamless financial systems, intelligent sensor networks—continue unabated.

Societal Role of the Web

The web infrastructure must be equally available for all—yet the world struggles with the imperative to meet broad societal needs such as enhanced internationalization through the accommodation of different languages, security and privacy, and accessibility for individuals with disabilities. On the economic and policy fronts, governments grapple with the digital divide and with the tension between free speech and misinformation.

During the pandemic-driven pivot to remote interactions, the web has functioned as a platform for sustaining engagement across many aspects of life. Virtual meetings became the backbone of the business world, learning environments from kindergarten to postdoctoral research moved to

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online environments, medical appointments moved to privacy-enabled telehealth platforms, food was ordered over secure apps, unemployment filings proceeded online.

All of these interactions are supported by web technologies that are the outcome of decades of development by a community of technologists and web stakeholders dedicated to expanding the capabilities of an open and interoperable platform. At the same time, the necessary shift to virtual has accentuated disparities and gaps.

Misinformation must be addressed at both the technical and nontechnical levels.

Web investment typically optimizes feature/function requirements in response to market demands, yet societal needs are an indispensable aspect of this virtual infrastructure and must therefore also be effectively addressed. The World Wide Web Consortium (W3C), a community of over 400 member organizations and over 10,000 technical participants, has produced hundreds of technical standards that define the technical architecture for the web[1] and infuses innovative technologies in a scalable, distributed system that leverages internet connectivity.

Internationalization

The web supports a wide set of scripts and character sets, yet it has not completely escaped its roots in the English language and Roman alphabet. Ethnologue lists 7117 languages spoken today,[2] and 91 languages have over 10 million speakers.[3] Some have widely different writing systems, and these may be read from left to right, right to left, or vertically.

To appropriately represent the world's myriad languages on the web, browsers must not only support diverse character sets but also appropriately render typographic features such as fonts, glyphs, annotations, formatting, line breaks, and justification. W3C has methodically identified and is addressing gaps in typography support across world languages.

Security and Privacy

Much has been written about online security and privacy,[4] so a summary is not needed here. However, several important perspectives are important to mention.

A secure infrastructure, free from privacy intrusions, is the sine qua non of an information infrastructure. Achieving this requires security enhancements at every level, including protocols, design of application programming interfaces, operating system design, software code reviews, and administrative controls that prevent social engineering attacks. While navigating misinformation and "fake news" as it relates to free speech is an important nontechnical issue, having an insecure infrastructure, where one person may impersonate another, exacerbates the problem. So misinformation must be addressed at both the technical and nontechnical levels.

Technically, the areas of security and privacy have inherent difficulties. When engineers design a function—whether for a phone, a cloud service, or a website—their focus is on delivering the function, rather than on adversaries who may want to hijack that intended function and use it for a malicious purpose.

Designers must imagine the existence of adversaries who would compromise security for ill-gotten gain or invade privacy to learn more about an individual than that individual is comfortable with. W3C addresses this by making available self-assessment questionnaires[5] and follow-up assistance to ensure that when new web standards are set, security and privacy considerations are addressed.

Accessibility

Accessibility has been an innovation driver for digital technologies that better meet diverse user needs and situations, and has become foundational to how digital technologies are developed.

As the web grows in complexity, so do the challenges of making it accessible for people with auditory, cognitive, neurological, physical, speech, and visual disabilities. All technologies should be reviewed at the design

[1] W3C Technical Reports, www.w3.org/TR/

[2] https://www.ethnologue.com/guides/how-many-languages

[3] Wikipedia, https://en.wikipedia.org/wiki/List_of_languages_by_number_of_native_speakers

[4] For example, *The Bridge* 49(3): Cybersecurity, fall 2019

[5] https://www.w3.org/TR/security-privacy-questionnaire/

stage to ensure that they support, and do not create barriers to, accessibility. W3C's Web Content Accessibility Guidelines[6] have been adopted worldwide as the reference for developing accessible content and applications.

Creating and producing accessible content for modern websites give rise to challenges at different scales. Web content is produced by millions of people with low to no technical skills, so it is essential that authoring tools of the future be able to create accessible content by default, including for complex technologies such as virtual reality.

Testing of accessibility conformance must also be able to be done at scale. There is increased demand for both manual testing of usable accessibility and fully automated testing that can scale to the largest websites in the world. As the use of artificial intelligence in accessibility testing becomes more sophisticated, it can be used to simulate approaches currently used in manual testing, for instance by identifying common pathways that users follow when interacting with websites and prioritizing these pathways for automated conformance testing.

[6] https://www.w3.org/WAI/standards-guidelines/wcag/

Ensuring a Future Infrastructure That Addresses Societal Needs

W3C has a formalized process[7] for generating standards that requires review by each of these "Web for All" aspects of our work, through the use of guidelines,[8] educational resources,[9] and review checklists[10] for the inspection of web standards under development. The strength of this foundation, as well as the continuity of a dedicated community and rigorous use of a replicable process, will determine how digital technologies evolve in the future.

Policymakers are recognizing this imperative, and helping fund research and development on fundamental elements of an infrastructure for the future. The moral and ethical need for the technology infrastructure to meet broad societal goals has never been greater. Gaps in the foundation must be addressed to be better prepared for the future. Key political and standardization fora need to do more to address these important societal needs.

[7] https://www.w3.org/Consortium/Process/

[8] https://www.w3.org/WAI/standards-guidelines/

[9] https://www.w3.org/WAI/Resources/

[10] Framework for Accessible Specification of Technologies, https://w3c.github.io/apa/fast/

The Future of Artificial Intelligence

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Rodney A. Brooks

In the proposal for the 1956 Dartmouth summer workshop on artificial intelligence (AI)—the first recorded use of the words *artificial intelligence*—the authors made clear in the second sentence that they believed machines could simulate any aspect of human intelligence. That remains the working assumption of most researchers in AI and engineers building deployed systems, but the full generality implied is still decades or even centuries away.

Current AI Capacity

Seeing AI systems work well at one narrow aspect of human intelligence often misleads people into thinking that all aspects of human intelligence are equally well matched by AI systems. But that is not the case. In particular, the aspects of intelligence that let humans, and indeed most animals, maintain an independent existence and pursue their own agendas while also tending to their shelter, safety, and energy needs have largely been ignored by mainstream AI research for the last 65 years.

The summit of achievement in making independent artificial beings may be found in the high-end models of the Roomba line of robot vacuum cleaners, which not only return to a base to recharge but also empty their waste bins into a larger static container there and have self-cleaning brushes. This is probably the limit of "free will" for AI systems for the foreseeable future as it is not an area of active research.

This means that despite worries expressed in the press and in recent books and essays, we are not going to see Hal-like systems, making independent decisions or doing things people do not want them to do. Nor will deployed AI systems be called on to reason about the moral action to take in some circumstance. However, engineers should, as is always expected, be ethical in their design decisions.

Patterns of AI Approaches and Applications

Since 1956 AI has been characterized by having, at any particular time, tens of diverse approaches to problems and aspects of intelligence with no real consensus on how everyone should proceed. There is no "standard model" to follow or to argue about.

Rather, there has been a constant pattern of a hot new idea emerging from the pack because of unexpected success in applications to some set or another of problems. This new idea then has high expectations developed for it while at the same time useful practical systems are being built on it. Then there is a slowing in progress. Before long, another idea emerges from the pack, and the pattern repeats. Often, old ideas came back for a second or even third time. These past patterns are not a predictor of future patterns, but if they continue it will not be a great surprise.

An incomplete, but roughly chronologically ordered, list of such hot ideas might include tree search, backward chaining, first-order logic, constraint-based systems, frames, the primal sketch, rule-based systems, expert systems, case-based reasoning, behavior-based systems, Q-learning applied to reinforcement learning, qualitative reasoning, genetic algorithms, regularization theory, support vector machines, graphical models…a well-established pattern.

Neural Networks and Very Large Datasets

We are on the third wave of neural networks, one of the topics at the 1956 workshop that continued to be investigated until the late 1960s. Their return in the '80s and '90s resulted in many applications; for example, small neural network systems have been reading the bulk of handwritten zip codes on US mail in high-speed sorting machines since then.

Recently much larger neural networks with the ability to represent much more complex separating manifolds have found many more applications. The success of these deeper networks has come from increases in computer power, very large datasets for training, and improvements in training algorithms. The far-field speech recognition systems that people interact with in their homes or on their smartphones are the most visible beneficiaries. In these and other applications, engineered front-end feature processing systems have been replaced by the first few layers of today's "deeper" neural networks.

Robot vacuum cleaners probably represent the limit of "free will" for AI systems for the foreseeable future as it is not an area of active research.

Proponents are exploring the hypothesis that larger training sets will enable engineering to be further replaced by learning. Others think that a hybrid, with representations of innate knowledge, will be needed in order to squeeze more capability out of networks. Many argue that what is most probably needed is an explicit representation of knowledge that matches the way humans explain their reasoning, especially if we want to get better natural language understanding than current capabilities. Speech-based assistants are good at identifying words, but not yet very good at understanding complex sentences.

Since 2012 deep learning has led to the construction of a huge physical and software infrastructure, supported by enormous cloud computing data centers. They employ graphics processing units, originally developed for video gaming and over time evolved to be attuned to the computations needed for training deep networks.

Very large datasets have been built, some scraped from information on the web, and some created by large groups of paid workers around the world. If researchers working on new techniques find ways to exploit these assets, then they may be able to rapidly bring their techniques to have big practical impacts. Or some other technique may turn out to be the next hot idea without that infrastructure.

The Next Decades of AI

Over the next few decades we will see more and more places where AI systems provide support to humans in carrying out tasks that are important to them, whether in their work, their communications, or their entertainment or play. AI systems will be widely deployed as subsystems that make bigger projects more reliable, more user friendly, and more efficient.

Although AI has come to the attention of the general public in only the last decade, it has been around for 65 years. It is not as far along as many fear, and it is probably not as far along as society needs it to be. There are plenty of challenges and opportunities ahead

Organizing Academic Engineering for Leading in an Entangled World

Robert Brown

Kenneth Lutchen

Robert A. Brown and
Kenneth Lutchen

The world and engineering were simpler half a century ago when *The Bridge* published its first edition, just a few years after the founding of the National Academy of Engineering. The world was less globalized, less connected; only a few countries competed for global economic preeminence. All this has changed. Most recently, covid-19 has laid bare the extent of global entanglement for good or (literally) ill.

We believe it is time for academic engineers to think critically about whether the organizational structures of the last century are appropriate for educational and research challenges going forward. It is time to begin to create the structures and organizations that will best serve students, schools, the engineering community, and the country throughout and beyond this century.

Academic Tradition and Its Challenges

Engineering disciplines are organized around industries established at the beginning of the last century, with the engineering science paradigm just beginning to take hold at the time of *The Bridge's* first publication. Discipline-specific engineering departments traditionally exercise primary

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This essay was distilled from a longer manuscript by R.A. Brown.

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responsibility for curricula, faculty hiring and retention, and definition of the requisite research and professional expertise of the faculty, with only weak coupling to the rest of the university.

Engineering departments are interconnected among universities by professional societies, which helped form the labor market for young faculty; they are less relevant in the world of online job postings and Zoom interviews. Accreditation of academic programs, originally put in place to establish minimal national standards for the professional disciplines, accomplishes this goal, but makes difficult—or actually discourages—academic innovation and effectively enforces disciplinary differentiation.

We propose a model for colleges of engineering built for the more complex and more convergent future.

For decades, academic and industrial leaders have talked about two defects in the academic engineering structure: (1) the slow rate of curricular change within disciplines, hindering the ability to keep pace with rapidly changing science, technology, societal needs, and greater complexity; and (2) obstacles that inhere in traditional departmentally based hiring, promotion, and reward structures and discourage faculty from moving outside their disciplines.

Over the last 50 years, interdisciplinary units have been established at universities with the aim of bridging disciplines and creating spaces for collaborations (see Klein 2010). Although there are many examples of successful interdisciplinary centers, we assert that they have been only partially successful. The centers largely remain decoupled from the curriculum and faculty hiring domains of academic departments and, hence, to a large degree, the defects described above remain.

Reorganizing to Move Forward

It is time to experiment with systemic change in academic structures. Departments should continue as organizational homes for faculty and students, especially undergraduates, but with radically increased porosity in the boundaries among disciplines. We propose a model for the college of engineering built for the more complex and more convergent future.

There have been many calls to action in the past. Recognizing the emerging interfaces among life sciences, physical science, and mathematics, an expert report (NRC 2014) called for a problem-solving approach, *convergence*, that cuts across traditional boundaries to form a comprehensive synthetic framework for tackling large, complex scientific and societal challenges. The report cited the need to create a culture that transcends disciplines and integrates knowledge, tools, and ways of thinking. However, even while identifying the same obstacles as have others—administrative barriers, promotion and tenure policies, faculty recruiting practices, and even the allocation of grant cost recovery dollars—the report offered no structural solutions. Most academic institutions have not yet been able or willing to reorganize themselves to align with the concept and potential power of convergence.

We suggest a new approach that recognizes the functional utility of disciplines but reduces their exclusive and independent roles in faculty hiring and promotion and in graduate and undergraduate education. Overlaid on the departmental structure would be *convergent* research initiatives that, by agreement, constitute the strategic focuses of the engineering college (which often need to align with those of the university).

In this organization, faculty hiring and resource allocation would be based on a collective evaluation of the college's needs for teaching, requirements for the strategic research areas, and the needs for foundational excellence in core areas that may or may not be represented in the convergent research areas. The weight accorded each faculty search may vary, but the overarching goal is to elevate the strategy of the college—and perhaps the university—to be on an equal footing with perceived disciplinary needs.

Making It Work

Myriad process and organizational issues must be addressed to make such a system work. Faculty would not necessarily be appointed in only a single department, so their promotion and tenure processes would need coordination and oversight from outside the department, possibly by an associate dean for faculty. The process for determining convergent themes has to be carefully considered so that legacy research thrusts don't become new versions of antiquated departmental structures. This requires formal review processes for the research themes and hard decisions.

The College of Engineering at Boston University is pushing in this new direction. Already organized in only three relatively large departments, the college is adopting processes that will lower departmental boundaries and push to the forefront a set of agreed-on convergent research themes. The college's leadership structure, faculty hiring, and tenure and promotion processes are being realigned for a college faculty that is more seamlessly integrated across traditional boundaries.

What will success look like? We envision a college faculty less constrained by department structure and more focused on collaborations that address major technological and societal problems and opportunities. We believe our college will be a more exciting place to be a bright, ambitious student or faculty member in the years ahead.

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Empowering Future Engineers with Ethical Thinking

Tom Byers

Tina Seelig

Tom H. Byers and
Tina L. Seelig

Now more than ever it is critically important for engineering graduates to be prepared to evaluate the consequences of the technologies they invent and scale.

In the past the impacts of new technologies—from nuclear power to genetic engineering—emerged over decades, and government regulations were able to gradually shape how the technologies evolved. Today, the time between concept and commercial application is compressed into a few years, or even months. Autonomous cars cruise down the road, drones hover above houses, and lab-grown meat may soon find its way into supermarkets. There is little time to carefully evaluate the potential impact of these innovations on our communities and the planet.

The benefits of speed of innovation have come with a hefty price. A number of well-known firms have stumbled because of behaviors that many consider unethical. Their meteoric growth resulted in decisions that were frequently questionable, and sometimes illegal.

In response, there is a growing effort among educators to ensure that future generations of engineers and entrepreneurs are equipped with the ethical

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skills and mindset required to understand the potential impacts of their inventions and make principled decisions.

Engineering educators need to seize this moment. Ethical thinking must be at the core of 21st century innovation, and ethics should be presented not as a system of barriers and constraints but rather as a series of frameworks and tools to be deployed throughout the innovation process.

Based on our experience at Stanford University teaching high-tech entrepreneurship and on our work with educators around the world, we have learned that ethics should not be bolted onto engineering and entrepreneurship education as an afterthought, but should be baked into the curriculum.

Ethical thinking uses many of the same critical thinking and creative problem-solving approaches leveraged in all other areas of engineering and entrepreneurship. Below are several approaches that can effectively prepare engineering students with the tools and mindset needed to consider the impacts of their future innovations.

Create New Courses Focused on Responsible Technology Development

Engineering students are eager to learn how to avoid the pitfalls they read about in the news. Courses devoted to exploring these issues can create meaningful change.

At Stanford University, students are lining up to take courses such as "Principled Entrepreneurial Decisions," which provides weekly, custom-designed case studies that focus on decision making in high-growth companies. Students are challenged to consider the principles that executives used as they dealt with the complexities of bringing new technologies to market, such as how the Cloudflare CEO balanced a principle of total content neutrality with an urge to stop providing web security services to a hate speech publisher.

In addition, "Computers, Ethics, and Public Policy," a collaboration among faculty in computer science, political science, and philosophy, requires students to complete technical assignments, policy memos, and philosophy papers. And a course titled "Ethics in Bioengineering," cotaught by a scientist and a bioethicist, prepares students to address the expanding number of ethical questions that arise in the life sciences. These courses are offered by Stanford's Computer Science and Bioengineering Departments, respectively.

Such courses attract hundreds of students who know that they will face myriad ethical challenges around the technologies they develop, from virtual reality to facial recognition software and designer babies.

Embed Ethics in Traditional Engineering Courses

In addition to separate courses, ethics conversations and case studies can be deployed in more traditional engineering courses. In our experience, students appreciate the chance to dive into ethical issues in courses on innovation, entrepreneurship, and leadership, as well as in technical courses in fields such as mechanical and environmental engineering.

Ethics should not be bolted onto engineering and entrepreneurship education as an afterthought, but should be baked into the curriculum.

In a Stanford engineering course called "Inventing the Future," students debate the potential utopian and dystopian consequences of various frontier technologies. Although we don't use the word "ethics" when teeing up the debates, the students naturally unpack the ethical implications of each invention, from personal robots to AI-enhanced surveillance in cities. The industry experts who visit the class to give feedback on student presentations often admit that the students uncovered positive and negative consequences of their own technology that they had not considered.

Educators can draw from a rich and growing set of available case studies. The Markkula Center for Applied Ethics at Santa Clara University, for example, has created engineering-specific case studies based on interviews with engineers in Silicon Valley and beyond. And the NAE's Online Ethics Center offers cases that take an experiential approach to ethics education for engineers.

Through cases and ethics-focused conversations, educators can ensure that all engineering and entrepreneurship students gain exposure to ethical frameworks and vital opportunities to practice ethical decision making.

Elevate Research into Ethics-Driven Technology Development

There is growing interest among scholars in studying the strategic advantages of responsible technology development.

A recent Academy of Management workshop ("Responsible and Ethical Innovation," July 2020) highlighted the expanding scope of this research. Studies have explored the use of measurement scales to assess responsible innovation (Zhang et al. 2019), the design of values-based product management (Brusoni and Vaccaro 2017), how executive compensation can be linked to corporate social responsibility (Flammer et al. 2019), and evidence that gender-diverse R&D teams produce more radical innovation (Díaz-García et al. 2013).

Presenting research on ethics and innovation in the context of engineering courses has the potential to fundamentally reshape how engineers and entrepreneurs define their mission, evaluate their metrics for success, build their teams, and prioritize the social impacts of innovation.

Conclusion

Engineers are problem solvers. And ethical thinking is a critical tool in their toolbox as they play a central role in shaping solutions to the world's major problems, from climate change and social inequities to public health, job creation, and global food security.

As educators, we must ensure that engineering students are equipped with the skills needed to evaluate the impact of the innovations they bring to life. This can be done by creating engineering courses focused on responsible technology development, infusing ethics-focused case studies and discussions into traditional engineering curriculum, and elevating research on ethics and innovation.

As Alan Kay famously said, "The best way to predict the future is to invent it." Now is the time to prepare engineering students with ethical tools that will enable them to invent the future with the care that future generations deserve.

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Imagining the Future of Vaccine Development

Arup Chakraborty

Bernhardt Trout
Photo by John Sachs.

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Human history is inextricably linked with infectious diseases. Smallpox and plague pandemics and epidemics have afflicted humans since antiquity. As recently as the 19th century, roughly one in 100 people living in New York City died of tuberculosis.

To an inhabitant of the 19th century, the early 21st century would not be recognizable. The prevalence of common childhood diseases and infant mortality is dramatically lower, in many parts of the world infectious disease epidemics are rare, and common bacterial infections are no longer fatal. These dramatic changes were wrought by human ingenuity, which resulted in better sanitation, antibiotics, and vaccines.

But the enormous human and economic toll of the covid-19 pandemic is a reminder that infectious disease–causing pathogens remain an existential threat to humanity. And this will not be the last pandemic. What if another virus emerges that is easily spreadable by casual human contact, is highly mutable, and causes a disease with a significant mortality rate?

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While vaccination has saved more lives than any other medical procedure, some pathogens defy successful vaccination using available strategies. For example, no vaccine exists for the human immunodeficiency virus (HIV) or malaria, nor is there a universal vaccine that can protect against the mutant strains of influenza that emerge every year.

It is not hard, however, to imagine a future where a connected pipeline of discovery, design, delivery, and deployment makes the rapid development of vaccines against diverse pathogens routine.[1]

Discovery

The human adaptive immune system enables the body to generate effective responses specifically tailored for pathogens to which it has not been previously exposed. Even more amazingly, a memory of past infections makes it possible to mount rapid and robust responses upon reinfection with the same pathogen.

To stimulate the immune system to develop memory for a particular pathogen, a vaccine contains some form of the pathogen. But the pathogen-specific nature of the immune response is a challenge for the development of vaccines against highly mutable pathogens. If the vaccine contains only a single strain of a mutable virus, the immune response will be specific for that strain.

A pipeline of discovery, design, delivery, and deployment will enable the rapid development of vaccines against diverse pathogens.

This challenge can be addressed by bringing together approaches and people from the life and physical sciences and engineering. Machine learning (ML) approaches and mechanistic modeling of systemic immune responses can be applied to massive sets of data on virus sequences and structures and combined with clinical data to potentially identify regions of the virus's proteome that cannot change without making the mutant strain unviable. Targeting these regions of the virus's proteins with a vaccine-induced immune response will trap the virus between being killed by the immune response or evolving mutations that cripple the virus's ability to replicate and propagate infection. Such discoveries could set the stage for developing pan-coronavirus vaccines, an HIV vaccine, a universal influenza vaccine, and vaccines that protect against new mutable viruses that could emerge and cause pandemics.

Many members of families of viruses that infect humans also circulate in animals (e.g., coronaviruses in bats and influenza viruses in pigs and birds). If a virus that circulates in an animal species adapts to infect humans, no one has immunity and a pandemic can result.

We imagine that 50 years from now, the knowledge gained from the research described above, along with global virus surveillance capabilities, may make it possible to *anticipate* the most likely types of pandemic-causing viruses. Such discoveries could enable the design of vaccines in advance.

Design

A key component of a vaccine is the immunogen, a form of a virus's proteins. Pathogen-specific immune responses are mediated by antibodies and T cells. The immunogens required to induce antibodies that target the mutationally vulnerable regions of a pathogen are different from those required to elicit T cells. Antibodies target the proteins that make up a virus's spike, while T cells attack short peptides derived from all viral proteins.

Systematic approaches to design immunogens that elicit desired immune responses in humans with different genotypes are not available. We imagine that developments in systems immunology that bring together systems-level modeling of the immune response, machine learning, data from animal models, and immune monitoring of humans with diverse genotypes will overcome this challenge. This will enable the development of algorithms and tools that can reliably design effective immunogens.

Delivery

Vaccines that are composed of the whole pathogen, either weakened or killed, have existed since the advent of vaccination. The kinds of vaccines that we imagine are not the whole pathogen but immunogens carefully chosen to contain parts of the pathogen.

[1] Some of the ideas discussed here are elaborated in Chakraborty and Shaw (2020).

If a pathogen's proteins are simply injected into an animal, nothing much happens. How can they be delivered in a way that elicits strong immune responses?

Immunoengineering is a rapidly developing field that, among other goals, aims to develop nanoparticle-based vaccine delivery modalities that can efficaciously induce strong immune responses to subunits of a pathogen's proteins. Indeed, the vaccines being developed for covid-19 employ nanoparticles and engineered viruses to deliver RNA or DNA corresponding to the viral spike protein.

The lessons learned from these and other ongoing efforts will provide the capability to design robust delivery vehicles for novel vaccines.

Deployment

Formulation and manufacturing of billions of doses of new vaccines usually takes many months, or years. Even the best of vaccines is useless if the formulation of its components is not stable and it cannot be manufactured at large scale in a reliable, robust, and cost-effective way. The current paradigm is batch manufacturing, in which individual steps are done separately without much integration. This is a recipe for slow scale-up times, inflexibility, and quality challenges, particularly when a rapid response is required.

Fortunately, solutions are being developed to ensure speed and quality and reduce cost. Integrated continuous manufacturing includes model-based control, a systems approach, and end-to-end flow. The basic technologies exist, but there is a barrier to industrial adoption due to perceived regulatory risks. Given the obvious benefits of integrated continuous manufacturing, these challenges need to be addressed for the benefit of the world.

The next 50 years will see not only integrated continuous manufacturing of vaccines but automated process development approaches based on ML technologies. Robots will systematically optimize processes, complementing the human creativity needed for the proper inputs to models and specifications into the algorithms. Ultimately, automated systems will both run the manufacturing equipment and enable process development.

Advanced manufacturing approaches and compatible regulatory policies will enable large-scale manufacturing of vaccines and therapies to begin shortly after successful clinical trials.

Data from the clinical trials being conducted for covid-19 vaccines and future studies will show how to optimally time and stage clinical trials for vaccines, and how some stages can be efficiently combined. Other valuable lessons will be learned about the infrastructure required to store, transport, and deploy billions of doses of a vaccine rapidly.

Conclusion

The connected pipeline of discovery, design, delivery, and deployment of vaccines that we imagine is not a fantasy. Building on current abilities and research activities, the future will likely be the present fairly soon. This will lead to a more pandemic-resilient world, and will be one more important step forward in the eternal quest to vanquish infectious disease–causing pathogens.

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Innovation Campuses: Graduate Education Spurring Talent and the Tech Economy

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Lance R. Collins

In fall 2017 ecommerce and cloud computing giant Amazon announced that it was going to build a second US headquarters and cities could compete for the 50,000 jobs that would accompany “HQ2.” The company received nearly 240 proposals.

While most leaned heavily on tax incentives, Virginia’s proposal, led by the Virginia Economic Development Partnership (VEDP), aimed to create an enabling environment for Amazon, along with other private and public sector organizations, to grow and succeed. The partnership’s pioneering approach to economic development focused on investing in the state through transportation, affordable housing, and higher education. The higher education component recognized that a strong talent base would both help attract Amazon and enhance the commonwealth’s already vibrant economy. Northern Virginia offers one of the strongest and most diverse talent bases in the nation, but persistent gaps and unfilled jobs remain (GWP 2020).

In developing the proposal, VEDP called on Virginia’s universities for ideas on partnering to grow talent and advance technology companies in the Washington metropolitan area. Virginia Tech’s bold ideas, land-grant mission to serve the commonwealth, and ability to scale priority programs made it a compelling feature of the state’s proposal.

The goal to “double the tech talent pipeline” was supported with a historic $1 billion commitment from Virginia to expand higher education to produce 31,000 new technology graduates over 20 years. The Tech Talent Investment Program included investments in other leading universities as well as plans for a Virginia Tech Innovation Campus in the DC metro area and expansion of undergraduate programs on the main campus in Blacksburg. Virginia Tech and the commonwealth are each investing $250 million to launch the Innovation Campus and support its development.

Anatomy of the Innovation Campus

The new Innovation Campus will foster a purpose-driven, action-oriented culture that distinguishes it from a traditional academic campus. It is located in the heart of the booming tech industry that includes giants like Amazon, Northrop Grumman, and Boeing, alongside a rich ecosystem of mid-size and smaller companies that provide the sharp tip to the innovation spear.

The campus affords the opportunity to reinvent graduate education and research in a way that is tightly linked to the economies of the private sector and the federal government's drive and spending. It will provide a platform for innovative research that both feeds and is inspired by advancing technology in the region. Faculty, selected based on their research and teaching, will be expected to engage deeply outside traditional academic circles, collaborating with industry and translating their work into commercial applications.

The Innovation Campus will focus on graduate degrees in computer science and computer engineering, with highly differentiated concentrations, studio classes, and experiential learning as well as opportunities to participate in programs and internships. By the time they graduate, students will have worked in teams alongside premier faculty and engineers from the companies that sponsor their projects.

This campus will eschew the traditional academic paradigm of theory first, then application. Students will acquire deep fundamental knowledge while learning how to use it to solve real-world problems. They will never wonder about the relevance of what they learn, as it will be revealed and reinforced through the project.

Students also will be exposed to subjects that broaden their knowledge beyond the technical so that they appreciate the context in which technology is deployed. Depending on their interests, they may study technology from a humanistic perspective, the potential business and market contexts of technologies, and policy and regulatory frameworks needed to ensure ethical development and use. The goal is to produce graduates who not only are technically skilled but also have the breadth, depth, and context to become pioneers and leaders in the rapidly evolving digital economy.

Students may study the business and market contexts of technologies, and policy and regulatory frameworks to ensure ethical development and use.

Recent events have renewed concerns about race and disparity. While minorities and women are notoriously underrepresented in the technology sector (GWP 2020), demographic diversity in the Washington metro area offers an opportunity to make a positive difference. The Innovation Campus will build on this comparatively strong base to augment racial, ethnic, gender, and socioeconomic diversity among its students. This is not just the right thing to do on a moral level; diversity brings a dividend: Studies show the positive impact of diverse teams on performance (Hunt et al. 2018; Page 2007). The prosperity associated with the tech fields must be open to all who are willing to put in the work to master the subjects.

Shifting Trends of Technology

The granddaddy of all tech ecosystems in the United States and the world is Silicon Valley. Born in the 1950s with the emergence of silicon wafer technology, its dominance remains the envy of the world. Successful startups grow quickly, and the best generate manyfold returns on investment in a few years. Silicon Valley's underlying mission is to invent new technologies that supplant the old. The operating word is *disruption*.

The urban tech scene is qualitatively different from Silicon Valley's. In urban centers, tech industries work in partnership with corporate giants that are driven by advanced technology. Consider the advertising, financial services, and retail industries headquartered in New

York City,[1] or the intelligence and defense industries in the greater DC area. The lifeblood of these industries is state-of-the-art technology, but development relies on *collaboration* rather than *disruption*. Proximity to the major players is vital—a concept at the heart of tech campuses like Innovation Campus. The tech campus is a gathering place for faculty, students, corporations, entrepreneurs, and venture capitalists—the full ecosystem.

Innovation districts are on the rise in major cities such as Atlanta, Brooklyn, Chicago, Detroit, Pittsburgh, and Seattle, where underutilized industrial areas are being reinvented (Katz and Wagner 2014). Situated on a former railyard in the backyard of the nation's capital, the Virginia Tech Innovation Campus is a model for municipalities to jumpstart their own tech ambitions.

Conclusion

In the new technology era, universities will continue their traditional role of nurturing brilliant minds to advance frontiers in research and knowledge. Tech innovation campuses can do even more, by working together with private sector companies, nonprofit organizations, the federal government and its agencies, even K–12 schools, and other partners, to drive technology forward while promoting both economic development and greater opportunity and inclusion of more diverse contributors.

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[1] Cornell Tech (https://tech.cornell.edu/) in New York City, the original "tech campus" sponsored by the city's Economic Development Corporation, graduates several hundred master's and doctoral students each year, and has started over 65 companies that employ more than 350 people and have raised $118 million since 2014. Inspired by their success, the University of Michigan is starting an Innovation Center in Detroit (Reindl and Jesse 2019), and the University of Illinois, in partnership with other universities, is spearheading the Discovery Partners Institute in Chicago (https://dpi.uillinois.edu/).

Virtual Reality 2070: Vision and Challenges

Carolina Cruz-Neira

Carolina Cruz-Neira (NAE) is the Agere Chair Professor of Computer Science at the University of Central Florida.

Virtual reality (VR) can be defined as the spectrum of technologies that enable a computer-mediated reality, ranging from an enhanced real world (augmented reality) to completely digital worlds. Over the coming decades VR will capitalize on the convergence of 21st century technologies and scientific advances in areas such as artificial intelligence (AI), networking (5G and beyond), advanced computing, and IoT technologies to transform how people work, think, communicate, and enjoy life. VR will provide digital ecosystems (such as digital twins) that mimic physical ecosystems and will make it possible for people to think and operate, feel and interact with others, and have a full life parallel to that of physical reality.

Furthermore, because this parallel reality does not have to conform to the laws of physics, people can create new ecosystems and worlds with organisms, technologies, and rules not possible in a physical form. This presents both an exciting opportunity and some challenges.

Possible Applications of Virtual Reality

VR can bring tremendous benefits in a wide range of aspects of life and society (figure 1), as in the following scenarios:

- Using available computing power and access to vast volumes of data, scientists can create virtual laboratories, free of the limitations of physical time and matter, to accelerate medical discoveries like drugs to prevent and cure diseases.
- With AI and machine learning technologies, educators can create individualized virtual learning environments, in which AI-guided tutors deliver materials at a pace and depth matching the student's knowledge level and learning preferences.
- With simulations, data sciences, and sophisticated rendering methods, engineers can explore design alternatives for a new concept and then develop, test, and plan its production virtually before proceeding to a physical product.
- Integrating imaging data, tests, history, and other data for each patient, doctors can use virtual bodies to plan customized procedures and treatments.
- Technologies such as Lidar, 360 video, aerial photography, and others make it possible to virtually visit the most remote corners of the world—or travel in time to explore places in the past.

Virtual reality will also enable new paradigms of social interaction, as it allows people to define a digital persona that may or may not be the same as who they are in the physical world—for example, with a different gender, race, or cultural background. It can thus enable people to experience the world and sociocultural situations from the point of view of others. This may enhance understanding and empathy.

VR 2020 versus VR 2070

VR has evolved from a limited, complex, and expensive technology in advanced academic laboratories or R&D industrial facilities to an affordable, simple consumer technology. But there is also limited diversity in platforms and VR is reduced to almost exclusively headset-mediated experiences.

Expanded Experiences

A first step to realize the potential of VR is to detach the current understanding of what VR is from the specific implementation platform. For instance, VR in the house or office may mean that the walls and other surfaces become the platform for immersion in a digital reality through embedded displays or projections. LED

FIGURE 1 *Clockwise*: Augmented reality enables doctors to have x-ray vision to see the results of medical imaging on a patient. Two experts collaborate in reviewing oil exploration data to make decisions about new well placement. Engineers and customers can review the design and operation of a new package sorting facility before it is manufactured and delivered. Students participate in a human anatomy lesson in virtual reality. All images courtesy of the Emerging Analytics Center at the University of Arkansas at Little Rock.

wall technology is rapidly evolving to be robust and to have enough resolution to create such walls, and projectors are starting to have ultralow throw distances that may make it possible to embed them in certain areas of offices and homes. These developments will better support teamwork and social interaction than headsets as users' physical bodies are blended into the virtual space.

A more controversial approach may be the use of neural implants that send information directly to the brain, making it possible to alter physical reality *at will*. And newer network technologies, like 5G and beyond, may enable the wireless transmission of data and computation results to VR displays, making VR much more pervasive.

In addition, VR 2020 will be not only a visual technology but one that engages all the senses, with aural, olfactory, haptic (touch and sense of force), and even taste displays. Today the technological advances in those areas lag behind the fast development of visual displays.

Need for Guidelines and Standards

Another step toward VR 2070 will be the development of guidelines and standards for both hardware and software. At present there is no universal interaction standard to ensure that technical performance parameters and the ways virtual worlds are manipulated are consistent no matter the hardware and software used to create that virtual space.

There is also no universal content development environment in which VR applications can quickly be prototyped, developed, tested, and deployed. Each application is developed almost from scratch, without consideration of compatibility across platforms. The visual content of some applications is beautiful and artistic, others more cartoonish and less detailed. Some have AI-controlled elements, others have scripted behaviors. Some are single user, others collaborative and remote. Some include intense computational models, others simplistic approximations.

Moreover, models of interaction in VR applications are widely variable. It is nearly impossible to be functional in VR unless the developers of each application provide specific instructions about which buttons to press, where to look in the VR app, and what parts of the virtual world are "interactable."

There are no guidelines on what level of "realism" is appropriate (including the need for sensory displays beyond visual) for VR applications to be acceptable and useful in a particular context. The considerable variation in the quality, details, and realism of a VR experience seems to be driven by individual developers' skills, knowledge, and resources, not based on any guidelines on what makes VR applications effective.

All this creates confusion among VR consumers. Some may love VR if their first experience is with a good app, others may hate it if it is a poorly designed app. Of greater concern, a badly developed VR system and app can cause physical and mental problems, motion sickness, confusion, anxiety, even depression, which can have serious repercussions for users.

Making VR 2070 a Reality

The definition—and enforcement—of standards is the biggest challenge to the broader use of VR by 2070.

If this and other challenges can be addressed, I believe that the limits of what is possible with VR will be the limits of human imagination and ingenuity. This makes the 21st century one of the most exciting times to be an engineer!

Strengthen Innovation and Inclusion by Bringing Opportunity to Talent

Nicholas Donofrio (NAE) is IBM fellow emeritus and retired executive vice president of innovation and technology.

Nicholas M. Donofrio

I have spent over 50 years as an engineer, technologist, and business leader committed to innovation. Innovation has been, is, and always will be the leading edge of economic, social, educational, and governmental success.

But we're holding innovation back. Not because, as conventional wisdom might suggest, we are failing to bring talent to bear on the challenges and opportunities before us. It's the opposite: We are failing to bring opportunity to talent. We must change that, now.

Experience has taught me that innovation is best defined by what it does, rather than what it is. Real and sustainable innovation

- starts by deeply understanding the problem, not by working backward from an answer;
- unlocks value by identifying opportunities and matching them with available skills and abilities; and
- relies on and welcomes everyone involved, not just a recognized "inventor" or "discoverer."

And innovation doesn't just "happen." It is enabled by environments and organizations that foster open, collaborative, inclusive, multidisciplinary thinking and working. Time and again, I have been reminded that the more open and inclusive the team, the more successful it is—because nobody knows in advance which team member is going to supply a critical piece of the value puzzle.

As an engineer, I learned long ago that nature for the most part abhors gradients, concentration spaces, and vacuums, empty spaces. Nature tends to smooth things out as evenly as possible, to create equilibrium. Throughout my career, I have seen that ability is spread across all populations and geographies without regard to categories like gender, race, sexual orientation, ethnicity, or nationality. Talent abounds everywhere.

Opportunity, sadly, does not. The pernicious, persistent effects of prejudice and privilege have unleveled the playing field, channeling opportunity to collection points accessible to the few, not the many. The civil rights movement and the civil unrest of the late 1960s brought this home for me as I was entering the workforce. As a fledgling engineer at IBM, I witnessed firsthand the enormous potential in bringing opportunity to talent.

In 1968, at the urging of Senator Robert F. Kennedy, IBM CEO Thomas J. Watson Jr. literally moved opportunity to talent when IBM announced and opened its newest manufacturing plant in the Bedford-Stuyvesant section of Brooklyn. The "Brooklyn Plant," as it was known, brought value to IBM and value and opportunity to a community that needed it. While this simple but bold move was not perfect in everything it set out to do, it did succeed in bringing opportunity to talent.

Others have learned from and improved on IBM's experience. For example, the 2017 NAE report *Engineering Technology Education in the United States* cites BMW's plant in Spartanburg, SC as another successful example of moving opportunity to talent.

Wise engineering judgment—indeed, good judgment in general—is always informed by history and experience. But over time it has proven to be the exception instead of the rule. Too often, in all fields of endeavor, leaders try to spur innovation only by bringing talent to opportunity. Why do we keep doing what we are doing hoping for different results? Why do we keep trying to move talent to opportunity instead of opportunity to talent?

The confluence of the coronavirus pandemic and George Floyd's murder and its worldwide aftermath brings home, painfully and urgently, the vital imperative to bring opportunity to talent to foster social, economic, and technological innovation at every level.

During the pandemic's widespread lockdowns and quarantines, the abrupt shift in where and how people work and learn has shown the power of technology: It's no longer a matter of physical *or* virtual interactions; they're now both points on the continuum of how people connect, learn, and work.

The outcry and awakening around social justice show how badly we lost our collective way after the progress of the civil rights movement—but also the incredible energy ready to remake and recreate our world. The only viable alternative is to lean into and build on this momentum to undo privilege and prejudice and strive harder for equality.

The unprecedented traumas and challenges of this historic time offer an opportunity like no other to welcome and embrace the potential in everyone to innovate. The options for everyone will be so much richer if we work to reblend our lives to be more thoughtful, meaningful, and inclusive. By committing and acting to bring opportunity to talent across all fields of endeavor, we will start a wave of social innovation that will serve the betterment of all.

It is time to spread opportunity as evenly as talent, and technology and industry can help us get there. Everyone must have the opportunity to be engaged, welcomed, and nurtured to be their best so that they can do their best and both contribute to and reap the rewards of innovation.

Circular Fashion 2070: Clothing and Textile Cycles, Systems, and Services

Rebecca Earley is a professor of sustainable fashion textile design and codirector of the Centre for Circular Design, University of the Arts London. Photo credit: Bec O'Conner for Black Neon Digital

Rebecca Earley

During the covid-19 pandemic in spring 2020, I considered what fashion might look like from the consumer's perspective in 5 years.[1] The "new normal" is changing the way people see the world, and increasing understanding of the role of fashion and clothing in the connected, global, ecological future. This essay takes three garment types and explores how they might be made and used in 50 years' time, drawing on insights from multiple research projects and partnerships at the Centre for Circular Design (CCD).[2]

Shirts That Last a Lifetime

Working with Research Institutes of Sweden on the Mistra Future Fashion Programme,[3] a "super-slow" shirt[4] was developed to demonstrate how to design clothes that last as long as the materials they are made from (Earley 2019).

[1] The Covid-24 Family Fashion Diary, https://medium.com/@rebeccaearley/the-covid-24-family-fashion-diary-2f755f6ea585

[2] https://www.circulardesign.org.uk/

[3] http://mistrafuturefashion.com/

[4] "Slow" contrasts with the "fast fashion" that transitions quickly from the catwalk to the mass market.

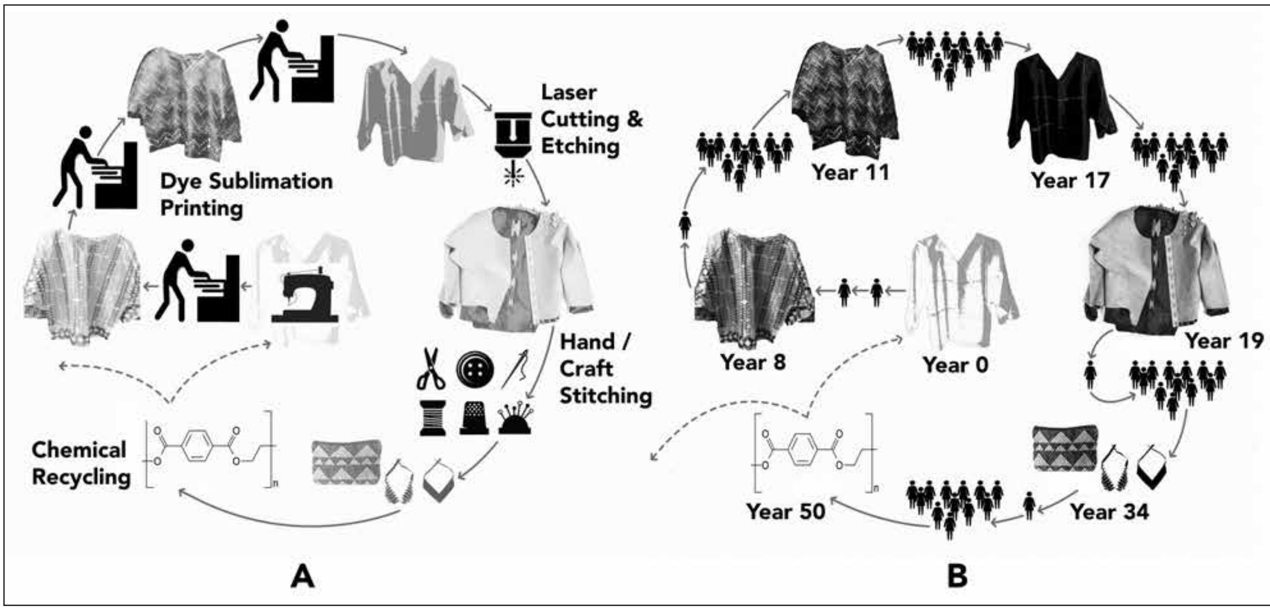

FIGURE 1 How one polyester shirt might last 50 years, get remanufactured multiple times, and be worn by many users. Cycle A shows the remanufacturing techniques that would change the shirt at key stages: digital dye sublimation printing, laser etching and cutting, hand manipulation and embroidery, with the final chemical recycling process taking place at year 50. Cycle B shows different user groups—from single ownership to sharing economy situations—as the shirt changes form and hands over the 50 years.

Polyester is a hugely popular and durable fiber, and in the right conditions can be recycled multiple times, reducing the need to use virgin oil resources.[5] Service Shirt used recycled polyester material for its first lives as a white then printed blouse, before becoming the lining for a jacket[6]; figure 1 shows its production and use cycles.

Many collaborations and partnerships are needed to achieve such longevity and circularity: the design process itself has many more challenges than the traditional, linear design approach (Earley and Forst 2019). There are multiple barriers for businesses, specifically around "value creation, value delivery, and value capture" (Pederson et al. 2018, p. 308).

Importantly, to make clothes last as long as possible, fashion *consumers* will need to see themselves as fashion *users*. They will need both to be persuaded to rent clothes and to develop a philanthropic attitude to fashion by investing in products that have been built to last (and are therefore more expensive than the average item).

A range of new logistical and communication systems and services will also be needed to flow and exchange the goods. Mending and care services will likely be in greater demand; some people may be willing and able to mend clothes more often, but many will find that with economic and time pressures they want new services. The thrift/charity shop sector will need to be totally redesigned: digitized systems will offer specific and bespoke products to users who have created filtered searches, and will allow online browsing and dispatch goods, after covid-19-inspired deep cleaning.

Dresses That Decompose

An estimated £140 million worth (around 350,000 tonnes) of used clothing goes into UK landfills every year (WRAP 2017),[7] much of it from unsustainable "fast fashion" brands (Niinimäki et al. 2020). Kay Politowicz and the CCD team have been exploring how fashion cycles might be both fast and sustainable.

Engineering "fast" material cycles to fit very particular fashion consumption habits—where traditional textile production processing is replaced by materials created using paper and packaging technologies, for example—

[5] According to *Forbes*, "Nearly 70 million barrels of oil are used each year to make the world's polyester fiber" (Conca 2015).

[6] A Fifty-Year Fashion Statement (Service Shirt), Circular Design Speeds project, https://www.circulardesignspeeds.com/

[7] In the United States, 11,150,000 tons of textiles ended up in landfills in 2017 (US EPA, Facts and Figures about Materials, Waste, and Recycling, https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/textiles-material-specific-data).

could result in clothes (or parts of clothing) that go into domestic composting processes after use.

Politowicz's ASAP collection in 2012 for VF Corporation tested the approach for a workwear brand (Goldsworthy et al. 2018). Next, by working with material and perception researchers at Innventia in Sweden, also part of the Mistra Future Fashion Programme, Politowicz created the Ultra-Fast Forward, Paper Leather, and Pulp It collections (Goldsworthy et al. 2019), using paper-like nonwoven materials, engineered through nontoxic finishing approaches for softness, strength, and stretch.[8] Some of the resulting materials underwent double-blind testing with a group of fashion users, and the results came surprisingly close to fine, lightweight cashmere samples (Lindberg and Rådsten Ekman 2019).

A vision for 2050 is an industry where fashion materials are made from recycled synthetics and agricultural/biowaste.

Fashion tastes and habits vary enormously over time; not all clothes can last a lifetime, and "an urgent transition back to 'slow' fashion" (Niinimäki et al. 2020, p. 189) might be resisted. Research shows that even when clothes are made well and are highly durable, circumstances mean that they may not be used or worn at all (WRAP 2017).

There are an increasing number of contexts where "better fast" materials could provide options that offer new opportunities to old clothes, to delight consumers rather than making them feel guilty. Fashion textile researchers working with engineers and materials scientists could produce lighter, nontoxic materials, component parts, and whole garments suitable for biological systems.

Jeans That Fall Apart

In 50 years technology will facilitate taking things apart, not just making them. One of the biggest barriers to achieving a circular economy for fashion and textiles is sorting and separating materials into the right recycling processes. CCD researchers have been looking at this challenge from different angles, including making textiles, material surfaces, and products that come apart (Forst 2019).

If a pair of jeans could be taken apart at the end of its useful life—the rivets, zippers, and labels easily and efficiently removed, the cotton pocket lining separated from the cotton/elastane–blended legs—these materials could be reused in their own particular way. Startups like the Belgium-based Resortecs are developing smart materials for active disassembly (Chiodo et al. 1998) using a polymer melt thread. They are targeting the denim industry and aim to "have around five ovens and dismantling lines, each dealing with 500–600 kilos of textiles per hour. In five years, we will have 20–30 million denims produced with our stitching thread."[9]

By 2070 new chemical recycling plants will be linked to sophisticated sorting facilities with textile disassembly ovens. They will be part of regional textile and clothing hubs, where flows are enabled between fiber producers, distributed manufacturing and retail units, consumer and user networks, and end-of-life collection and sorting. It's a very different picture from what exists today and it's where pioneers like Cyndi Rhoades,[10] founder and CEO of cotton and polyester chemical recycling venture Worn Again Technologies, have been building the foundations for change for many years. Rhoades' vision for 2050—presented at the first World Circular Textiles Day, October 8, 2020[11]—is an industry where no virgin materials are grown or extracted; instead, all fashion materials are made from recycled synthetics and agricultural/biowaste.

Systems Change Ahead

Enough materials have been produced to clothe people for the next 50 years. Land can be used to grow food instead of cotton, and oil left in the ground instead of used to manufacture and transport polyester and other synthetic fabrics.

In the Trash-2-Cash project,[12] the CCD team discovered that this fashion future vision requires *systems*

[8] Pulp It, Circular Design Speeds project, https://www.circulardesignspeeds.com/

[9] Cédric Vanhoeck, founder/CEO of Resortecs, interview by author, June 24, 2020.

[10] Cyndi Rhoades, Worn Again Technologies (http://wornagain.co.uk), interview by author, July 9, 2020.

[11] https://www.arts.ac.uk/whats-on/world-textiles-day

[12] https://www.trash2cashproject.eu/

change, driven by pioneering new collaborations. As we explored design-driven material innovation approaches as a diverse group of stakeholders (Tubito et al. 2018), producing six new regenerated material “mastercases,”[13] we learned that we need face-to-face connections, coupled with an understanding of our skillsets and how they can best be combined to traverse disciplinary boundaries (Earley and Hornbuckle 2017).

Accepting that some people will always want regular “newness” in their wardrobes, regenerative, circular fashion will be needed at a variety of speeds, offered as both product and service. It’s quite a challenge for designers and engineers for the next 50 years.

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[13] https://www.trash2cashproject.eu/#/mastercases/

Projected Applications of the Laser in the 21st Century

J. Gary Eden

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This year marked the 60th anniversary of the discovery of the laser. Few optical or electronic devices have more significantly and directly impacted the quality of life worldwide and, not surprisingly, the NAE designated the laser as one of the 20 foremost engineering achievements of the 20th century (Constable and Somerville 2003).

Most early predictions of laser applications proved to be inaccurate (a well-known hazard of all prognostications), but a myriad of unforeseen and yet transformative applications became reality. The laser was the engine for spectacular advances in areas from surgery and medical therapeutics to materials processing (e.g., cutting, welding, film deposition, annealing), information storage and retrieval, metrology, and time and frequency standards. It has also given birth to entirely new industries such as optical communications and laser radar.

Looking forward to the next 50 years, it is likely that new classes of lasers will profoundly transform several applications.

Living Cells and Tissue

One indication of future potential is the recent realization of lasing from living cells expressing green fluorescent protein (GFP; Gather and Yun 2011). Although these experiments required an optical cavity and external pump source several orders of magnitude larger than the cells themselves, they nevertheless demonstrated that laser emission can be produced from a fluorescent protein grown in a single cell.

Figure 1 shows the green laser spectrum and map of the emission intensity generated from GFP in a mammalian cell. When combined with the demonstration of a wide variety of nanolasers (such as quantum dots) over the past 2 decades (Geiregat et al. 2019; Klimov et al. 2000; Ma and Oulton 2019), this breakthrough suggests that in situ biomedical lasers will be introduced and developed into a routine optical diagnostic of both neurological and biochemical processes.

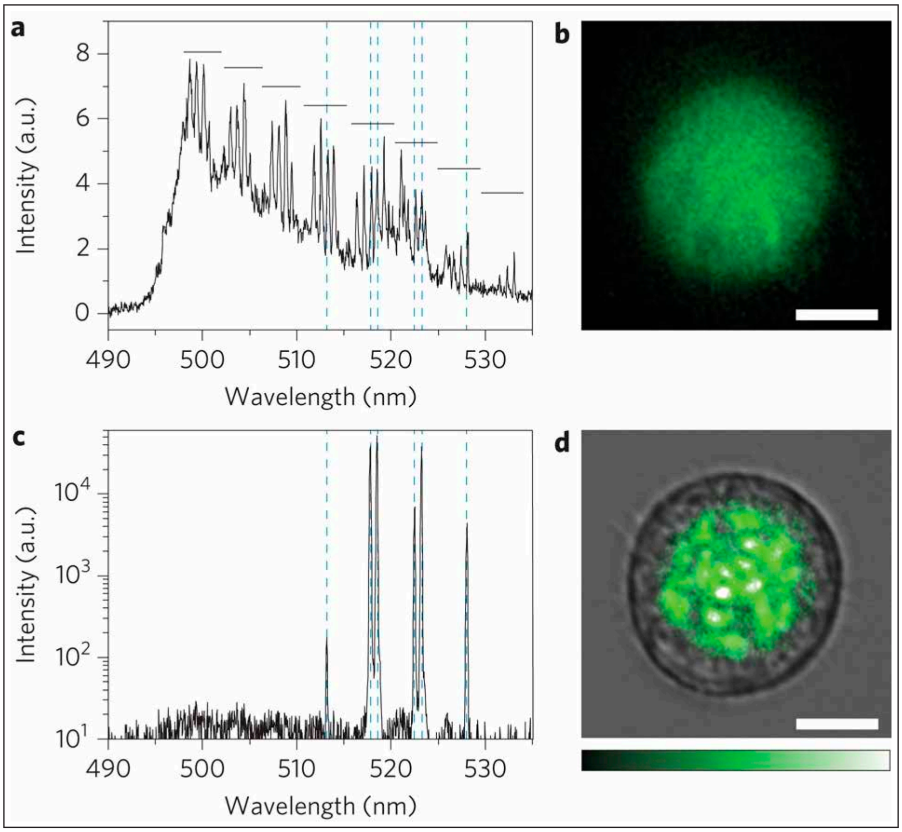

FIGURE 1 Laser spectra and optical images for a single mammalian cell expressing green fluorescent protein. Below- and above-threshold results are presented in panels *a–b* and *c–d*, respectively. a.u. = arbitrary unit. Reprinted from Gather and Yun (2019) with permission from Nature Photonics.

The integration of micro- or nanoscale lasers with animal or human tissue will face a number of hurdles, such as the development of new types of optical resonators capable of being chemically interfaced with an arbitrarily chosen cell and yet providing the spectral selectivity (Q) required for laser oscillation to occur. Delivery of optical pump/electrical power to the cellular or nanoparticle laser medium and access to the optical signal produced by the laser-tissue interaction are other formidable challenges.

When solved, the resulting family of lasers will open a door to exploring the local chemical environment of cells and tissue.

Autonomous Vehicles

The widespread introduction of autonomous vehicles capable of navigating congested urban traffic will require compact, onboard laser-ranging (Lidar) systems of unprecedented precision. Because the mapping resolution of the Lidar system is directly dependent on the temporal widths of the pulses emitted by the system and the bandwidth of the detector(s) receiving the backscattered radiation, new and compact laser optical systems emitting picosecond pulses and designed to cover large angular intervals quickly will be developed. Instead of reliance on narrow laser beams that are scanned mechanically, it is likely that overlapped, intentionally broad laser beams will be introduced to Lidar systems so as to decrease the time required for the acquisition of one complete scan around the vehicle.

In this context, autonomous vehicles currently rely on GPS for navigation but it is quite possible that autonomous navigation of the future will demand an onboard atomic clock driven by an inexpensive laser or a lamp. Accordingly, the mass production of a new generation of low-cost atomic clocks will be a priority for the navigation of both terrestrial and airborne vehicles.

X-Ray and Deep-UV Imaging and Photochemistry

Another frontier for laser physics and engineering is the development of compact and efficient lasers and incoherent optical sources at short wavelengths, ranging from 1 nm (x-ray region) to 200 nm. The first lasers in the soft x-ray region were reported in the last cen-

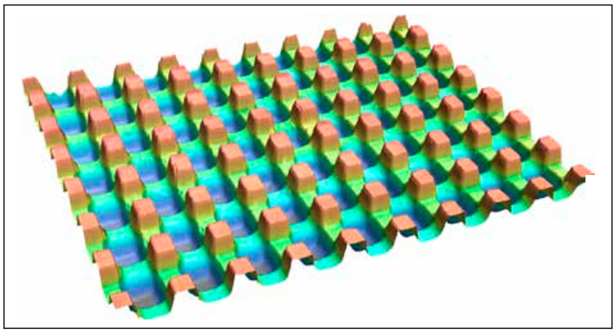

FIGURE 2 False color images of 3- and 4-layer nanostructures produced in polymer polymethyl methacrylate (PMMA) by illuminating the surface through a mask with 172 nm radiation from a flat lamp. The thickness of each level is 240 nm and the periodic pattern of square posts is an optical grating. The *xy* plane and *z* (vertical) axis are not to scale. Reprinted from Mironov et al. (2020) with permission from the Royal Society of Chemistry.

tury, but breaking this wavelength barrier has typically required large laser systems for producing hot plasmas to radiate the desired high-energy photons (Macchietto et al. 1999; Martz et al. 2010; Zhang et al. 1997).

Despite the complexity and cost of laser-generated soft x-ray systems at present, a prominent example of potential applications of 1–200 nm photons is the 13.5 nm system manufactured for photolithography by the Cymer subsidiary of ASML. By exploding micro-droplets of tin with a high-energy carbon dioxide laser, more than 200 W of average power is produced at 13.5 nm.

The technological advances in mirrors, mask design, materials, and laser design necessary to reach this milestone are enormous but this multiyear effort has been rewarded. These 13.5 nm incoherent sources are responsible for regaining the momentum of the semiconductor industry, following Moore's law to the 10 nm level and beyond. Continued industrial and university research and development to build on the existing soft x-ray and deep-UV source base will culminate, over the next few decades, in efficient and compact sources at discrete wavelengths throughout the 1–200 nm region.

History has shown that the availability of new sources of electromagnetic radiation invariably leads not only to previously inaccessible areas of fundamental research but also to new processes and products as well. Of particular interest are promising opportunities in microscopy, materials analysis, thin film processing, and photochemistry. Furthermore, because many applications of short-wavelength radiation do not require the laser property of coherence, for example, incoherent sources such as lamps and the ASML photolithographic exposure and stepper systems mentioned above will play a major role in transitioning short-wavelength radiation sources to industry.

As one early example, a series of flat lamps emitting at several wavelengths in the deep ultraviolet has been introduced, and those emitting at 222 nm are being manufactured for the disinfection of surfaces and room air during the covid-19 pandemic (Anderson 2020). Similar lamps operating at 172 nm ($h\upsilon$ = 7.2 eV) have enabled photolithography at this wavelength and are capable of directly fabricating optical components in polymers and multilayer nanostructures in various organic materials (Mironov et al. 2020).

Figure 2 shows two laser confocal microscope images (in false color) of 3- and 4-level nanostructures formed in polymethyl methacrylate by a 3-minute exposure of the surface, through a mask, with a 172 nm lamp. The periodic pattern of square posts is an optical grating and each color-coded layer is 240 nm thick.

Nanolithography with deep-UV lamps reduces the cost of optical exposure systems by several orders of magnitude, relative to existing systems, while eliminating the requirement for processing in vacuum and rinsing with toxic solvents. These results provide a window into the capabilities of future nanolithographic systems.

Recent developments provide only a hint of the impressive advances that undoubtedly lie ahead. Because it is in the ultraviolet that photon energies begin to match the energies necessary to break most chemical bonds, the potential benefit to humanity and industry of developing 1–200 nm wavelength sources of high average power (1–100 W) and efficiency is staggering. Reaching this goal will necessarily entail dropping the cost of generating a photon (or a mole of photons) by 2 or more orders of magnitude, allowing photons to be regarded as chemical reactants similar to the conventional liquids or gases that are the mainstay of existing chemical syntheses.

In short, inexpensive deep-UV and soft x-ray photons will usher in photochemistry on an industrial scale. Since the energies of photons are well defined, photochemical processes not accessible to thermally activated (Arrhenius) chemistry are expected to become available, increasing product yield and specificity.

Conclusion

Several new classes of lasers and lamps will surely be developed over the next 50 years, and the mid- to far-infrared regions are particularly attractive because of their value in imaging and environmental sensing. Regardless of the laser and incoherent sources that will become available, it is certain that these novel sources of photons will broaden dramatically the commercial, environmental, and healthcare applications for which the renown of the laser is already considerable.

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Nuclear Salvation

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Kerry A. Emanuel

I am a climate scientist highly motivated to find the best and fastest route to decarbonizing energy. As with many of my colleagues, I have felt an obligation to engage directly with the public on the issue of anthropogenic climate change. Collectively, we have become adept at presenting the compelling scientific evidence that human civilization is being put at considerable risk by dramatically increasing the content of long-lived greenhouse gases, especially carbon dioxide.

Audiences are understandably put off by this negative message, however, thus we are inclined to step outside our professional comfort zone and talk about how civilization might solve the problem. To do this effectively and honestly, we have to understand the technology and economics of power generation and carbon extraction. I have no special expertise in energy technology or economics and no professional allegiance to any particular method of solving the problem, but I am fortunate to have access to energy experts at my home institution.

Two things are crystal clear: To avoid the worst risks of climate change the global economy must be thoroughly decarbonized over the next few decades, and progress is nowhere near fast enough.

Projected Electricity Growth

Demand for electricity is likely to nearly triple over the next 40 years. Globally, about 940 million people—almost three times the population of the United States—are without access to electricity; providing them with electric power is an essential step in lifting them out of poverty. Decarbonization of vehicles, today responsible for about a quarter of global greenhouse gas emissions, will also drive up demand for electricity.

The task is thus not only to decarbonize existing power grids but to extend them and to build new carbon-free grids in the developing world. In addition, major hard-to-electrify markets such as industrial processes, residential heating, and maritime transport rely overwhelmingly on combustion of fossil fuels, and in doing so account for about 35 percent of total carbon emissions: those sectors also urgently have to be decarbonized.

A few nations with small populations and plentiful non–fossil energy have decarbonized electricity; Norway with abundant hydro power and Iceland sitting atop an enormous geothermal source come to mind. Otherwise, nations that have successfully decarbonized electricity, such as Sweden, Switzerland, and France, did so largely with hydro and/or nuclear power, and they did so very quickly—within a dozen years or so. These are reality-based examples of how to decarbonize fast.

By contrast, most nations that have pushed hard to ramp up solar and wind power alone have seen relatively slow growth in carbon-free energy and have not reduced their emissions appreciably. Germany, for example, managed to ramp up solar and wind power to almost 40 percent of net production, but because it is shutting down its nuclear power plants, it has reduced greenhouse gas emissions by only a small fraction. It also has one of the highest electricity costs in western Europe, has increased volatility in the European power market, and is compromising the stability of the European power grid.

Advocates of solar and wind rightly point to steep declines in costs of solar photovoltaics and wind turbines in painting a bright future for those sources. At low market penetration, the intermittency of these power sources is balanced by dispatchable sources such as natural gas. Once their market penetration becomes substantial, it becomes necessary to store energy during periods of low sunlight and/or wind, and the considerable costs of storing energy must be added to the production and operating costs of solar and wind arrays.

Solar, wind, and hydro also have environmental costs (as do all energy sources), and most hydro sources are already being exploited, so there is not much further capacity for growth.

Challenges to Nuclear Adoption

Nuclear power has its own liabilities, real and imagined. In the West, inefficient manufacturing practices, together with the low cost of fracked natural gas and high subsidies of fossil fuels and renewables, have created major economic obstacles for building new nuclear plants. Long delays and cost overruns of reactors currently under construction in the United States and Europe have led to capital costs three times higher than those of equivalent plants in South Korea. The steep decline of new nuclear construction in the West has also caused trouble for manufacturing supply chains and nuclear engineering talent, both of which are vital to the industry.

Industrial processes, residential heating, and maritime transport rely overwhelmingly on combustion of fossil fuels and account for about 35 percent of total carbon emissions.

On top of this, the nuclear industry has arguably been terrible at marketing itself. The word "nuclear" is often associated with inconceivably destructive weapons, terrorism, and lethal radiation, so much so that nuclear magnetic resonance imaging (which has none of these problems) was unpopular until someone had the bright idea to simply drop the word "nuclear," resulting in MRI scanners that are now commonplace.

Although nuclear energy is considered dangerous by many, there has been only a single fatal accident involving radiation (Chernobyl) and a handful of nonlethal accidents. But these, like aircraft accidents, weigh heavily in the popular imagination, aided by popular disaster films.

Advantages of Nuclear Energy

Modern nuclear reactors are very reliable and robust machines. Per kilowatt-hour generated, nuclear is among the very safest sources of energy, comparable to solar and wind and much safer than hydro and all fossil fuel sources. Transport and storage of spent fuel are technically manageable and in fact routinely practiced (Finland and Sweden are close to opening permanent repositories), but face substantial popular resistance.

Environmentalists and others who argue that new nuclear energy is too costly may be right so far as their analysis pertains to the West. But in several eastern nations, nuclear energy is alive and expanding. South Korea has been building new 1 GW reactors for $2–3 billion both at home and in the Middle East. There is vigorous competition between China and Russia for the nuclear power export market, and, owing in part to the income generated from exports, these nations are also developing and building advanced reactors that are much more efficient and even safer than existing light water reactors.

Using the current South Korean capital costs, all of the projected global electrical power need of 5 terawatts in 2040 (IEA 2018) could be generated by building about 125 2 GW plants per year at a cost of $500 billion per year, about 0.6 percent of current gross world product (GWP) (CIA 2019). This does not include likely cost reductions from innovation and mass production. Moreover, shuttering fossil fuel plants results in large reductions in respiratory disease and deaths, at the economic equivalent of about $400 billion a year by 2040,[1] so the $100 billion net annual cost of decarbonizing is roughly 0.1 percent of GWP.

Capital costs of building solar energy overnight storage with current technology would run in the hundreds of billions of dollars per year, but judicious combinations of nuclear and renewable energy would greatly reduce the need for storage, while nuclear heat could help decarbonize the large and growing industrial demand for high-temperature heat sources. Even conservative estimates of the costs of unmitigated climate change are far higher than the costs quoted here; for example, the Intelligence Unit of *The Economist* magazine estimates that the annual cost of climate change by 2050 will be 3 percent of the world's GDP (EIU 2019), or about $3 trillion.

Concluding Thoughts

The elimination of fossil fuels from the global economy is both technically and economically feasible if nuclear energy is brought to bear on the problem alongside renewables. But history may well record that the decline of nuclear energy in the West merely shifted nuclear innovation and production to the Far East. Fortunately, bills and programs with bipartisan support are now being implemented by the US government to regain nuclear technology leadership, offering some hope of progress.

As a climate scientist, I do not care where carbon-free energy comes from, but as a citizen I am disappointed that my country is not yet a serious player in the green transformation of the roughly $7 trillion global energy market.

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[1] Assuming 7 million premature deaths per year (from the World Health Organization, https://www.who.int/airpollution/infographics/en/) and the value of a statistical life in 2040 of $2.3 million and a working life of 40 years.

Applying Engineering Systems Thinking to Benefit Public Policy

Maryann Feldman

Paige Clayton

Maryann P. Feldman and Paige A. Clayton

The past 50 years have arguably been defined by economics and the neoliberal agenda, marked by the rise of economic reasoning, with its emphasis on a free market ideology (Applebaum 2019). The focus on markets and a diminished role of government have failed to deliver on the promise of widespread prosperity. Income disparities have reached levels not seen since the Industrial Revolution. Technological advances and productivity increases have been significant but have come at the expense of increased workers' wages and with the accumulation of wealth by a few entrepreneurs and investors in a limited number of cities (Feldman et al. 2020).

The covid-19 pandemic revealed longstanding structural inequities in the United States, exposing inadequacies in government policy, lack of health insurance protection for the most vulnerable, an undersupply of affordable housing, and an inability for working people to earn a wage that allows them to live with dignity. These inequities are not inevitable and call for creative solutions and problem solving.

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Conventional economic strategies often focus on stopgap measures aimed at the most conspicuous problems. As a result, we as a society have failed to create sustainable paths for widespread prosperity. The type of applied systems thinking that characterizes engineering is required. Rather than confining inquiry to technological systems, society will gain over the next 50 years if engineers apply their expertise to solving larger societal problems (Petroski 2010).

Role of Engineers in Addressing Societal Problems

While not well acknowledged by the public, everything in commerce depends on engineering: raw materials are grown or mined through highly engineered technologies, and manufactured products and advanced services depend on engineered systems. When engineers apply their methods used in building infrastructure and designing complex systems to the realm of public policy, great gains in social progress will be realized.

However, the past half-century demonstrated that technology fails to realize its potential when the legal system or the prevailing economic order is unwilling to modify to allow technology to operate under the best conditions for producing beneficial results. Nowhere is this more obvious than in societal failures to alleviate problems of climate change and health care, among others.

Advances in telehealth could improve the lives of millions of rural Americans, yet policy has not kept pace in supporting the required broadband infrastructure.

Engineers are at the forefront of developing renewable energy sources to address climate change. Consider the entrepreneurial startup bioMason, which uses inexpensive, widely available, and ecologically responsible materials to fabricate bio-based building modules that replace energy-intensive brick masonry and concrete.

Advances in telehealth have the potential to dramatically improve the lives of millions of rural Americans, yet policy has not kept pace in supporting the required broadband infrastructure. The Wireless Research Center of North Carolina is an engineer-led innovation hub that, with public support, has contributed significantly to the state's rural economy (Clayton 2018). A national-scale effort is needed.

There are other exemplary cases that focus on specific products and projects (e.g., the work of Engineers without Borders). Imagine the potential if engineering problem solving were unleashed to address large-scale systemic problems.

Yet, although societal needs are well known, the pathways to address them are underdeveloped. Technological discoveries that address broad societal concerns are underfunded by venture capitalists, who favor lower-risk and incremental projects. Realizing the transformative nature of engineering requires redesigning systems to focus on societal benefits over profits.

Valuing Varied Perspectives

Social scientists have explained the dimension of problems, but long-term and socially agreed upon solutions have proved elusive. Implementing innovative ideas is at the heart of what engineers do: they use their knowledge to pragmatically create.

In the knowledge economy the ability to generalize engineering skills to a broader range of nontechnical problems and topics provides a competitive advantage. Many occupations are at risk of automation due to artificial intelligence (Frank et al. 2019). A human advantage lies in the ability to define problems and to see the solution from different perspectives. This is the forte of engineers.

As the field attracts greater numbers of women and underrepresented minorities, the variety of solutions offered will expand. Engineering benefits from the breaking down of stereotypes and the growth of early-education STEM programs. More diverse ideas can be realized only by the inclusion of greater numbers of women and minority engineers from underrepresented populations. The outcome will be an integration of social perspectives and systems with technology to work toward improving the human experience for all.

Expanding Engineering Literacy

Over the next 50 years, the work that engineers have done to broaden the engineering curriculum to incorporate the humanities and social sciences will pay handsomely as all education will incorporate more engineering content. The definition of literacy has changed over time as society has become more sophisticated, placing greater demand on education.

Increased technological sophistication requires that all citizens have a greater understanding of basic engineering principles and concepts. This knowledge and the greater realization of human potential will enable more individuals to envision solutions to both non-market and market problems, and to start companies that create products that enrich the human experience.

Robotics, quantum mechanics, and advanced computing, among other leading-edge fields, will continue to push the boundaries of people's lived experience. This boundary expansion can and should be positive and equitable.

Looking Forward

Having dominated global public discourse for over 30 years, the neoliberal agenda to reduce government has run its course. A new counterargument is emerged, with government as a vehicle for collective action and an agent to advance the objectives of citizens (Feldman et al. 2016). Government is the only entity in the economy that has the mandate to promote wellbeing and prosperity. Reliance on the market has not yielded a more just society. New thinking is required that is solution oriented. Engineers are solution architects and problem solvers.

Within 50 years, we project that Congress will have more engineers than lawyers, a welcome sea change. Rather than being called on to provide a quick technological fix, engineers work best when involved in the formulation of the response to a problem. There is a sense that pragmatism—an attribute that engineers bring to their work—is missing from the current political landscape.

We are optimistic that engineering over the next semicentennial will provide the fact-finding, problem-solving, and solution-implementing approaches that were glimpsed, but ultimately not realized, during the rise of economic reasoning.

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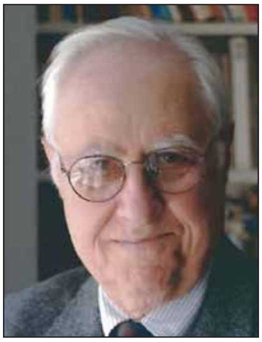
Engineering and the Elixir of Life



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Samuel C. Florman

We are approaching the end of 2020, 75 years removed from a horrific world war that ended with the introduction of nuclear weapons, only to find ourselves in the grip of a fearsome pandemic and shocked by near revolutionary crises of racial conflict. At the same time, as engineers, it is our professional obligation to plan for improvement, and, according to the charter of the National Academy of Engineering, "to serve the nation in connection with significant problems in engineering and technology." Considering need, challenges, new directions—well, I wonder if I'm the sort of engineer who is equipped to meet the challenge.

I am a civil engineer and my career has been in construction. Ah, construction, that art, that profession, that science—one of the most glorious ancient achievements of the human race. Construction needs no special commentary from me. It will carry on with honor as it always has.

But as for facing the future, the problems that cry out for attention and solutions, construction simply does not seem ready to show the way. We dream of grand buildings in grand tomorrows, but tomorrow's buildings will not solve the problems that threaten us today.

Yet I want to participate in planning for the future. And it so happens that I have recently found a worthy cause, a way to serve the nation as the Academy requires. Water supply and distribution. Needy, worthy, appropriate. Also, for me, personal happenstance enters into the picture.

In 2003 the NAE produced a volume titled *A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives*. It was my pleasure to play a minor role as a member of the book development committee and to contribute a one-page "Perspective" sharing stories and insights in connection with one of the 20 achievements. The topic to which I was assigned was water supply and distribution—not as a need, but as an achievement. It fit nicely into my personal inclinations then, and does now.

As a child growing up in New York City, my experience with water supply verged on the idyllic. My father was enchanted with the system of lakes, streams, aqueducts, tunnels, and reservoirs that brought a grand supply of water to our apartment in Manhattan, and he passed on his enthusiasm to me. My mother expressed appreciation for the medicinal and chemical triumphs that had made available water a healthy part of life. I was fascinated by the turbulence of buildings under construction, and beyond the handsome towers I took delight in the parks and beaches at our disposal.

As a student I took to mathematics, then engineering, and found hydraulics to be a subject with appeal. At the end of World War Two, as a newly commissioned officer in the Navy Seabees, I found myself in charge of Japanese workers building a small earth fill dam that provided pure water on a Pacific island. Working harmoniously with ex-enemies and discovering life's elixir, pure water, amid vast expanses of ocean—it sort of brought philosophy into the picture.

When I started to make a living in the construction industry I further came to appreciate the complex role of water—technical and political—in our society. And, when, in the early 1970s, with my family I became the owner of a small cabin by a lake just 50 miles north of New York City—and served on the community lake committee—I was amazed to learn of the role that government had come to play in the world of water supply. We purchased special fish to control the growth of weeds, then were obliged to use fish that were neutered to keep the numbers under control.

Amazement turned to wonder when I became acquainted with the encyclopedic *Century of Innovation* project. In the early years of the 20th century waterborne diseases had been rampant—typhoid, dysentery, cholera. But the introduction of chlorine made an enormous difference, and the engineered control of rivers, the use of dams, canals, sewers, reservoirs, desalination—the introduction of superb engineering—brought civilization to new heights.

But just as I think these comforting thoughts, I come across a recent *Engineering News-Record* (July 20/27) reporting that Chennai, India, a city with a population of more than 8 million, for more than 4 months last year had run out of water. People lined up to get their allotment of water that was brought from the countryside by rail car and tanker truck. "The first major city in the world to go completely dry." And the future threatens more trouble. Very much more.

This experience sent me scurrying to libraries and questioning experts. And what did I find? The US government is busily occupied with water problems in this country. In the May/June 2020 issue of *Civil Engineering* I read, "On May 6, the Senate Committee on Environment and Public Works unanimously passed … amended versions of the America's Water Infrastructure Act (AWIA) of 2020 (S.3591) and the Drinking Water Infrastructure Act of 2020 (S.3590). Combined, the two bills would authorize more than $18 billion in federal spending on various water programs." And there follows a list of agencies and government-funded programs that is dazzling. Solutions, at least domestically, seem to be far ahead of me.

So perhaps I can put aside my dream of helping our noble profession solve the problems of water supply. We have a long way to go, both here and overseas, but I am optimistic that engineers—with the support of socially responsible legislators—will demonstrate the Seabees' "Can Do!" spirit and do what needs doing.

In turbulent times it is all too easy to forget the inner rewards of this profession, which I described nearly 45 years ago as the *existential pleasures* of engineering. We engineers can derive deep satisfaction from the very nature of the work itself: thinking, solving, fixing, making. These activities are inherently rewarding. They help give meaning to our lives, and also bring fulfillment that might just be inexplicable. But how especially rewarding then to devote ourselves to projects such as water supply, for the good of humankind, and indeed sustaining life.

Engineering Financial Markets?

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Richard N. Foster

As the world reels from the impacts of the coronavirus pandemic, growing climate instabilities (including the worst forest fires in California's and Colorado's history, as well as unusually numerous hurricanes), and increasing distrust among the world's nations, questions about how to build and rebuild the world's economies going forward—locally, nationally, and internationally—have never been more urgent.

The question is really how to rebuild the world's economies in a more sustainable way. Put another way, Can market and financial health be "engineered" to reduce these shocks in the coming decades?

Engineering's History of Social Impact

Engineers have always been a vital part of defining and meeting major challenges. Indeed, they have conceptualized, designed, and built a host of the world's defining advances, including

- railroads and the numerous and vast bridges that made them economically worthwhile
- reliable equipment to generate and deliver electricity (AC or DC) to millions of homes, bringing light to the dark and extending productivity

- the first "lighter than air" vehicles, which subsequently changed relationships between nations and generated substantial wealth for airline industry employees and investors alike
- large-scale facilities for producing the drugs to defeat the influenza that was killing millions in the first decades of the past century
- integrated circuits, which released the power of digital computers and led to a reenvisioning of the telephone as a computer that could carry voices to the most distant lands
- new sources of radiation for medical imaging (CT scanning, MRI, ultrasound) and new approaches to surgery (robotics).

All of these had and continue to have significant economic and social impacts. Is it now possible to "engineer" the world's financial markets? Can engineering methods be used to calm the markets and design them for growth without turbulence?

Early Economic Thinking

History shows that others have long thought about ways to influence—through design—markets and finance:

- In the 7th century BCE the astronomer and mathematician Thales, according to Aristotle, became rich through olive speculation.
- Pope Innocent IV, in a commentary on canon law in roughly 1250, justified the charging of a risk premium for assets.
- Ten years later St. Thomas Aquinas endorsed insider trading, making profits based on information not known to the buyer.
- In 1654 Blaise Pascal and Pierre de Fermat developed the first derivative pricing formula by solving the "problem of points." It is now known that their solution converges to the continuous-time Black-Scholes option pricing model.
- In 1738 Daniel Bernoulli published *Exposition of a New Theory on the Measurement of Risk* in Russia. The manuscript was not published in English until 1954, 10 years after John von Neumann and Oskar Morgenstern introduced expected utility in the *Theory of Games and Economic Behavior*.
- In 1926 Norbert Weiner, the originator of cybernetics, developed the theory of random processes, based on James Clerk Maxwell's late 19th century development of the kinetic theory of gases, providing the basis for Robert Merton's 1960s theory of continuous-time finance.

These examples may seem to suggest that there is a natural link between finance and engineering. But in reality the challenges of engineering financial systems are quite different from any that engineering has previously addressed.

> *Can engineering methods be used to calm the markets and design them for growth without turbulence?*

The simple summary is that financial systems think about themselves, and they think about themselves thinking about themselves. This recursive behavior undermines predictability, which is typically a core requirement of and value delivered by engineers.

Market Reflexivity

The experience and wisdom of George Soros provide an instructive example.The Hungarian-born American polymath studied for his PhD at the London School of Economics under the philosopher Karl Popper. Popper argued, and Soros deeply believed, that the absolute truth can never be known with certainty. As Soros (2009) wrote, "Even scientific laws can't be verified beyond a shadow of a doubt," and this thought became the core of his theory of "reflexivity" (circular relationships between cause and effect, especially as embedded in human belief structures[1]).

"Reflexivity" as presented by Soros (2009) is based on the observation that "Scientific laws are hypothetical in character and their truth remains subject to testing. Ideologies which claim to be in possession of the ultimate truth are making a false claim; therefore, they can be imposed on society only by force." Soros would not have made a productive engineer. He saw the potential flaws in all systems, even those of his own design.

[1] https://en.wikipedia.org/wiki/Reflexivity_(social_theory)

Soros applied his theory and beliefs in the weeks leading up to Black Wednesday in Britain, September 16, 1992. It was that day that the UK government was forced to make the exceptional move of withdrawing the pound sterling from the European Exchange Rate Mechanism, after a failed attempt to keep the pound above the lower currency exchange limit. At the time, the United Kingdom held the presidency of the European Communities.

Market participants think about how other participants in the market are thinking. Bridges do not think about other bridges.

In 1997 the UK Treasury estimated the cost of Black Wednesday at £3.14 billion. The crisis damaged the credibility of Prime Minister John Major. The ruling Conservative Party suffered a landslide defeat in the 1997 UK general election and did not return to power until 2010.

Soros, however, made over £1 billion in profit by short selling sterling based on his belief that finance was not "engineering." Engineering requires clear estimates of uncertainty and he did not believe that finance could ever provide those assurances. Finance was thus quite different from conventional engineering.

Doubts about Finance as Engineering

Soros is not a trained engineer but others—including many trained engineers who now make their living in finance—also believe in the reflexivity of financial markets. This group bets that the markets sometimes have it wrong.

Others have joined the chorus of financial engineering critics:

- Financial engineer Nassim Taleb (2007) recognizes the market's susceptibility to extremely rare, hard-to-predict, high-impact events that he calls "black swans."
- Felix Salmon (2009), a financial analyst and writer, points to the "Gaussian copula," the apparent correlation of random and independent variables in "high-dimensional" systems. In other words, given systems of sufficient complexity it is a statistical certainty that variables with no causal connection between them will be shown to be mathematically correlated.
- Ian Stewart (2012), emeritus professor of mathematics at the University of Warwick, points out that, in the Black-Scholes model routinely used to value options, key variables—the risk-free rate and volatility—are assumed to be constant, but in the real world they are not. Indeed, they are not always predictable—even the timing of their likely unpredictability is unpredictable.
- Scott Patterson (2012), a *Wall Street Journal* investigative reporter, cites high frequency trading as a major cause of market volatility and preferential treatment of select firms.

Civil, electrical, and chemical engineers do not bet on the uncertainty of science; they bet on its certainty. And these are just a few of the fields where that certainty is fully justified. They bet that the science is right. They bet that they will be able to set reliability estimates for future forecasts.

Unfortunately, that is not the way markets always work. While there are many estimates of future "volatility," experienced traders know that none are routinely reliable—they can change in an instant when politics change, an unexpected economic crisis occurs, or a pandemic surges. Such events fall well out of the range of reliable "engineering" estimates. Their only characteristic is that the patterns observed today are unlikely to be the patterns of tomorrow.

Said another way, markets think about themselves thinking about themselves; bridges do not think about themselves. More accurately, market participants (there are no markets without participants) think about the thoughts and thinking of other participants in the market. That is the essence of finance. That is what Soros and other "punters" do. It is essential to their work. But it does not work when designing bridges or dams or computer systems or new drugs.

Of course, there are segments of the market where, and points in time when, the volatility is predictable, and in those cases bets are made and leverage increases. But in all cases, these are old, well-established sectors of the economy. They are not in the new, largely undefined areas of the economy that are likely to grow, such as artificial intelligence, machine learning, and

CRISPR-Cas 9. Engineering winning financial bets on the future prices of tires is imaginable. Betting on the future sales of electric vehicles is not.

Concluding Thoughts

For millennia engineers have been sensing, defining, and solving societies' and the world's most pressing problems and opportunities. Often, they have had to invent new ways of characterizing and then solving problems rather than simply applying what worked in the past. Indeed, not infrequently they have had to discover new science to be able to achieve their objectives.

On this 50th anniversary of *The Bridge* the need for engineers to help define and address the world's newly emerging problems is clear. For the past 2000 years, engineering and engineers have risen to the challenges ahead.

That said, engineers and their methods are not wholly predictable. We should be quite pleased that they are not. They will ensure our future by tackling the world's largest and most important problems. They will do it, as they always have, not only by applying reliable methods from the past but by inventing, discovering, and developing new methods to meet opportunities and challenges, no matter how difficult—including finance. That is what engineers have always done and that is what they will continue to do.

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The Future of Quantum Computing Research

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Quantum computing emerged as a research area in the late 20th century yet has only recently experienced a dramatic rise in press coverage and corresponding popularity. While some of this is inevitably rooted more in hype than science, a look into the future suggests that quantum computers do, in fact, have the potential to greatly improve many areas of everyday life. Because a quantum computer can process data in ways that a traditional, classical computer simply cannot, certain problems that will be intractable on even future state-of-the-art supercomputers will be reasonable for quantum computers to tackle, providing benefits to government, industry, and society.

Several decades of predominantly academic research has led to the successful operation of small quantum computers, but many basic research challenges remain before the benefits of mature quantum computers can be realized.

What Are Quantum Computers?

Quantum computers and classical computers share the same goal: to manipulate data to answer questions. The way they manipulate the data, however, is fundamentally different.

Quantum Mechanics Principles: Superposition and Entanglement

Quantum computers are not simply very advanced classical computers, rather they are an inherently different computer type whose operation is rooted in some of the more exotic principles of quantum mechanics. Two of these principles are key to understanding how quantum computers manipulate data: *superposition* and *entanglement*.

Superposition is the ability of a quantum entity to simultaneously exist in multiple "states." While traditional two-state systems, like the transistors that serve as the bits of a classical computer, must definitively be in either the off (0) or on (1) state, a quantum system with two levels can be in both simultaneously, in a superposition of 0 *and* 1. A quantum system in a superposition has only a probability of being in the 0 or 1 state until measurement, which definitively collapses it to 0 or 1. The ability to assume a superposition state is a key characteristic of qubits, the fundamental unit of quantum information.

Entanglement is a phenomenon in which component quantum entities are created and/or manipulated such that their individual identities are lost and only the collective (entangled) entity can be described. This collective description persists even if the entangled system is spread out over a large physical distance (the phenomenon Einstein dubbed "spooky").

A quantum computer carries out quantum operations prescribed by a quantum algorithm on qubits that can be in superpositions and entangled. Through the algorithm, the probabilities of certain outcomes are enhanced and others depressed, even to zero, such that ultimately, when measurements are made at the end of a quantum computation, the probability of obtaining the correct answer is maximized. This exploitation of quantum mechanics and probabilities is what distinguishes quantum from classical computers.

Continued Coexistence of Quantum and Classical Computers

It is important to understand that quantum computers will (likely) never replace classical computers. The derivation of Shor's algorithm in 1994 uncovered one type of problem intractable to a classical computer but efficient on a quantum computer: factoring. Here, "efficient" means "in a time of practical relevance." The factoring problem underlies the security of the RSA cryptosystem, which underlies the security of nearly every online transaction, and this security is guaranteed only by the intractable nature of the factoring problem on a classical computer.

There is no reason to believe that every problem of relevance will be amenable to a quantum speed-up. Thus, the long-term vision is that quantum computers will work in consort with classical computers in various ways depending on the target application.

The exploitation of quantum mechanics and probabilities is what distinguishes quantum from classical computers.

Challenges in Building Quantum Computers for the Future

Today's small quantum computers need to be significantly more sophisticated to execute the quantum algorithms needed for most practical applications. Thinking toward the next 50 years of research, several scientific and engineering challenges need to be overcome to realize large-scale quantum computers. Following are some examples of these challenges.

Increasing the Number of Qubits

The quantum computing model that carries out quantum operations prescribed by a quantum algorithm as described above is known as the *gate-based* model and is one of the most promising for large-scale quantum computations. Current state-of-the-art gate-based quantum computers have on the order of 50 qubits, whereas carrying out complex algorithms of practical relevance will require millions to billions of qubits.

All leading gate-based qubit systems have scaling challenges, which differ depending on the physical qubit type in use (e.g., trapped ions, superconductors, and semiconductors can all be used as qubits[1]). These scaling issues range from the need for an unmanageable

[1] These are three of the most prominent qubit types, but a significant amount of research is devoted to others as well, especially for applications beyond data manipulation (e.g., for data storage/quantum memories or quantum sensing). Different qubit types will likely be better for different applications.

number of lasers[2] to difficulty connecting and operating large numbers of qubits.

Increasing the Qubit and Qubit Operation Quality

To carry out any sophisticated quantum algorithm the qubits in the system must be able to maintain their quantum states for at least an amount of time necessary to carry out quantum operations on them. This retention time is known as the *coherence time* and it is a challenge to extend it for most current qubit types.

Similarly, quantum algorithms require that quantum gate operations (like creating superpositions or entanglement) be carried out with high "fidelity," which is nontrivial. Increasing coherence times and fidelity will require interdisciplinary skills in physics, materials science, and engineering.

Quantum Error Correction

Just as classical computers have error correction protocols, quantum computers need the same capability. The properties of quantum mechanics, however, preclude directly using classical error correction algorithms on quantum systems.

Error-correcting codes exist for qubit systems, but implementing them remains a major challenge. Without error correction, complex quantum calculations like those needed for practical applications are likely impossible. Achieving reliable error-corrected, fault-tolerant multiqubit operation will be a major milestone for the field in the next 50 years.

Underlying Classical Technologies

Many of the challenges associated with constructing sophisticated qubit systems extend beyond the qubits themselves. For instance, improved lasers, detectors, and classical control mechanisms will all be crucial over the next several decades of quantum computing research. It's expected that many engineers beyond those with quantum mechanics backgrounds will be increasingly important.

Outlook

A number of scientific and technical problems are likely amenable to quantum speedups. In addition to the factoring algorithm of importance for today's encryption systems, problems related to optimization and logistics and the simulation of material and chemical systems will likely benefit from quantum-based approaches. Improvements stand to impact areas of vital importance such as targeted pharmaceutical drug and advanced material design, airline logistics, and machine learning as well as areas of (arguably) less importance such as streaming TV and movie recommendations.

Additionally, an active field of research is devoted to developing not only new quantum algorithms to expand the application space of quantum computers but also a deeper understanding of what problem types have structures that may make them favorable for quantum approaches.

With research and engineering problems spanning the quantum sciences, classical engineering, computer science, and mathematics, the next 50 years of quantum computing research and development will be exciting, challenging, and rewarding.

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[2] The number of lasers needed scales roughly linearly with the number of qubits in the system. This is manageable for systems of tens of qubits, but not with millions or billions of them.

The Future of Voting

Juan E. Gilbert

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The 2000 presidential election forever changed voting in the United States. In that election Florida used a paper ballot that left voters uncertain about their selections after they cast their ballot. Analysis of the paper ballots showed that the voters were right to be uncertain. The entire nation became all too familiar with the term "hanging chad."

Afterward, many citizens wondered why they were still voting on paper. Technology had advanced in nearly every sector of life—except voting.

In response to the problematic election, Congress passed the Help America Vote Act (HAVA 2002), allocating millions of dollars to make voting more secure, usable, and accessible. But is the election process now better than it was in 2000? Many would say not so much. In some elections voters have stood in line to vote for hours, in others their intent has been called into question, as in the 2000 presidential election (e.g., the Minnesota 2008 and Alaska 2010 Senate races; Duchschere and Oakes 2008; Medred and Saul 2010).

Attempts to go paperless have included direct recording equipment machines, which didn't print a paper ballot but simply recorded voters' selections through mechanical or electrooptical components and then tallied the results at the end. Without a paper trail, many experts questioned the integrity of such machines (e.g., Appel et al. 2009; Schwartz 2018). No one could know with certainty that votes had not been changed.

FIGURE 1 A ballot marking device. Reprinted with permission from Election Systems and Software.

Given the current state of technology, there is no known way to secure a digital ballot.

Ballot Marking Devices

Questions about foreign interference in the 2016 presidential election led to an expert study on voting (NASEM 2018). Of the resulting recommendations, probably the most discussed is that all elections should be conducted with paper ballots that are either produced by a ballot marking device (BMD; figure 1) or hand-marked by the voter. BMDs typically use a touchscreen with headphones and switches for accessibility. They allow voters to make their selections and then print a ballot showing those selections.

But recent studies have criticized BMDs because some voters do not verify the printed ballot (e.g., Appel et al. 2019). The BMD may print the wrong selection if the voter makes a mistake in their selection, there is an error in the code, or the system has been hacked. If the voter doesn't review the ballot, the selections may have been changed without their or anyone else's knowledge. If enough voters don't notice, an election's outcome could be changed undetected.

Improved Accessibility

Improved accessibility is an area that has shown significant gains since the 2000 presidential election. HAVA requires that all citizens be able to privately and independently cast a ballot. Initially, each voting place had to have at least one accessible voting machine. This created a separate but equal approach to voting that did not work very well because, given the relatively infrequent use of the accessible voting machines, poll workers didn't know how to set them up.

But HAVA spurred advances to make voting more accessible for people with disabilities, resulting in technologies and methods that did not exist in 2000. For example, I developed an open-source, universally designed voting machine called Prime III (Gilbert 2016); since then other BMDs have implemented universal design features. These features mean that the machines are designed for everyone to use independent of their ability (Sabatino and Spurgeon 2016). So voters with disabilities can now use the same machines to vote as anyone else.

In 2020 the covid-19 pandemic further complicated voting as voting by mail and absentee voting increased significantly. For voters with disabilities, voting by mail can be a challenge as the voter has to hand mark and sign the ballot before mailing it back. The good news is that several states are adopting accessible measures for absentee voters through an online ballot marking interface. This allows voters to use their accessible technology (e.g., a screen reader) to mark, review, and then print and mail the ballot.

Where Are Voting Technologies Headed?

Many people wonder, "Will we have internet voting any time soon?" The answer is no. Technical advances currently do not support it. Furthermore, there is no strategic research initiative at the national level to address the security challenges of internet voting.

The ability to manipulate a digital ballot still exists. Until there's a guarantee that a digital ballot can be secured, internet voting will not happen. Even with end-to-end cryptographic systems (Chaum et al. 2008), encrypted files can be deleted or destroyed. Encryption doesn't protect against deletion.

However, I see potential options for experiences comparable to internet voting that result in paper ballots. Accessible absentee voting is an example. Future voters may use a video conferencing format to verify their identity and then mark their ballot and print it at a remote location (e.g., the precinct courthouse or polling location), monitoring it through their computer during this process. It's like a BMD where the interface is the voter's home computer and the printer is at the precinct.

In the future BMDs will probably still be used, but with a major interface makeover. To address the concern about voters not reviewing their ballots, transparent BMDs may have a printer behind the touchscreen: when voters touch the screen to cast their vote their selections will be printed on paper and voters will have to interact with the paper through the touchscreen before the vote is registered (audio options will also be available). This option would require voters to review their ballot in order to advance the voting process.

Conclusion

Technical advances in voting have moved very slowly and will continue to do so unless the government designates progress in this area as a national priority or moonshot, with corresponding financial support. Nevertheless, based on progress to date—such as the development of a universally designed machine that is accessible to all voters regardless of ability—I am optimistic about the impact of future advances to make voting more secure, reliable, and accessible.

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Consciousness and Convergence: Physics of Life at the Nanoscale

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The consciousness with which science is pursued plays a critical role in shaping scientific worldviews, the fundamental questions asked, and the technologies created and their ultimate impacts on society.

My childhood exposure, while growing up in the rural landscapes of Mississippi, to meditation and Eastern philosophy instilled in me a worldview that it should be possible to understand the far reaches of the universe and living systems with one integrated, holistic conceptual framework that is self-consistent and mathematically rigorous. As a physicist and physician-scientist, I founded Nanobiosym as a research institute and idea lab to consciously converge physics and biology at the nanoscale in an emerging field we call *nanobiophysics*.

From Reductionism to Convergence

Over the past 500 or so years, modern science has made great strides, albeit in a predominantly reductionist paradigm, whereby complex systems were assumed to be fully understood as the simple sum of their parts.

Twentieth century physics and biology largely developed as separate disciplines. Physics was formulated in the context of nonliving matter. Its mathematical language dealt primarily with closed systems that operated at or near equilibrium; any interaction with the environment was considered, at best, a small perturbation to these closed systems. In contrast, living systems are fundamentally open and continuously exchange matter, energy, and information with their environment.

Despite the advent of thermodynamics, statistical mechanics, and quantum mechanics, physics had not yet developed adequate mathematical and conceptual tools to predict the behavior of nonequilibrium systems that are strongly coupled to their environment. Nanotechnology provides the practical tools and conceptual platform to bring the seemingly divergent worlds of physics and biomedicine under a common roof.

Using DNA Nanomachines to Probe the Interplay of Matter, Energy, and Information

Biological information is replicated, transcribed, or otherwise processed by nanoscale biomotors or molecular engines that convert chemical energy stored in nucleotides into mechanical work. The dynamics of a molecular motor depend not only on the DNA sequence it reads but also on the environment in which it operates—the environment influences the way cells process the information encoded in DNA (Goel 2008, 2010).

We have developed a self-consistent physics framework to quantitatively describe how environmental cues (e.g., temperature, ambient concentrations of nucleotides and other biochemical agents, the amount of mechanical tension or torsional stress on the DNA) directly couple to the dynamics of the nanomotor (figure 1). The resulting information will yield a better understanding of the context-dependent function of these DNA-reading nanomachines (Goel 2008, 2010; Goel and Herschbach 2003), with potential impacts and applications described in the next section.

Our framework (Goel 2002) suggests that the information or number of bits stored in a DNA motor system is much larger than conventionally assumed (Goel 2008), that the DNA, the replicating motor, and its environment constitute a dynamic and complex network with dramatically higher information storage and processing capabilities. The information storage density results, in part, from the motor itself having several internal microscopic states, each representing a decision point in the nanomotor's trajectory.

As the nanomachine moves along DNA it must process information and integrate environmental inputs from multiple levels to determine exactly how it reads the DNA. Learning how to control and manipulate the performance of nanomotors externally is a critical hurdle in harnessing them for ex vivo applications. By identifying or engineering appropriate external "knobs" in the motor

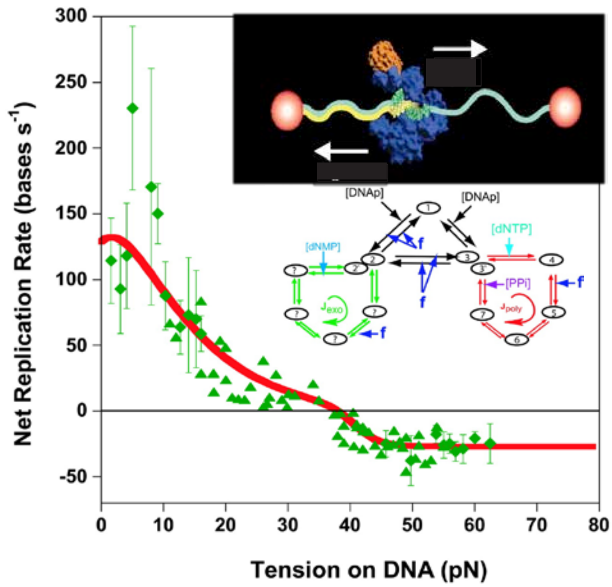

FIGURE 1 Experimental data for tension dependence of net DNA replication rate can be explained by a network model of a nanomachine. A single DNA molecule is stretched (tension *f*, in piconewtons, pN) between two beads (top). In each forward step, the enzyme (DNA polymerase, DNAp) motor incorporates one nucleotide (dNTP) into the DNA and releases one molecule of pyrophosphate (PPi) into the surrounding solution. As the enzyme motor visits the sequence of states $3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 3'$, it completes one polymerase cycle (red); a switch of $3 \rightarrow 2$ enables the sequence $2 \rightarrow 2'$, completing one exonuclease cycle (green). Distinct cycles for polymerase (red) and exonuclease (green) pathways are linked by a cycle (black) involving binding or unbinding of the motor to the DNA. This biological network corresponds to the internal state transitions that occur in this DNAp-DNA complex functioning like an algorithmic state machine undergoing internal transitions as the DNAp motor enzyme translocates along a molecule of DNA. Jpoly denotes the net forward or polymerization rate and Jexo denotes the net backward or exonuclease rate. The experimental data from single molecule experiments are denoted via the green triangles and diamonds and indicate the net replication rate at a given force or tension on the stretched molecule of DNA. The red trendline describes how our network model can reconcile our simple open biological network models with actual single molecule experimental data. Arrows indicate how the network dynamics are coupled to various environmental parameters where transition rates between internal nodes are proportional to external environmental parameters such as ambient concentrations of enzyme, nucleotide, or pyrophosphate or tension *f* used to stretch the DNA. dNMP = deoxyribonucleoside monophosphate; Jexo = flux or net rate of exonuclease activity; Jpoly = flux or net rate of polymerization. Adapted from Goel and Vogel (2008) and Goel et al. (2002).

or its environment, its nanoscale movement can be tightly regulated, switched on and off, or otherwise manipulated on demand. At Nanobiosym we are harnessing the nanomachines for a variety of practical applications, from portable diagnostics to molecular manufacturing of biopolymers, biological classical and quantum computation, nanoscale information storage in biomaterials, and ultraefficient energy transduction schemes.

Rewriting the Rules of Medical Diagnosis with Nanobiophysics

Current best-in-class molecular diagnostics systems are based on a 35-year-old method that requires large bulky machines and extensive overhead infrastructure, complex sample transport logistics, highly trained personnel, large volumes of expensive reagents, and centralized lab facilities. This system does not lend itself to real-time decentralized precision testing for hundreds of millions of people, as is required in the covid-19 pandemic.

To decentralize these mainframe machines outside of a lab or hospital setting will involve overcoming critical engineering barriers to achieve accuracy, precision, speed, smaller sample sizes, and user-friendliness. My research lab has demonstrated the ability to control molecular machines and more generally molecular reactions at the nanoscale, enabling faster, smaller, IoT-connected, precision-engineered diagnostic devices as well as improved precision and quality control in manufacturing DNA molecules (Goel 2014, 2020).

Nanobiophysics will transform medical diagnosis in practical yet profound ways. Earlier, faster, more accurate detection of infectious diseases can help contain or prevent global pandemics like covid-19, Ebola, avian flu, and SARS, and reduce multidrug-resistant strains of diseases such as HIV, tuberculosis, and malaria.

Today's gold standard for testing HIV viral load costs $200–300 and can take 2–3 weeks to deliver a result from a centralized lab. In sub-Saharan Africa, the tests can take up to 6 months, given the cost, lack of infrastructure, and difficulty in transporting specimens for molecular level diagnosis. We have developed a platform (the Gene-RADAR) that reduces that time to under an hour, with price points 10–100 times more affordable—all without the need for running water, constant electricity, or highly trained personnel.

The covid-19 pandemic exposed critical gaps in the US public health testing infrastructure. With available testing technologies, less than 5 percent of the population has been tested each month. To reopen the US economy and rehabilitate industries, community-based precision testing is needed for hundreds of millions of people per month. To restore public confidence, the testing technology must be accurate and precise, ideally with no (or very few) false negatives or false positives.

Conclusions

Nanomanufacturing processes, much like macroscopic assembly lines, need procedures that offer precise control over the quality of the product, including the ability to recognize and repair defects. The use of nanotechnology to elucidate physical and biological networks can help with this and is just beginning to reveal its potential in other areas.

Viewing a molecular motor as a complex adaptive system that is capable of utilizing information in its environment to evolve or learn may shed light on how information processing and computation can be realized at the molecular level. And by replacing hospitals and centralized labs as the core of healthcare delivery, nanobiotechnology can put the patient and consumer at the center of the healthcare ecosystem.

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Expanding Engagement in STEM

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Latonia M. Harris

What might the US engineering community look like in 50 years? As an African American woman I belong to an underrepresented group in this community. My story may provide some clues on how to ensure a robust engineering pipeline.

Born in Selma and raised in Detroit, I come from a working-class family; neither of my parents completed college and not all of my grandparents completed high school. I studied at well-respected universities and earned a BSE, MS, and PhD in chemical engineering. Today, I lead multidisciplinary teams in a large pharmaceutical company, developing transformational cancer therapies to improve the length and quality of life for patients who have very little hope.

I am passionate about my work in the pharmaceutical industry, and I love my career. One of the few things I am more passionate about is finding ways to support American youth in achieving academic excellence and considering careers in STEM.

My election this year to the NAE triggered deep self-reflection. What made the difference in my life? What can concerned individuals do to ensure a positive transformation in the US STEM community over the next 50 years?

Challenges in the US Engineering Community

Young Americans are not drawn to engineering in numbers sufficient to meet the demand for STEM expertise in industry. The United States needs to fill 3.5 million STEM jobs by 2025, but 2 million of them will go unfilled because of a lack of highly skilled candidates (Deloitte 2018).

Women, Hispanics, and African Americans are underrepresented in US industry and academic engineering.

- Although women are half the US population, they earned 26 percent of engineering bachelor's degrees in 2018—an increase from 2009, when they received 19 percent.
- Hispanics represent 15.3 percent of the US population and received 11.4 percent of engineering bachelor's degrees in 2018, up from 6.6 percent in 2009.
- African Americans are 13.4 percent of the US population, but received only 4.2 percent of engineering bachelor's degrees in 2018—less than the 4.6 percent they received in 2009 and 5.4 percent in 2002 (Roy 2018; Yoder 2011).

Despite these statistics, I can imagine a bright future where engineers and other STEM practitioners are held in high esteem; where talented youth, passionate about problem solving and innovating, earn engineering degrees and enter STEM disciplines at unprecedented rates; where the representation of engineers at all levels of academia and the corporate world is in line with gender and racial distributions in the population.

Being introduced to the engineering field at a young age in a fun and exciting way was an important milestone.

How can all children in America get the support and opportunities to reach their dreams, perhaps pursuing careers in STEM?

The Role of Support Programs

A comprehensive support system includes educators in and outside of the classroom who expose youth to the exciting world of science and engineering.

My experience is illustrative. In middle and high school, I participated in the Detroit Area Pre-College Engineering Program. Through its Saturday programs, I was first exposed to engineering disciplines. That is when, as a high school freshman, I decided to earn a PhD in chemical engineering. Being introduced to the engineering field at a young age in a fun and exciting way was an important milestone.

University administrators also provided key support. They sponsored summer enrichment programs where high school children from Detroit public schools spent time living on the University of Michigan–Ann Arbor campus, learning about STEM and gaining confidence navigating the college environment. From the moment I stepped on campus, I was destined to be a Wolverine.

The University of Michigan Minority Engineering Program Office introduced me to role models and motivational speakers from industry, and the program's dedicated staff helped me hone skills that have served me well throughout my career, demanding excellence every step of the way. Again, people invested in me as a young person, motivating me to do my best in college with a focus on STEM.

Industry partners also created early opportunities and meaningful STEM experiences. For example, during summers, Dow Chemical sponsored students to work under the supervision of fantastic STEM mentors. My daily interactions with scientists and engineers there solidified my commitment to become an engineer. And in college, organizations like the National Action Council for Minorities in Engineering, National GEM Consortium, 3M, and DuPont provided financial support through scholarships. Dow and DuPont offered undergraduate internships.

Throughout my career I have received support from mentors and sponsors who share best practices, serve as sounding boards, and help open doors that may otherwise have been inaccessible. I pay it forward, mentoring and sponsoring others as they navigate their careers.

The support I received on my engineering journey has been varied and extensive, but none was more impactful than that of my parents. They were the consistent positive force in my life, encouraging me to always do my best. They passed on their exceptional work ethic and taught me to respect others, valuing the gifts that each person possesses. Their support prepared me to withstand challenges throughout my life.

Realizing Change in the Decades Ahead

My story may seem simplistic to some: lots of support and opportunities lead to success. But the challenge of increasing the representation of minority groups in STEM is quite complex.

Experts have written volumes on the factors that contribute to underrepresentation of minority groups in STEM. Over the decades, countless organizations, with talented and caring individuals dedicated to improving and diversifying the American STEM community (Slaughter et al. 2015), have attempted to address these issues in the US education system.

To realize transformation during the next 50 years, we must stand on the shoulders of giants and learn from their experiences (Hrabowski 2015; Slaughter et al. 2015; Vest 2005). Successful programs should be expanded countrywide to benefit more youth. And programs must remain current to be effective. Education and STEM are currently "marketed" to children fascinated by TikTok and Instagram.

In addition, the challenge of increasing STEM diversity is intertwined with the quest for social justice, educational improvement, and gender equity. It is impossible to address diversity in STEM without considering these other factors.

Of all the support needed to equip children for STEM careers, I believe the most important comes from the individuals who interact with students daily, including parents, friends, teachers, and other caring adults.

Uniting as a community to support school-aged children can be very effective. This is particularly important for African American children, who may experience threats to their confidence, self-esteem, and sometimes physical safety. Individuals in communities can protect children from biases that might diminish their educational experience and assist them in managing in a world where they are too often invisible to people in positions of authority or, worse, where they may be subtly or overtly underestimated. We must protect the precious spirit of our children. They deserve a supportive environment in which to flourish.

Action is needed now to ensure a robust engineering community in which all groups and perspectives are well represented in 50 years. The engineering community will benefit from actively communicating with all youth about exciting and rewarding careers in engineering. With support from schools, universities, industry, and community, STEM careers will be accessible to a much larger portion of US society. Society and industry have much to gain from unlocking the immense potential in all children (Abreu 2014; Dzirasa 2020; Hofstra et al. 2020; Schindler 2019).

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Incorporating the Arts to Create Technical Leaders of the Future

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Linda A. Hill

Engineering education should be reimagined to create a new generation of technical leaders prepared to dream, invent, and steward the future.

What Do I Mean by a Technical Leader?

I mean a leader like Ed Catmull, cofounder of Pixar, who with his colleagues leveraged the intersection of technology, art, and business to create the new industry of computer-graphic animation and build one of the most successful studios of all time. He received his PhD in computer science from the University of Utah in 1974 and retired in 2019 as president of Pixar and Disney Animation. Throughout his tenure, Pixar harnessed the power of both engineering and storytelling to capture hearts and minds across the world and remind us of our common humanity.

Why has Pixar been so successful? Because, like his cofounder Steve Jobs, Catmull understood the power of the arts and design to transform customer and cultural experiences. As he puts it, technology, the arts, and business are all first-class citizens in the company.[1] In addition, "We're not just making up how to do computer-generated movies, we're making up how to run a company of diverse people who can make something together that no one could make alone" (Hill et al. 2014, p. 8).

[1] Personal communication, Oct 2.

Catmull set the stage for dozens of artists and researchers to innovate, with profound impacts both on how films were made and experienced and on the evolution of the computer graphics industry more generally. In 2019 he was selected for the A.M. Turing Award, often referred to as the "Nobel Prize of Computing."

How Can the Arts Help Develop Technical Leaders?

Although many believe otherwise, leaders are more made than born. Over the next 50 years, education will play a prominent role in developing engineers into leaders equipped with both technical expertise and a passion to learn with and catalyze action among diverse actors eager to innovate.

Drew Faust (2014), former president of Harvard University, explained that a liberal arts education can be "a passport to different places…and different ways of thinking." Tomorrow's engineers will need to not only appreciate how technology and data analytics inform and shape every interaction and experience—for better *and* worse—but also be equipped to apply technical and other skills to make bold, human-centered decisions and build agile organizations and ecosystems. For that, their education will depend on a fusion of technology, the arts, and leadership.

The arts provide space to grapple with existential questions of identity, purpose, and complex societal challenges while cultivating communication skills and the ability to build connections with others. Through participation in the arts, engineers will develop different ways of thinking about human-centric and nature-inspired design, including empathy and critical problem-solving skills to frame and ask generative questions both to uncover what really matters to stakeholders and to engineer solutions consistent with biomimicry (instead of only or primarily mechanistic) principles.

Moreover, the arts provide a forum for engineers to exercise their moral imagination—to pursue not just what should be, but what *could* be.

Lessons from Current Leaders

My collaborators and I have spent hundreds of hours with men and women who have built organizations that can innovate with speed and a sense of shared purpose. Not surprisingly, many of our interviewees have been engineers using technology to fulfill bold ambitions.

We learned that game changers who shape the future understand that leading innovation is not about setting direction and inspiring people to follow—this conception of leadership works only when the solution to a problem is *known*. The wicked problems engineers will face will demand novel, sometimes audacious solutions. The role of leaders will not be to come up with a vision and move people to follow them, but rather to *engineer environments* in which people with diverse—and divergent—talents can cocreate a better future.

Leadership development is largely a process of learning by doing. Engineering education in the future will include immersive and experiential pedagogical methods, where students practice leading innovation. Like pilot certification, engineers will be required to complete *leadership practicums* to earn leadership certification. The goal is to inspire engineers to acquire the mindset, knowledge, and networks required to innovate time and again, through collaboration, diversity of contributors, experimentation, coping with failure, and inclusive decision making.

Existing Initiatives

A number of initiatives exist to encourage cross-disciplinary discourse and make education more integrated and problem-focused.

For example, at the MIT Media Lab, Neri Oxman has pioneered the new field of material ecology to construct art installations, products, and buildings that are biologically informed and digitally engineered.

> *The arts provide a forum for engineers to exercise their moral imagination—to pursue what* could be.

Larry Smarr and his colleagues at the California Institute for Telecommunications and Information Technology (Calit2) have created a "collaboration-ready," purpose-driven ecosystem of faculty and students from engineering, the physical, biological, and social sciences, and the arts and humanities to address a range of pressing societal needs: from working with firefighters to create crisis response technologies to creating analytics for personalized medicine and the visualization of ocean pollutants.

Conclusion

The need for leaders able to traverse systemic problems and orchestrate action for the collective good is acutely clear. Integration of engineering and the arts will determine how effectively schools educate coming generations of technical leaders. How courageously deans, administrators, and educators navigate complexity with moral integrity and hone *collective genius* to address unprecedented challenges and yet-to-be imagined opportunities will set the stage for innovating the future.

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Peace Engineering

Joseph Hughes

Philip Breedlove

Joseph B. Hughes and
Philip Breedlove

Creating a more peaceful world is an aspiration shared by generations. Converting aspiration to achievement has been elusive. Creating peace is a wicked problem with no universally shared definition of success.

Peace engineering focuses on incremental, realistic, and compounding progress toward peace through applications of technology, the engineering design process, and system-based approaches. As a solution-driven field, peace engineering applies technologies from all engineering disciplines—from those behind basic services (power, water, and sanitation) to emerging capabilities (internet of things, distributed sensors, network analytics)—in an integrated framework for system-of-systems analysis and visualization.

Why Now?

Engineering strategies to improve the quantity and quality of positive behaviors and to reduce destructive behavior are now achievable. The rapid global growth and adoption of technology create this opportunity not afforded previous generations.

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Peace, conflict, and violence involve human behaviors that were previously constrained to qualitative analysis. Today, however, technology detects, measures, analyzes, and influences human behaviors in real time with high levels of precision. Coupling these new quantitative capabilities with qualitative methods and existing engineering tools enables system-of-systems understanding never before possible.

Motivation

Expressed in economic terms alone, the global cost of violence was an estimated $14.5 trillion in 2019—10.6 percent of world economic activity (GPI 2020). In human terms, the impacts of violence on individuals, families, and communities are enormous and impossible to quantify (Waters et al. 2004).

Peace, conflict, and violence are emergent properties of complex systems.

Near-future challenges, both local and global, present concerns about increasing conflict in the coming decades (Brown 2008). These challenges are created by an environment of finite/diminishing resources, exacerbated by climate change, human displacement, dense urbanization, and population growth, among a growing list of concerns.

Framework

To address the societal motivations for peace engineering in the context of technological opportunities, we propose a framework with three central premises.

First, *problems require systems-based solutions*. Peace, conflict, and violence are emergent properties of complex systems. A more peaceful world is possible only when a wide range of practices and professions are fully engaged. On a global level, diplomatic, informational, military, and economic institutions collaborate in these efforts. Peace engineering does not replace these functions: it is an additive capability made possible by the growth and adoption of technology globally.

Peace-enabling technologies are used, for example, to address the basic needs of power, water, transportation, and sanitation; improve security using personal sensing technologies and geospatial analysis; expand access to education and health care via the internet; remediate environmental pollution that causes public health disparities; and analyze and better understand human behavior through data analytics.

Second, *an ounce of prevention is worth a pound of cure*. As noted above, the costs and impacts of conflict that turns violent are staggering. Reconciliation is fragile, requires generational time periods, and costs much more than the initial conflict. Engineering to avoid violence, address structural conflict, and take proactive measures is the priority of peace engineering.

Third, *context is critical*. It is essential to determine what peace should look like before entering any action or conflict. To help create a sustainable solution, peace engineers must understand the root causes of a conflict and address them using all tools available. And to dampen existing violence and create a durable reconciliation, peace engineers must address the current context.

Peace Engineering and the Engineering Process

Making or maintaining peace is more of an art than a science. Peace engineers follow the basic engineering problem-solving approach to bring objectivity, rigor, and quantitative analysis to this "art."

Design Process

Peace engineers use the engineering design process to recognize and define the problem, build and/or adapt tools and processes to collect relevant data, and form courses of action (COAs) and test them with data to select paths for solutions.

For example, in eastern Syria hundreds of small towns are without basic services. Creating a COA that integrates the installation of distributed power systems, well water, household sanitation, and high-speed communications is a first step in reconstruction after violence has subsided and to avoid a return to violence.

Then, as every engineer does, peace engineers follow implementation with constant evaluation and adjustment of the selected COA to best find and sustain peace.

Scale, Intensity, and Dimension

For peace engineers, the problem formulation phase of engineering design considers the parameters of scale, intensity, and dimension (Schirch 2013).

Scale ranges from interpersonal conflict to group conflicts to multinational or global intergroup conflict.

Conflict *intensity* is typically bounded by structural violence and direct violence. There are many forms of structural violence that vary in scale and intensity. Inequity, greed, racism, limited access to critical resources (e.g., water), corruption, chronic economic stress, religion, and political challenges are examples of structural violence.

Peace engineering focuses on opportunity and innovation to target structural violence and create broad foundations for sustainable peace. For example, facilitating communication between individuals or groups in conflict is a longstanding method to address root causes of structural violence.

A new tool referred to as "Peace Data" (Guadagno et al. 2018) provides real-time analysis of communications—including group identity information, behavior data, longitudinal data, and metadata—that can be used to measure, analyze, and promote direct communications across group difference boundaries that are central to a conflict.

The transition from structural to direct violence occurs with triggering events that can move a conflict rapidly into a domain of active or kinetic conflict. Once active conflict begins, peace engineers focus on deescalation. Without "off ramps," active conflict grows, and the level of violence can become catastrophic.

The *dimensions* of conflict include time, numbers and types of actors, geography, culture, and technology.

Future Implications

Any field that professes the ability to solve substantial, intractable, societal challenges such as creating world peace, solving world hunger, or eradicating poverty should be met with great skepticism. We do not assert such a claim. Peace engineering will not solve or prevent all conflict in the world. But we believe it can contribute to measurable progress toward a more peaceful world by

- changing how engineers think about conflict;
- reducing the human, social, and economic impacts of violence; and
- creating tested, replicable pathways for proactive, sustained, and scalable peace.

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Engineering Interventions to Reduce Plastic in the Environment

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In 1970 just over 30 million metric tons of plastics were produced globally for use; now that number stands at 359 million metric tons (Geyer et al. 2017[1]; PlasticsEurope 2019). As of 2017, a cumulative 8.3 billion metric tons of plastics had been produced.

Plastics are unquestionably useful. And many consumer items are made from plastic because the needed monomers, like ethylene, are available at very inexpensive prices. But too many of them end up in the waste stream.

Plastics: An Unsustainable Convenience

Because 40 percent or more of plastics are used in packaging and other single-use items, 6.4 billion metric tons of plastics had already become waste by 2015. Only 9 percent of plastic waste has been recycled on average globally, and 12 percent has been incinerated. This means that 79 percent ended up in landfills, mismanaged on land, or in the ocean. Plastics are now found everywhere in the environment, from the deepest part of the ocean to the highest peaks in the world and all points in between.

Between 5 and 13 million metric tons of plastic enter the oceans each year from mismanaged waste (Jambeck et al. 2015; Lebreton and Andrady 2019), equal to about a dump truck of plastic entering the world's oceans every

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[1] Further statistics in these first three paragraphs are from Geyer et al. (2017).

minute. Globally, hundreds of seabirds, whales, fish, shellfish, and turtles are impacted each year by plastic, whether from ingestion or entanglement (Wilcox et al. 2013, 2015; Worm et al. 2017).

Even with current mitigation practices, improved waste management systems, and cleanup, new research shows that 20–53 million metric tons of plastic will enter all aquatic systems per year by 2030. Much more aggressive reductions, improvements, and cleanup are needed (Borrelle et al. 2020).

Role of Engineers and Engineering

Effective engineering involves not just designing a construction project or technical intervention but a systems approach that accounts for diverse people and communities. It needs to incorporate sociotechnical designs, like improved waste management systems that include the informal waste management sector, which keeps plastic out of the ocean by recycling it in many countries around the world, as well as deep stakeholder engagement from start to finish, acknowledging that community leaders and members have local and native knowledge that not only contributes to but improves designs and approaches.

Engineers can help not just by developing more and improved waste management infrastructure but by decoupling waste generation from economic growth by leveraging technology with context-sensitive designs. Technology and shipping and logistics systems mean greater availability of reusable packaging. For example,

- just as milk used to be delivered in glass bottles that were returned and reused, individuals can now purchase a stainless steel ice cream container (available online) that can be returned and refilled;
- reusable cups and to-go containers can be tracked and associated with users for automatic payment with radio frequency identification (RFID); and
- reusable containers can be refilled with trusted brands from a truck that travels through a community.

If packaging is needed, it can be made from biodegradable materials, such as new polymers like polyhydroxyalkanoates (PHA) that behave like traditional plastics in specifications but biodegrade at their end of life.

In addition, mobile app technology, available to billions of people around the world, can be used for on-demand collection of waste and recyclable material as well as reports of litter with, for example, *Marine Debris Tracker*, to inform upstream interventions for common items found in the environment and on the coastline. This information can empower communities with data to make decisions about ways to reduce marine litter that fit their specific context.

These are some of the ways both new and "old" systems can enhance efficiency and reduce waste in today's high-tech society.

Concluding Thoughts

People could be more thoughtful about where, when, and how they use and dispose of plastics. But to move forward to, for example, a circular economy, entire systems need to be engineered and changed. Can we take cues from nature where every output becomes an input in each system?

As engineering proceeds over the next 50 years, it is critical to take a diverse and holistic approach, while learning lessons from the past to engineer the future.

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Precision Medicine in Cardiology through Research, Innovation, and Intellectual Property

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Over 4 million people are admitted to hospitals annually with a diagnosis of acute coronary syndrome (ACS), which includes unstable angina and acute heart attack. The three most common underlying mechanisms for ACS are plaque rupture (40–60 percent), plaque erosion (40–60 percent), and calcified plaque (10 percent) (figure 1).

Plaque rupture has been well characterized for several decades, but the diagnosis of plaque erosion in living patients became possible only in 2013 (Jia et al. 2013), based on the 1991 invention by an engineer at MIT, James

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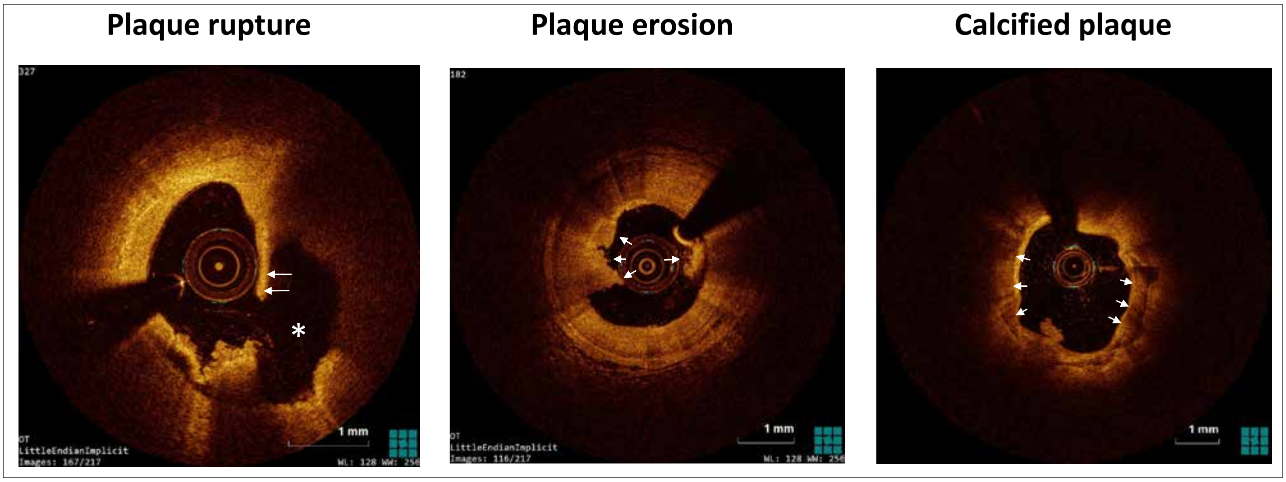

FIGURE 1 Three underlying mechanisms of acute coronary syndrome: plaque rupture, plaque erosion, and calcified plaque. Plaque rupture demonstrates discontinuation of the fibrous cap (arrows) and an empty cavity (asterisk), previously filled with lipid-rich necrotic core. Plaque erosion shows preserved vascular structure and lumen (the superficial endothelium—the innermost layer of the vessel wall—has peeled off). The protruding structures (arrows) are a platelet-rich thrombus (blood clot). Calcified plaque shows superficial calcification with low signal intensity (arrows), which differentiates calcified plaques from other types.

Fujimoto, of optical coherence tomography (OCT), a high-resolution imaging technology (Huang et al. 1991).

Compared to conventional intravascular ultrasound at a resolution of 150–250 microns, OCT has 10-fold higher resolution using a catheter-based system to achieve a resolution of 10–15 microns. This enables visualization of the microarchitecture of a vessel wall, including atherosclerotic plaques. As a result, it is now known that plaque erosion has three distinct morphological characteristics: preserved vascular integrity, a larger vessel lumen, and a platelet-rich thrombus (blood clot; figure 1).

Although it is now understood that the three ACS conditions have distinctly different pathobiology, patients are treated uniformly with a coronary stent. Complications with stents are a major problem, however; renarrowing occurs in 10–40 percent of patients even with a drug-coated stent. Another catastrophic complication, stent clotting, can occur even after many years; the majority of these patients experience heart attack with a high mortality rate.

A proof-of-concept study (Partida et al. 2018) found that treatment with antithrombotic medications may be an option, avoiding use of a coronary stent in ACS patients with plaque erosion. OCT imaging and other technologies may yield additional effective treatments.

Technology for Precision Medicine: What's Needed

The OCT imaging–based approach is one of the first attempts toward precision medicine in cardiology, making it possible to tailor therapy based on an individual's underlying pathobiology rather than applying uniform treatment to all patients with the same clinical diagnosis.

A key technology that is not yet available is a noninvasive imaging test that can identify plaque erosion. In the future, when a patient presents to an emergency department, the probability of plaque erosion could be estimated using simple clinical and laboratory tests, and confirmed by a noninvasive imaging test. If the test shows plaque erosion, the patient can be triaged to a conservative treatment and avoid invasive procedures.

If the findings of the plaque erosion study (Partida et al. 2018) are replicated using this noninvasive test in large-scale studies, the management of millions of ACS patients around the globe may be improved. Such a revolution will be possible through collaboration among engineers, technology transfer professionals, entrepreneurs, and physician-scientists—and can likely be achieved within the next 10 years.

The Changing Landscape of Patents and Technology Transfer

Historically in technology transfer, entrepreneurship, and innovation, patents have been considered the most prized form of intellectual property. But recently both academic and commercial technology transfer practices have recognized and begun capturing the value inherent to data and know-how.

A patent owner has the right to exclude others from making, using, importing, and selling a patented innovation for a limited term unless authorized under a patent license agreement. Such licenses are neither easy to negotiate nor free, but it is through licensing that academic technologies have not only penetrated but also in some cases determined the market.

Important technology gaps—such as a noninvasive imaging test that can identify coronary plaque erosion—need to be bridged.

Moreover, through licensing, among other types of agreements (e.g., sponsored research, codevelopment), research has expanded its economic and social footprint and incentivized further innovation. Not often is the relationship between science and economic interests in such lockstep.

Although the space for US patent protection may be decreasing and/or the threshold for patent eligibility increasing, there has been a shift toward codifying other forms of intellectual property, such as data and know-how.

Data

Data, which can encompass study results, patient data by indication, images, usage data, and analytics (among many other forms), have not traditionally been identified for their monetary value. But the recent impact of data analytics, evolving algorithms, and machine learning across many specialties, including cardiology, is undeniable.

Medical data can be used to develop, train, improve, and validate algorithms, and associated or resulting software can be categorized as an FDA approval–required medical device, which can change paradigms of clinical practice and contribute to evidence-based medicine. The data are not subject to patent protection costs, but they do come with privacy protection concerns (e.g., HIPAA, the EU General Data Protection Regulation), which are not trivial.

Data are invaluable and could lead to the next big diagnostic, preventive, or therapeutic modality. To that end it will be important to identify the most efficient ways to gather, organize, store, and transfer data in a manner compliant with all applicable laws and regulations.

Know-How

Know-how has typically been shared freely in the academic community or pursuant to a consulting agreement with a commercial partner. Most consulting agreements stipulate that any intellectual property (know-how, patents, or otherwise) that arises from the consultation belongs to the commercial partner.

In academia, consulting agreements do not usually fall under the purview of a technology transfer office, as they pertain to intellectual property that does not belong to the academic institution. Only relatively recently have academic institutions recognized know-how as a significant and proprietary asset—and one that has been leaking out the "back door" of consulting agreements.

Licenses vs. Patents

Unlike patents, neither data nor know-how (or copyright, for that matter), provided they are properly protected, incur the same costs or come with an expiration date. They can therefore be used to extend the royalty-bearing term under a license well past the term of a patent and they can be licensed to more than one party (in contrast to know-how captured in a one-time consulting agreement).

Conclusion

The dichotomy between the approaches to data and know-how in academia and industry needs to be reconciled in order to benefit research and innovation, and this is the responsibility of technology transfer professionals. In the meantime, crucial technology gaps—such as a noninvasive imaging test that can identify plaque erosion—need to be bridged.

Innovators in both academia and industry are necessary to advances in all fields, including patient care. They, and engineers and physician-scientists, need to identify data and know-how and to work with their technology transfer office to codify the values of these assets—not just economically but, more importantly, for their potential scientific and social impacts.

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Accelerating Innovation in the Water Sector to Meet Future Demands

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Access to safe and reliable drinking water is a basic human right, yet over 2.2 billion people do not have it (WHO/UNICEF 2017). A similar number live in countries experiencing water stress, which is expected to be exacerbated by an increase in global water demand—20–30 percent by 2050—driven by population growth, development, and changing consumption patterns (Burek et al. 2016). In addition, warmer air and water temperatures, along with changing precipitation patterns, increase water pollution, while extreme weather events may further weaken already compromised infrastructure. These challenges, if left unmet, will threaten future public health, food stability, ecosystem health, and economic growth.

Services to provide safe water are important to global economies. Water needs to be available, accessible, and treated to acceptable quality for its intended use (consumption, cooking, agriculture, energy). Total annual revenue for the US water and wastewater industry is over $139 billion, and the global water market is estimated to be over $500 billion (Maxwell 2013).

One would expect that such serious challenges in an industry as important as water, combined with the impact that water has on the economy, would incentivize innovations in related technology, institutions, and management. But despite pervasive, worsening stressors around water quantity, quality, and infrastructure, innovation in the water sector is very slow.

Barriers to Innovation in the Water Industry

To be innovative, an industry must value and invest in innovation. Industries such as automotive, entertainment, computing, and consumer goods value innovation because it drives profitable growth. It is counterintuitive that innovation in the apparel industry, for example, would be higher than in the water industry, which is so central to public health and economic growth.

But the water sector has inherent barriers to innovation: capital equipment has a long design life, plants tend to be large and centralized, and water institutions are regulation-based, risk-averse, and biased to inertial dominance of existing technologies (Kiparsky et al. 2013).

To meet the need for safe water amid myriad water resource stressors, the industry must shift focus from reliance on traditional water resources to alternative water resources such as desalinated seawater, groundwater, reclaimed stormwater, greywater, and treated wastewater, and develop protocols to expedite evaluation and implementation of novel treatment processes.

New and Sustainable Water Treatment Systems

As stressors on water quality and quantity worsen, conventional water treatment processes are increasingly unable to meet future water quality goals; they require high chemical and energy inputs, are complex to operate, create large waste streams, and are resistant to retrofitting. Sustainable treatment processes are necessary to reliably remove current and emerging contaminants without creating a heavy chemical burden or high byproduct stream.

New treatment systems would include a mix of robust, efficient processes that are also low in both cost and energy requirements. The timeline between development and widespread deployment of novel treatment processes to treat these sources to acceptable quality must be reduced.

Alternative resources require treatment processes designed to deliver water services that are reliable, safe, accessible, affordable, and culturally acceptable in the face of climate change, population growth, development, environmental degradation, and regional conflict. This challenge requires investment in the development and implementation of next-generation water treatment systems.

State-of-the-Art Membranes

Next-generation water systems will include decentralized systems and low-cost community-based systems that complement or replace large centralized water infrastructure (Gleick 2003). An attractive unit operation for many of these applications is membrane filtration, as membranes can be used alone or as part of a multibarrier, component-based system that can be tailored to suit the intended use of the water. Membranes come in varying configurations, from tight, dense reverse osmosis (RO) membranes that reject most trace contaminants, to low-pressure membranes such as micro- and ultrafiltration.

Alternative resources require treatment processes designed to deliver water services that are reliable, safe, accessible, affordable, and culturally acceptable.

Traditional thin-film membrane systems are a mature worldwide industry with applications in the desalination of brackish and saline sources and incorporation in bioreactors. These polymeric materials represent the state of the art in membrane fabrication with their great transport properties, large surface area, small footprint, and relative affordability.

Membrane Research and Innovation

To meet the challenges of affordability, energy efficiency, and sustainability, issues such as concentrate disposal, fouling, and energy use have to be addressed. Membrane researchers have long chased the goal of reducing the energy cost of desalination—for example, by greatly reducing the energy use to nearly the thermodynamic limit—but scaling and concentrate disposal are still major issues.

A promising area of research in membranes is the development of novel materials that may disrupt the polymeric thin-film membrane industry. For example, the coupling of traditional membrane polymers with nanomaterials such as graphene oxide (Igbinigun et al. 2016) has shown promise by increasing permeability and reducing fouling.

Membrane distillation is also gaining popularity, as it operates at lower pressures than RO and at lower temperatures than traditional distillation processes.

Researchers have developed innovative methods to embed light-absorbing nanoparticles in the surface to use solar energy to drive the distillation process (Dongare et al. 2017). Others have designed block copolymer–based materials with synthetic nanochannels to increase selectivity and permeability and reduce fouling of membranes (Sadeghi et al. 2018).

How to Accelerate Innovation?

These research findings could be transformative for next-generation water purification, but they often stall at the bench or lab scale. In the water industry, new treatment processes must undergo extensive evaluation and testing before being accepted by water utilities. Often, researchers use simplified versions of systems with simulated water streams, making translation to real water sources uncertain.

But even when new systems are tested at the bench scale using actual source water, geographical and seasonal variations in water quality stretch testing and evaluation to months or years. Utilities often will not consider testing for a new process until successful operation is proven at another utility, and even then, in-house testing is necessary to determine operational protocols and effluent quality.

One way to accelerate implementation of novel technologies is to prioritize industry-university partnerships. These partnerships can be mutually beneficial, exposing university researchers to testing protocols, scalability, and cost barriers early in the research timeframe, while the utility or industrial partner gains important insight into a novel process using its own source water in testing much earlier in the process.

One promising initiative is the Leaders Innovation Forum for Technology (LIFT), undertaken by the Water Research Foundation and Water Environment Federation (a water industry association) to increase innovation by connecting universities and utilities for research, development, and demonstration of new technologies (Brown et al. 2019).

Useful partnerships have also developed organically when a utility taps faculty and students from local universities to help fill knowledge gaps in prospective new technologies. One such example is a longstanding partnership in Washington between the District of Columbia Water and Sewer Authority's Blue Plains Advanced Wastewater Treatment Plant and several local universities: Howard University, George Washington University, Virginia Tech, and the University of the District of Columbia. This partnership provides opportunities for graduate students to perform applied research onsite at the treatment plant while researchers at the utility and universities work collaboratively on the development and implementation of innovative technologies.

The water sector will benefit when more such partnerships are developed and supported.

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Artificial Intelligence: From Ancient Greeks to Self-Driving Cars and Beyond


Achuta Kadambi


Asad Madni

Achuta Kadambi and
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Artificial intelligence (AI) is more than 2000 years in the making, dating back to the ancient Greeks. To protect his island from pirates, it is said that the first king of Crete, Minos, received an unusual gift from Hephaestus, the Greek god of invention and blacksmithing: a bronze robot known as Talos. Like clockwork, Talos was conceptually programmed to circle Crete thrice daily, throwing stones at nearby ships (Mayor 2018).

AI relates to a form of execution demonstrated by machines that traditionally has been associated with humans or animals. The ancient robot Talos defended an island—an action ordinarily performed by humans. The self-driving cars of today seek to replace a human driver. These examples, both ancient and modern, fall under the realm of "weak AI" that is preprogrammed to address tasks that would have been given to a human.

If AI has been here all along—from Talos to self-driving cars—where will the field go next? The untapped future of AI, where revolutionary progress awaits, lies in "strong AI," where machines teach humans. When humans learn from such machines it is possible to receive unexpected insights that yield a change in practice.

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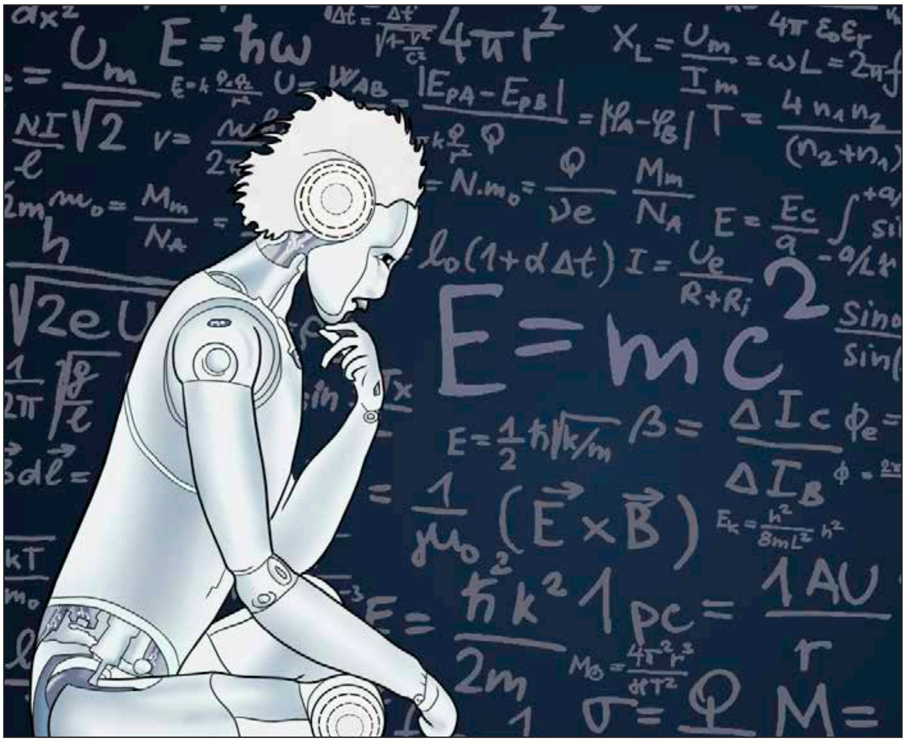

FIGURE 1 Can machines be taught how to discover the laws of physics? This conceptual figure illustrates the potential of a machine that can rediscover Einstein's equations. Figure credit: Kyle Icban. Printed with permission.

AI as a Tool of Scientific Discovery

One future of strong AI lies in scientific discovery, a disruptive tool to unblock stagnated fields of science. In fact, this is a field where AI must be used. Where humans can apply only the same known techniques in their arsenal, the unexpected insights from AI might be the wiggle needed to get the wagon wheel out of the rut.

To see the impact of AI on scientific discovery, consider the field of physics. The past 30 years have seen little progress on fundamental questions such as how to explain the wave function collapse (von Neumann 2018). Part of the challenge is that physical observations have become both much more expensive to collect (so-called *big science*) and difficult to interpret by humans. From Newton to Einstein, there has been a remarkable jump in the complexity of the observations required to validate a theory.

But the modern physicist has something that neither Einstein nor Newton had: ever increasing computational power. This motivates a new paradigm for physics, which we call *artificial physics*. The artificial physicist can operate in a way that is almost contradictory to a human. Where a human can test a small set of curated theories on a sparse set of data, a machine can test a huge number of combinatorial possibilities on massive datasets. It is a radical change in approach, and one that may yield radically different results.

Figure 1 illustrates conceptually a computer program that can rediscover Einstein's famous equations. We have not yet observed a technology that can automatically intuit these equations—one of the challenges is that Einstein's equations are a human-interpretable construct—but a solution might build on work in symbolic equation generation (Schmidt and Lipson 2009).

However, the road ahead to scientific discovery is not easy. Human engineers and computer scientists will have to create the artificial physicist. Interpretability will be a challenge. How is it possible to ensure that the output equation of an artificial physicist meaningfully maps to what humans can interpret?

To see why creating artificial physicists is difficult, let us consider a simplistic example of building an AI engine to discover the laws of projectile physics. The goal of our AI engine is to observe numerous videos of projectile motion and eventually elucidate the textbook laws of projectile physics. Unfortunately, this problem is very difficult: the AI engine does not know what the scene parameters are (e.g., velocity, gravitational constant). It needs to learn such parameters as well as the governing equation (e.g., a parabola).

In our initial tests, we ran into a situation that deep learning practitioners would be familiar with: the neural network returns a symbolic expression that is accurate in predicting projectile motion, but it is based on artificial parameters (i.e., latent variables). These latent variables are not indicative of actual scene parameters, like velocity or gravity.

Frontiers to Be Explored

The future of AI lies in grappling with these nuanced challenges. There are multiple frontiers that could be explored.

- *Interpretability.* If a machine is to teach humans new insights, both partners must speak the same language. Imagine a hybrid team of two physicists: one is an artificial intelligence, the other a human.
- *Novel algorithms and architectures to implement AI.* Today, neural networks ("deep learning") are the dominant approach to implementing weak AI. However, such methods are preprogrammed rather than self-thinking.
- *Unblocking traditional fields*—not just physics but chemistry, medicine, and engineering. The word choice of "unblocking" is deliberate. It is one thing to use AI as a tool to augment human performance in a field—much as computers help an author searching for a word definition. It is entirely different to have the AI drive the research field in unexpected and meaningful directions.

An example of unblocking in action can be found in the optical sciences. Progress in optical design long held that Fourier-coded apertures were optimal (Nugent 1987). With the advent of AI, optical scientists have been successfully using AI algorithms to create unexpected aperture masks that depart from—and outperform—Fourier masks.

For thousands of years humans have been teaching AI to do our chores. It might be time that we let AI teach us how to innovate in new and unexpected ways.

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The Role of Technical Standards in Enabling the Future

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Predicting the future using technical standards seems counterintuitive, but examining their history indicates otherwise. Six successions of technical references/standards—symbols, measurements, designs, similarity, compatibility, and adaptability (figure 1)—are based on general set theory (Krechmer 2005b). Each succession, a paradigm change, enables a period of increasing value creation: bartering, measuring, building, manufacturing, networks, and openness. The most widely used standards from one succession may continue during the following successions.

Standards successions offer an evolutionary technology model, showing why market control occurs and where new value is created.

Bartering

Human creations—such as the use of fire, tools, prepared plants, animal parts, structures—emerged before recorded history. As early humans found that they could benefit from each other's tools and resources, they learned to barter, a new value creation and one that required communication. Beginning well before 10,000 BCE, cave art includes a graphic protolanguage using symbols (von Petzinger 2016). These *symbols*, the first succession, set the stage for increasing communications.

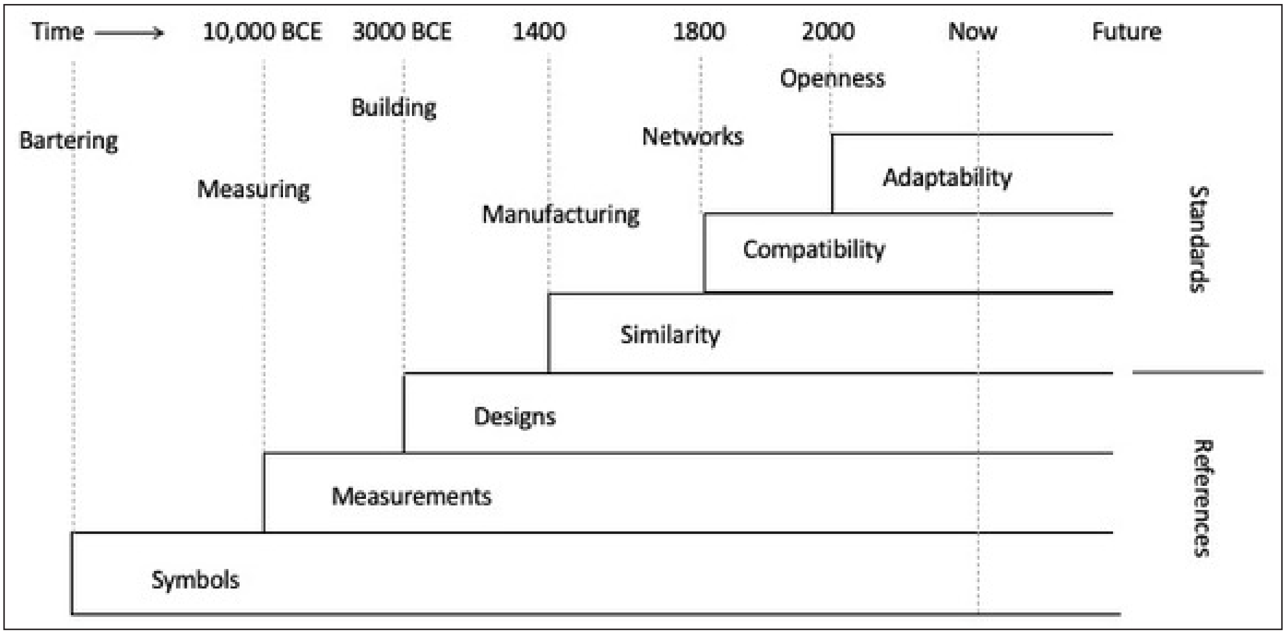

FIGURE 1 Succession of references/standards codifies the history of technology.

Measuring

Settled societies started about 10,000 BCE and often developed unique products to trade (Bunch and Hellemans 1993).[1] As communities were established and expanded, counts and measures were necessary to grow enough food in an area or to barter resources with others. The Sumerians, for example, developed standard measures of weight, volume, and length. *Measurements*, the second succession, helped create more value.

Building

About 3000 BCE, the planning and building of larger structures, including wooden ships, began around the world. The seven wonders of the ancient world were human-built structures, and they required designs using symbols and measuring. These *designs* or sets of references, the third succession, predict the completed structure.

Manufacturing

The first assembly line, producing sea-going galleys, began in Venice about 1400. Repetitive assembly applies and creates *similarity* (David 1987), the fourth succession, and similar goods increase efficiency.

As an example, while the liter standard ensures the same measure of liquid in a barrel, a reference barrel design defines similar construction and shape among barrels. Making each barrel similar offers economic advantages to the barrel maker in manufacturing efficiencies, to the trucker in handling efficiencies, and to the bartender in use and maintenance (Krechmer 2005a). The desire for greater efficiency, a self-reinforcing effect (Arthur 1988), creates larger markets. As a market becomes larger, controlling it becomes more valuable:

- Patents and copyright—new value systems—allow market control.
- Cartels emerge, controlling industries and markets, requiring antitrust law.
- Controlling a useful standard (e.g., barrel size) is also a form of market control.

Networks

Networks began with railroads (~1800), then water and gas distribution companies, newspapers, electric power, and broadcast and communications, among others. The larger the network, the more desirable; the more desirable the network, the larger. This self-reinforcing effect often creates one dominate network.

When a network connection is complex and not standardized, only the network owner can provide a connection to it. This is another form of market control,

[1] The further historic references in this essay are from this book.

so networks are often government regulated as a utility (new value system) to reduce different forms of market control. Additionally, when *compatibility* is recognized, a connection (physical) or interface (virtual) to a desired network may be standardized, reducing market control and increasing value.

> *Standards successions offer an evolutionary technology model, showing why market control occurs and where new value is created.*

Without network compatibility standards, market control is greater and growth is often reduced. Network connections by railway gauge, pipe threads, electrical outlets, and telegraph and telephone wires were originally owner controlled, which slowed market growth and still makes multicountry travel more difficult. Independent compatibility standards for electronic mail, the internet, the web, and wireless and cellular networks developed as these networks were created, speeding market growth.

The effect of later standardization on the US Public Telephone and Telegraph (US PT&T) network became clear when the Federal Communications Commission Part 68 regulations standardized compatibility (von Alven 1983), supporting divestiture of the US PT&T (reducing market control) in 1984. Over time, new companies innovated using the Part 68 compatibility standards and created large new markets for private telephone switches (PBXs), answering machines, data modems, and feature phones. Standardized compatibility, the fifth succession, makes such innovation possible.

Openness

The openness succession began when smartphones connected to networks in 2000. By 2020 web-based services (companies) supporting searches, mapping, electronic health records, ecommerce, social networks, and finance offered autonomous functions. The connection to these web services is via application programming interfaces (APIs).

Few web service companies are cartels, but all control their markets using APIs. The copyright control of APIs is under review by the US Supreme Court (2019). All APIs could, in theory (and should for health, safety, or antitrust law), allow competing networks to connect. The above history of networks indicates that when controlled APIs are standardized, greater value will be created and distributed.

Standardizing future compatibility may require an independently developed and maintained API and adaptability standard that defines a peer-to-peer meta-function that compares, negotiates, and selects from a menu of services from both sides of the API (Krechmer 2000) and separates API control from the network owner.

This meta-function also supports proprietary operation by transferring—in both directions—a trademarked character string (e.g., "Amazon") that identifies proprietary ownership. Trademark strings (a new value system) allow networks to control their innovations and still support standardized APIs. Similarly, specific national or regional requirements (e.g., the EU General Data Protection Regulation) could be identified.

Implementing *adaptability*, the sixth succession, will create new self-reinforcing effects: individual desire for specific compatibility, functionality, or security; network owner desire for proprietary value (sans monopoly); and nation-state desire for control of virtual borders. It will also significantly improve troubleshooting.

Predicting the Future

Each succession of technical references/standards—symbols, measurements, designs, similarity, compatibility, and adaptability—predicts and enables emerging future value. At this point web services companies should help develop and implement adaptability standards for APIs defined and maintained by independent standards development organizations.

Both adaptability (a new succession of standards) and openness (an emerging technology requirement) are quite likely to have significant influence on technology development for hundreds of years. Even the impact of the 200+-year-old compatibility succession is still not fully understood (e.g., on patents; Krechmer 2005c) and likely to remain so for many years. As adaptability increases, history and logic predict more innovation, expanded markets, and further openness.

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Accelerating Growth of Solar Energy

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In 1970 silicon solar cells were used for powering satellites but were too expensive for terrestrial applications. Now they are the fastest-growing source of bulk electricity in many locations, accounting for an impressive 43 percent of worldwide net electricity-generating capacity expansion in 2019 (figure 1, pie chart; REN21 2020).

In 2008 the NAE named as one of its 14 Grand Challenges for Engineering[1] "Make Solar Energy Economical." At the time, solar panels cost about $4/W (Feldman et al. 2012), far too expensive to be a practical power source for the world. In 2020 the cost can be less than $0.20/W and solar electricity power purchase agreements have been reported for prices as low as 1.35 cents/kWh (Bellini 2020)—less than half the average 2019 US wholesale price of electricity (3.8 cents/kWh).[2]

Growth in Solar Capacity, Day and Night

Solar deployment has grown consistently faster than predicted (Haegel et al. 2017), apparently accelerated by a positive feedback loop in which public enthusiasm drove policy incentives, which drove deployment and lower costs, which further increased enthusiasm, in a repeating cycle (lower circle

[1] www.engineeringchallenges.org/

[2] Derived by averaging the data for 2019 at https://www.eia.gov/electricity/wholesale/#history (Jul 4).

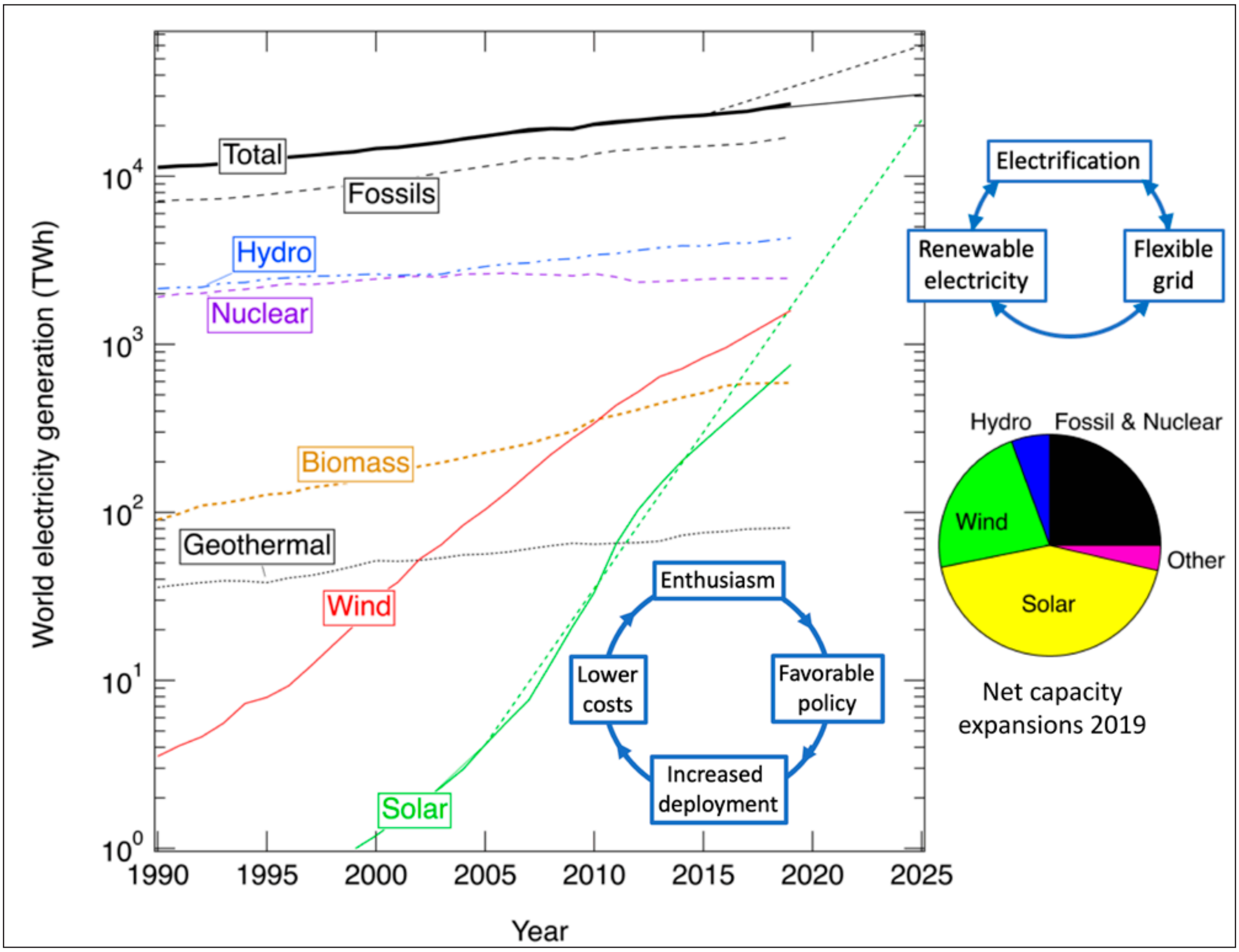

FIGURE 1 Graph of historical world electricity generation by technology and pie chart of net electricity-generating capacity expansions in 2018–19. The lower positive feedback loop fueled surprising growth of solar (green line) in 2005–15. The dotted green line shows how continuation of that growth would enable solar electricity to meet most of the world's electricity needs by about 2025, a level that would be practical only if world electricity demand increased by massive electrification as shown schematically by the dotted black line and as reflected by the positive feedback mechanisms shown in the top right loop. Based on data from REN21 (2020) and US Energy Information Administration, International data: Electricity (https://www.eia.gov/international/data/world, accessed Jul 4).

in figure 1). Growth between 2005 and 2015 was so rapid[3] (a factor of 63) that if the same relative rate continued solar electricity generation would approach the entire world electricity demand by about 2025 (dotted green line in figure 1).

Having delivered 2.8 percent of the world's electricity in 2019 (REN21 2020), solar energy has now entered a new era in which the primary challenge is to identify ways to use variable solar electricity to provide power at every moment of the day *and* night. Fortunately, impressive advances in lithium ion batteries in recent years are enabling use of solar electricity after the sun sets. The Colorado Public Utility Commission recently accepted an Xcel Energy proposal to reduce costs by prematurely retiring a coal-fired plant and replacing it with a combination of solar plus batteries (Jackson 2020). This is a ground-breaking instance of solar and storage unseating fossil fuels, competing directly on cost and at the request of a utility.

Wind electricity has also decreased in cost and wind as a resource is often strongest at times when solar resource falls short (at night, in winter, and during storms). Large deployment of wind and solar, coupled in a smart way with expanded deployment of technologies available today, can create a cost-effective and

[3] US Energy Information Administration, International data: Electricity (https://www.eia.gov/international/data/world, accessed Jul 4).

highly reliable electrical grid with 90 percent of electricity generated by carbon-free sources (e.g., Phadke et al. 2020). Strong policy action could enable this 90 percent milestone by 2035 (Phadke et al. 2020).

The Role of Positive Feedback

Just as the solar industry grew much faster than expected in recent decades, it may be poised for further impressive growth driven by an additional positive-feedback mechanism involving renewable electricity, electrification, and tools that improve grid flexibility (upper right circle of figure 1). Electrification of the transportation and heating sectors using electric vehicles and heat pumps not only reduces reliance on fossil fuels but also increases efficiency, reducing the total energy needed (Kurtz et al. 2020).

Key elements of the flexible grid will include large storage capabilities, transmission, and demand management to maintain tight balance between electricity supply and demand at every moment of the day. The feedback makes the job easier; for example, electrification of transportation will introduce flexible loads (vehicle charging) that may be shifted to times of electricity abundance.

> *New and updated technologies such as liquid air, gravity, thermal, and geomechanical storage may provide scalable energy storage options.*

Continuing the enthusiasm-driven positive feedback loop and adding coordinated implementation of electrification and flexible grid technologies will accelerate the transition while reducing cost.

New Technology Needs and Research Opportunities

Reaching the goal of 100 percent of electricity generation without using fossil fuels will require new technology. For example, the seasonal fluctuations of energy demand are problematic without some form of seasonal storage or long-distance transmission.

It may be that hydrogen coupled with fuel cells could solve the problem by using surplus electricity to split water into hydrogen and oxygen, then using the hydrogen later to regenerate the electricity. In addition to chemical storage like hydrogen, new and updated technologies such as liquid air, gravity, thermal, and geomechanical storage may provide scalable storage options.

The best pathway to a 100 percent zero-carbon grid is under debate, but many studies have identified possible pathways to achieve this by 2050. Coupling this energy transition with electrification will reduce carbon emissions associated with transportation and heating and will accelerate the conversion of the grid by increasing both the demand for renewable electricity and the flexibility of the grid (e.g., assuming that electric vehicles can charge during times of abundant electricity).

While today's photovoltaic technology has advanced enough to drive the grid, it is still in its infancy. Just in the last 5 years, the silicon-based solar industry has changed product lines, shifting to advanced monocrystalline silicon solar cells and to bifacial cells and modules. Companies are developing modules that deliver more than 500 W. In parallel, cadmium telluride modules are now made larger and more efficient.

Debate persists about the technical trajectory of photovoltaic technology. The power generated by a single solar panel continues to increase and there is a vision of practical tandem solar cells with substantially higher efficiencies. Tandem cells capture high-energy photons (mostly visible light) with a high-band-gap solar cell and lower-energy photons (mostly near-infrared light) with a lower-band-gap solar cell. Some companies are starting to commercialize tandems using higher-band-gap perovskite cells coupled with the low-band-gap silicon tandems. In addition, solar panels are being engineered to replace building materials, and they can be integrated into cars and be made with any color to better blend into the environment.

Solar energy has made amazing progress over the last 50 years, enabling visions of a new era of growth accelerated by coordinating solar's growth with electrification and flexible grid advancements. When *The Bridge* celebrates its 100-year anniversary, solar may be the world's largest source of energy.

Acknowledgment

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Digital Manufacturing: Breaking the Mold

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To appreciate the future impact of additive manufacturing not only on industry but on economies and their constituents, it is important to have some perspective on the scope of manufacturing, including the impacts and disruption of digital technologies over the past decade.

Economic Scope of Manufacturing

Manufacturing is fundamental to both developing and advanced economies and represents approximately 17 percent of the world's GDP. For developing nations it provides a pathway for rising incomes and living standards, while for developed nations it is a vital source of innovation and economic competitiveness given its substantial contribution to research and development. Moreover, innovation and advances in large-scale manufacturing have made it possible for the average consumer to afford items such as automobiles, electronics, and other complex devices that otherwise would be out of reach for most people, even in developed nations.

The world economy could more than double in size by 2050 (PWC 2017). This will drive additional production capacity, which will bring with it high-wage jobs, increasingly in high-tech areas, wherever manufacturing is located.

Over this same period, digital manufacturing[1] is likely to transform various manufacturing sectors and shift longstanding patterns, such as reducing the typical decline of local manufacturing sectors after peak output. A predictable cycle occurs when residents whose living standards and discretionary income increase with the rise of manufacturing jobs begin demanding more from the service sector, effectively diversifying the local economy as it reduces dependency on factory work.

Additive Advantages

Additive manufacturing has begun to prove itself a powerful vehicle to usher digital manufacturing and its related services into today's supply chains, in turn improving the sustainability of the manufacturing sector as local economies evolve. While the technology has been incubating over 30 years, only in the past 5 years, at the hand of Moore's law, have the computer processing, networking infrastructure, and data storage industries evolved to the point that additive can deliver on the promise of digital manufacturing. That promise can be characterized in at least three ways.

Stronger Connections among Consumers, Designers, and Products

Additive manufacturing (also called 3D printing) enables a closer connection among consumers, designers, and products. It is one of the first widely accessible digital production technologies permitting designers to focus entirely on the functionality and aesthetics of a product, as compared to designing for manufacturing.

To illustrate the distinction, when designing a part using injection molding, engineers are constrained by the injection molding process, including the development of a steel mold and the way the part is formed and released from the mold. Using additive manufacturing, designers and consumers alike can model a product using a range of software design packages, with free online tools and varying levels of design rules and file processing sophistication. With this new freedom, people can design, iterate, and convert their concepts to physical objects without the deep experience and formal training required for more traditional production technologies such as injection molding or computer numerical control (CNC) metal work.

This dynamic has also ushered in the opportunity for cost-effective customization and personalization. Examples of this transformation can be seen in the dental alignment and in-ear hearing aid markets, driven by the ability to eliminate forms and molds in favor of digital scans and advanced production process flow.

Reduced Costs

In traditional manufacturing it can take millions, and sometimes billions, of dollars to set up a factory to realize large-scale production of a single product type. Because additive manufacturing largely removes the need for custom tooling (e.g., molds), the costs to produce small numbers of parts, including a single part, drop precipitously. Companies and individuals can have prototypes produced more economically and pursue new business models that inject more service dollars into the $13.8 trillion US manufacturing industry.[2]

Additive manufacturing permits designers to focus on the functionality and aesthetics of a product, as compared to designing for manufacturing.

The promise of digital and additive manufacturing is that much of the product-specific expenditure will give way to management of the production processes and file management, both of which are largely common to an exponentially larger set of items to be produced on a given additive platform. Moreover, the elimination of much of the hard tooling corresponds to less time associated with developing and sourcing the tooling. The net result is not only cost savings but acceleration of time to market.

[1] *Digital manufacturing* leverages computer processing and networking to integrate systems and processes across the entire production value chain, including design/rendering, engineering, production, quality, and logistics. *Additive manufacturing* is a production process in which material is added to a form (as compared to subtracted, as in metal cutting technologies). Frequently referred to as 3D printing, the process typically entails a computer-controlled process that creates three-dimensional objects by depositing materials, usually in layers.

[2] World Bank, Manufacturing, value added (current US$), https://data.worldbank.org/indicator/NV.IND.MANF.CD

Redistributed Profits

Profit pooling is expected to shift from factories and highly trained personnel to those who own the designs, production inputs (e.g., scans of patients for dental aligners), processing and quality guidelines, and digital infrastructure/repositories.

Distributed manufacturing will drive discrete goods manufacturers to begin fracturing and regionalizing in a similar fashion to what has been witnessed across the retail industry with companies such as Amazon and Alibaba. Additive manufacturing is one of the first tools to intentionally disintermediate the supply chain to the point that barriers to entry are reduced to near zero and production systems are rendered as ubiquitous and available as 2D printers.

Challenges: Intellectual Property and Regulation

While additive and digital technologies reduce the friction associated with realizing the production of goods, they create other challenges for corporations and governments. The overarching goal is to more quickly and cost effectively make goods available across the globe, but how this is done in an equitable and safe manner requires careful consideration.

The intellectual property landscape will face numerous challenges as designers' creations are made more readily available and accessible for production. Given today's tight connection between design, engineering, and production using traditional manufacturing, ownership is assigned throughout the value chain as robust manufacturing service agreements clearly define ownership and payment schedules.

In migrating to an environment where designs, in the form of digital files, can be freely passed to any networked printing device, the ownership and associated monetization for the design owner will drive new structures and business models. For perspective, consider the migration from CDs to digital MP3 files a decade ago and the disruption it created for the music industry.

Another area where government agencies, such as the Food and Drug Administration, will need to be diligent is in the application of standards and guidelines for how products enter the market. With the ability for anyone with a 3D printer to make a product, the need to track the source of origin will be critical.

Counterfeiting is not a new or digital issue, but the ability for files to be "ripped" and to have parts more easily produced and sold will be a continuous challenge. To ensure that products do not pose a danger to consumers, stringent guidelines need to be established and more information made available about a product's source, for the benefit and safety of consumers both individual and industrial.

Conclusions

In thinking about how these dynamics will impact manufacturing and economies over the next 50 years, it is clear that digital manufacturing typified by the use of 3D printing will shorten supply chains and ultimately shift value chains and profit pools. Reduced barriers to entry will reward agile operators and benefit consumers by providing tailored products to buyers with reduced lead times.

Manufacturing will be increasingly decoupled from developing nations that offer low-cost labor in exchange for better supply chain responsiveness driven through online retail. With this dynamic, many facets of the manufacturing value chain will begin to assimilate retail businesses and find their place closest to consumption. Along with this freedom will come the ability to better accommodate real-time geopolitical and policy changes by optimizing production and logistics trade-offs.

Finally, the covid-19-related supply chain disruptions showed that additive manufacturing enabled the distribution of designs to not only industrial printers but those in maker labs and even people's homes, decreasing the time to produce and deliver critical supplies to frontline workers.

Extrapolating from the ways communities responded to the pandemic, the future will reward those who make the best use of highly refined design paired with immediately available production assets. The business model used by companies such as Airbnb and Uber will begin to deliver a better product experience for customers and will drive the types of manufacturing efficiencies heralded as part of the Fourth Industrial Revolution.

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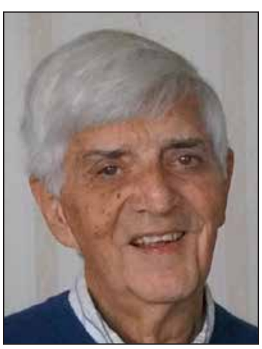
Inventing the Future

Robert W. Lucky



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There is a quotation about predicting the future attributed to Alan Kay, a pioneer in computer science. “The best way to predict the future,” he said, “is to invent it.”

Of course, we engineers do often invent the future, but sometimes not the futures that we had intended. The spirit of Kay’s quote is that we plan the future that then comes about because of our inventions. We do that all the time for next year’s products. But what about the longer term? Can we successfully plan and invent a future 20 years out, or is this an unreasonable goal?

There are many examples of success and failure at planning the future. President Kennedy said that we would go to the moon. We did. The Bell System said that we would have Picturephones. We didn’t.

In 2000 the National Academy of Engineering published a list of the 20 greatest engineering achievements of the 20th century (www.greatachievements.org), and in 2008 it identified a prospective list of 14 Grand Challenges for Engineering for the new century (www.engineeringchallenges.org). The first list included such achievements as electrification, the automobile, the airplane, and the internet. The second list, of aspirations, included affordable solar power, power from fusion, and secure cyberspace.

All of the achievements in the first list were evolutionary developments over decades, and their social impacts were realized over even longer periods. With the possible exception of laser technologies, none of them was based on a singular invention, but rather on an incremental path of development and acceptance while the world changed in unpredictable ways over the duration of that path.

Setting a goal for the future is almost a prediction in itself. I remember with embarrassment my participation in a televised discussion about the future in about 1980. The other participants painted bleak pictures of the future in their respective domains. When it was my turn, as the "technologist," I said that technology would improve the quality of life in the future—and that "we would have big TV sets." The others looked at me with derision, which was well deserved. It was a silly and useless prediction, even though it was probably the only prediction on that show that came true.

But now I wonder: What should I have said, knowing what has happened since? Perhaps instead of saying we would have big TV sets, I might have said that we would have small telephones. That would have turned out to be a much more significant prediction, and it could have been predicted in 1980. Moore's law of exponential progress in microelectronics technology had been known since 1965 and the year that it would enable a pocket-sized phone could have been predicted. But here is the rub: in 1980 we didn't know that we needed small telephones! Much of the future is like this. At that time the internet was in its infancy; its future emergence—at the time completely unforeseen—greatly enhanced the utility of a small telephone.

Planning the future may involve a long-term goal, but it is important to have a sustainable pathway with waypoints for possible adaptation and redirection. Sustainability is not just a technical issue but also that of support through funding, usually either government financing for a social or military purpose or industry support based on market mechanisms. However, I am wary of plans or procurement contracts with long-term goals that limit freedom for change as technology and conditions inevitably change.

I remember two research projects from the 1970s and '80s that illustrate some of these issues. One was the development of fiber optic network technology, the other involved open-ended research on neural networks.

The fiber optics project continues to this day, with incremental progress that has been incorporated in commercial networks at many points along the way. Relevant inventions have occurred with regularity, including improved fibers and lasers and the Erbium-doped fiber amplifier.

In contrast, the neural network project was a case of a technology looking for an applicable problem, and it was very difficult to maintain support at that time. Decades later, there were breakthroughs in mathematical algorithms that, combined with a growing recognition of the importance of large datasets, led to neural networks becoming a centerpiece of the surge in machine learning. For neural networks, their time had come. This may be true of many technologies; there is a time of ripeness, and a time when they are fallow, awaiting an unpredictable breakthrough.

The neural network example also illustrates the fundamental change in engineering that has evolved over recent decades. Back in the late portion of the last century, I remember a kind of motto recited by researchers working in the materials research division. "Everything must be made of something," they said. It's still true, of course, but not in the way they meant it then.

Today, like the neural network, much progress is virtual, inspired by mathematical analysis, implemented as algorithms in software, and even designed by computers themselves. It's as if things are now actually made of "nothing." It is, however, an enormously powerful and flexible, though difficult and expensive, nothingness.

Although none of the Grand Challenges has yet been attained, the list has aged well and still represents important social aspirations. If 2020 was to be a waypoint for these projects, engineers could assess the progress of each and reassign aims for the next waypoint. For example, fusion power may require breakthroughs, while affordable solar power might arrive from steady engineering improvement of known technologies. The secure cyberspace might never happen, but could be a work in progress as long as there is an internet.

So, can engineers predict the future by inventing it? In the short term, yes. In the long term, probably not, but we can nevertheless imagine and aspire to what we might accomplish that would be of benefit to all of humanity and plan accordingly.

A New Categorical Imperative

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In 1973 the German philosopher Hans Jonas posed the central ethical test for modern technological society. He observed that previously the "good and evil about which action had to care lay close to the act, either in the praxis itself or in its immediate reach," whereas a new categorical imperative now required that the "future wholeness of Man [be included] among the objects of our will" (Jonas 1973, p. 38).

This essay briefly explores one implication of Jonas' imperative: Can the technologies that the next 50 years of engineering advancement are likely to spark remain subject to democratic control?[1] Many of those technologies will have a broad reach, increase social complexity, and deliver uncertain consequences. So establishing and sustaining organizations and processes for democratic control may prove to be a significant challenge.

Assessment of Consequences

It requires little imagination to grasp the magnitude of what is in store. Just consider two technologies whose primary capacity, transporting people and goods, is identical: an automobile and an autonomous automobile.

Relatively simple "rules of the road" govern the operation of a traditional vehicle and address a relatively narrow range of consequences that might arise,

[1] By democratic control I mean the entire panoply of referenda, laws, regulations, and court decisions as well as nongovernmental actions such as social movements.

such as safety and environmental damage. In contrast, the operation of autonomous vehicles is controlled—for better or worse—by the choices embedded in (whose?) programmers' codes. Rather than restricted consequences, large-scale introduction of autonomous vehicles is likely to have far-reaching ones, including but hardly limited to employment, privacy, security, and liability. If there are issues associated with evaluating the safety and environmental impacts of the automobile, how much more difficult it will be to weigh the wider set of effects linked to autonomous automobiles.

Distributions of power, gender, and status influence what outcomes are realized and which groups and individuals are affected by them.

Democratic control of future technologies requires both epistemic insight and institutional constancy. For the first requirement, compiling a complete catalogue of consequences for any given future technology is likely to be a sizable undertaking. The well-understood availability and accessibility heuristics bias which effects come into immediate focus; analysts concentrate on the technology's primary capacity, often ignoring "downstream" impacts.

Furthermore, a technology's advocates naturally emphasize its benefits while diminishing its harms. For opponents, the emphasis is reversed. In general, the effects of technology are in a deep sense socially constructed. Distributions of power, gender, and status, among other things, influence what outcomes are realized and which groups and individuals are affected by them. Thus, in a highly interdependent and tightly coupled world, the more subtle effects of a technology as they reverberate over time and space may be close to incomprehensible.

Challenges of Regulation

If identifying the wide-ranging consequences of future technologies is problematic, sustaining institutions that are committed to constancy—the second requirement for democratic control—is likely to prove at least equally challenging. To illustrate, I concentrate here on the dominant mode of democratic control, formal regulation.

To regulate is to control by rule, a process that clearly necessitates having a *causal* appreciation of how options affect outcomes. At the most basic level, regulators must possess a thorough knowledge of the technique that undergirds the technology (e.g., the software of the 737 MAX). Moreover, they must recognize, to use another example, how pesticide limits influence the full set of consequences, including income distribution, environmental justice, and the viability of natural habitats.

Historically, the chief complaint about regulators' behavior has been their vulnerability to capture by the very interests they oversee. Those concerns are likely to be heightened if only because the balancing of opaque, ambiguous, and incommensurate outcomes resists transparent explanation. Thus, as the demands on regulators mount and expectations of them multiply, their constancy will increasingly be threatened.

Balancing Control, Promise, and Complexity

It may be that democratic control of technology has always been questionable. Fifty years ago, the arguments by Charles Lindblom (1965) about the "intelligence of democracy" and the National Academy of Sciences' faith in a cybernetic model for "technology assessment" (NAS 1969) seemed plausible and reassuring. Both certainly appear less so now and probably will appear even less convincing in the future. So what is to be done?

At the risk of being labeled a modern-day Cassandra or Luddite, there simply is no silver bullet on the horizon. Policymakers and the attentive public will have to acknowledge that democratic control of future technologies is by no means assured.[2] Resources will have to be secured to augment the analytic capacities of advocates, opponents, nongovernmental organizations, regulators, legislators, and judges. Otherwise surprises—both pleasant and unpleasant—will inexorably surface.

Moreover, safeguards will have to be strengthened to protect the competence and responsiveness of the democratic institutions charged with controlling how large-scale, complex, and disruptive future technologies are deployed. It is probably unrealistic, however, to expect the institutions to completely avoid errors. But if they have proactively and aggressively built up a

[2] The climate change debate certainly reinforces this point.

reservoir of trust over the years, their mistakes will tend to be viewed as human and not malevolent.

Scientists, engineers, and others often speak about the “promise of technology.” And rightly so. But for all its validity, that claim typically discounts the unanticipated, the disturbing, and the dislocating “side effects” of technological innovation. In this writer’s view, society has mostly maintained control over how technologies have been executed, albeit sometimes only tenuously. But given the properties of many emerging and future technologies—broad reach, increased social complexity, and uncertain consequences—it remains a very open question whether the same conclusion will be drawn 50 years from now.

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Future of Weather Forecasting

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In *The Signal and the Noise*, the noted statistical analyst Nate Silver (2012) examined forecasts in many categories and found that most demonstrate little or no skill and have made little or no progress in accuracy over the decades. The lone exception he found was weather forecasting. Before attempting to predict what is ahead for weather forecasting, it is important to understand how weather prediction became such a success story.

Background

Benjamin Franklin was the first to observe that northeastern storms (nor'easters) begin in the Southwest; he proposed models to describe the progression of storm systems and published some of the first weather forecasts.

During World War I English mathematician Lewis Fry Richardson postulated that fluid dynamics equations could be used to forecast the state of the atmosphere. It took him months to calculate a 6-hour forecast by hand, only to get impossible results due to errors in his calculations. But his mathematical approach was vindicated in the 1940s with the invention of computers. Since the 1970s, weather forecast models have been run on the world's fastest, most powerful supercomputers, spurring advances in both computer technology and weather modeling.

Government Forecasts

Through World War II, weather forecasts were mainly issued by the government. After the war a few meteorologists who had left the military began services that offered customized forecasts to weather-sensitive businesses, but until the 1960s forecasts available to the public came almost entirely from the US Weather Bureau, now the National Weather Service (NWS). They were limited in scope and accuracy, typically covering only today, tonight, and tomorrow, with few details, and they often missed major events. In those days, weather forecasters were often the butt of cartoons and jokes ("The only job where you can get paid for being wrong!"). Many meteorologists were passionate and driven to improve the accuracy of forecasts and build respect for their trade.

Since then, NWS has greatly improved the available data—with Doppler radar, satellite observations, and more detailed and accurate computer-generated forecast model output—and thus the quality of its forecasts and warnings.

Commercial Forecasting Innovations

Much of the increased value and utility of weather forecasts for the public and for business has been spurred by commercial weather companies, such as AccuWeather, which I founded as a Penn State graduate student in 1962.

These companies have introduced hundreds of innovations—forecasting techniques and products, patented technological advances, improvements in accuracy and hyperlocalization, better television displays, mobile apps, colorful and more meaningful newspaper maps, and clear communications. They also consider the potential impact of weather forecasts to help people and businesses make the best decisions, thereby saving lives, protecting property, and increasing business efficiency and profitability.

Advances in communications technology and cell phones have expanded the timeliness, perceived accuracy, and value of forecasts and warnings through better displays and enhanced wording and communications.

Partnerships

The American weather enterprise, consisting of meteorologists working in government, universities, and commercial weather companies, has advanced the science of weather forecasting from general predictions for the next day or two to timely life-saving warnings, specific hyperlocal minute-by-minute forecasts for the next several hours, highly detailed forecasts for the next several days, and even daily forecasts 90 days out.

Until recent decades, all observational data came from government agencies. Today, commercial companies also provide unique datasets from lightning detectors, microsatellites, drones, crowdsourcing, mesonets, and in-vehicle sensors, stored and distributed via the internet and cloud technology.

The hyperbolic rise in data and how to best access, store, process, analyze, display, and utilize them will be a challenge for the weather enterprise.

As data from all sources grow exponentially and computer models improve, forecasts and warnings will become even more accurate, timely, and hyperlocal and extend further ahead. Yet the hyperbolic rise in data and how to best access, store, process, analyze, display, and utilize them will be a challenge for all parts of the enterprise.

The Forecast for Forecasting

With growth in the scale of data and the need for fast access to information, new ways of curating data will be necessary. Many off-the-shelf technologies will be challenged in balancing speed and cost. It will take creativity and innovation in data engineering to meet the expectations of consumers and businesses.

Perhaps the greatest change in weather forecasting has been from meteorologists' reliance on their experience, education, and knowledge of atmospheric processes to their increasing dependence on computer models and parameters derived from those models. In the future this trend will accelerate, with algorithm weighting of hundreds of computerized forecast models, using artificial intelligence to choose the best outputs from each forecast source. Combinations of algorithm-based input will vary with the weather, parameters, location, seasonality, model performance, and other factors, to achieve the greatest accuracy and best impact depending on the purpose of the forecast.

Over the next several years, the greatest benefits from continually improving weather forecasts are likely to come from the incorporation of forecasts in new technologies and systems, such as wearables, energy management, predictive analytics for business, intelligent homes, smart cars, agriculture, supply chains, and transportation.

Weather and climate events have an annual impact of trillions of dollars on the global economy and remain a top concern of leaders worldwide (WEF 2020). Companies are increasing their proactive use of weather information to analyze their operational data and key performance indicators to identify relationships and turn them into predictive analytics at a localized level to reduce weather impacts and drive improved results.

Each sector of the weather enterprise will continue to play an important role. The NWS provides the basic data and models; universities conduct research and train future meteorologists; and the commercial sector, the primary interface to end users and driven by competition among companies, leads innovation in weather forecasts and warnings, hyperlocalization, detail, personalization, presentation, communication methods, usefulness, and the impact of weather on people's health and activities.

Conclusion

In 1900 a hurricane struck Galveston, Texas, and killed 12,000 people. Since then loss of life from flooding, lightning, hurricanes, tornadoes, blizzards, and other severe weather has decreased in this country by an order of magnitude because of the success chronicled by Nate Silver. That trend will continue because of the increasing accuracy and precision of weather forecasts and warnings effectively communicated and better tailored to the specific needs of people and businesses. This is already resulting in rapidly falling fatality and injury tolls from severe weather events because of better decisions by people and companies and more profitable outcomes.

The American weather forecasting success story is one of progress and an exemplary public-academic-private partnership. With further advances in the science of meteorology and the unique contributions of each sector of the weather enterprise, progress in weather forecasting will increasingly benefit the nation's economy, public safety, and quality of life for everyone.

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Inclusive Human-Centered Machine Intelligence


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Asad Madni

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As engineering strives to better people's lives, human-centered technologies—enabled by converging engineering advances in sensing, computing, machine learning, data communication—will draw on machine intelligence[1] (MI) to help understand, support, and enhance the human experience. The challenge is to create technologies that work for *everyone* while enabling tools that can illuminate the source of variability or difference of interest.

Consider, for example, speech and language technologies for children to use conversational MI systems. Automatically recognizing and understanding child speech is far more challenging than adult speech because of variability and differences due to developmental changes along physical, cognitive, and socioemotional dimensions (Narayanan and Potamianos 2002). Health conditions that impair communication ability (e.g., autism spectrum disorder) present further challenges.

[1] This overarching term encompasses artificial intelligence, machine learning, and other engineering capabilities and technologies (e.g., adaptive sensing, communication, interfaces) that enable intelligent engineering systems.

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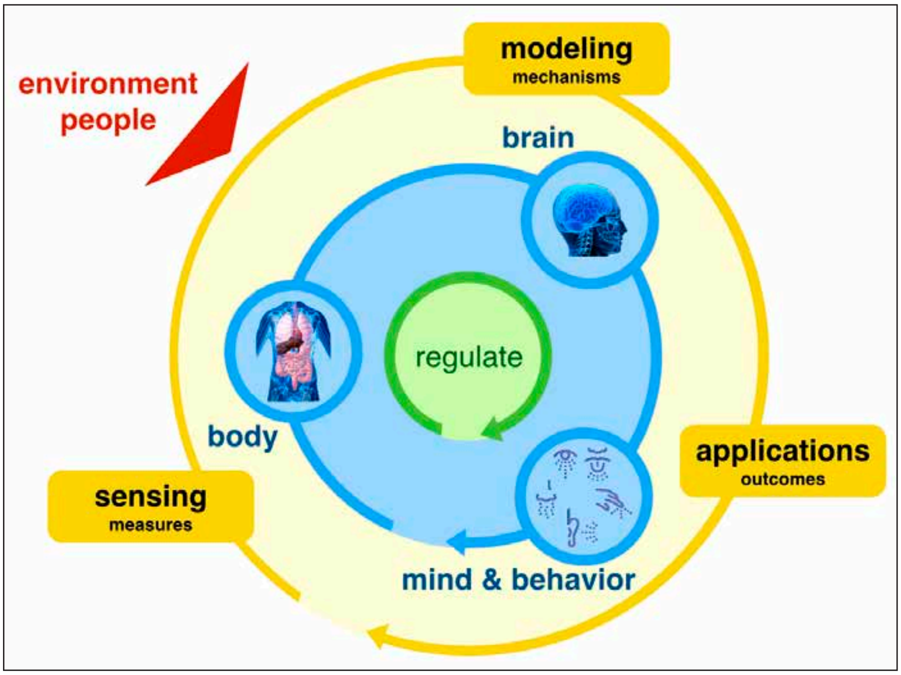

FIGURE 1 Engineering advances can enable new insights into brain-body-behavior mechanisms of individuals and their interactions with the world—including in how they regulate to maintain balance in the presence of ongoing changes—and support human-centered applications across domains such as health, learning, and media entertainment.

The ability to measure, analyze, interpret, and act on children's speech data can enable broad inclusive access for them. It can also offer valuable tools and insights to scientists in discovery and clinicians in individualized treatment planning (Bone et al. 2016, 2017).

In addition, MI can create technologies for diversity and inclusion awareness by, for example, shining light on representations along dimensions of gender, race, age, appearance, and ability in entertainment and advertisement media (Guha et al. 2015; Martinez et al. 2019; Ramakrishna et al. 2017).

An Engineering Lens into the Human Condition

The dynamics of the human state, behavior, and actions result from complex brain-body mechanisms and interactions with the world and are influenced by both individual and contextual variability (figure 1). And many aspects of human physical and psychological traits, states, and behaviors are not directly observable or accessible.

Human behavioral signals available aurally and visually in speech, body language, and movement offer a window into decoding not just what people are doing but how they are thinking and feeling, their intent and emotions. People infer these using their sensory perception and judgment, often relying on observations of verbal and nonverbal behavioral expressions and appearance. There is tremendous variability across people and contexts, in both human expression and human processing of behavior cues (which can be subjective and idiosyncratic).

MI approaches can help analyze human trait (e.g., age), state (e.g., emotion), and behavior (e.g., speech) dynamics (Narayanan and Georgiou 2013) to enable contextually rich sensing, create computational measures, and design models to understand complex mechanisms (e.g., the human ability to be resilient) and to predict behavior change, all while tackling challenges ranging from noisy measurements to uncertainty in human-centered representations. At a simple level, this could entail determining who is talking to whom about what and how, using automated audio and video analysis of verbal and nonverbal behavior.

MI can also be used to recognize and assess higher-level states like emotions. Behavioral, physiological (e.g., heart rate, respiration, skin conductance), and environmental signals (e.g., location, soundscape, light, temperature, air quality) together offer possibilities for understanding dynamic cognitive, affective, and physical human states in context. Furthermore, MI could help detect and analyze deviation from what is deemed typical.

These MI techniques can in turn facilitate or enhance decision making by humans—and by autonomous systems—in the context of a given application. In mental health, for example, MI can contribute to novel screening, diagnostics, and treatment support including just-in-time implementation and response monitoring (Bone et al. 2017).

Engineering Challenges in Enabling Inclusive Human-Centered Machine Intelligence

Several factors affect the ability of an engineered MI system to serve the needs of *all* users. The dimensions of individual variability—physical, cognitive, affective, and social—are multifaceted and interconnected. The right data and an engineering approach that adequately accounts for this variability are paramount.

Research to ensure algorithmic fairness in machine intelligence has gained much ground recently (Chouldechova and Roth 2020). Engineering models should perform at the same level regardless of variability not central to the intended task or experience, through either appropriate coverage of the data that informs the design or, more critically, the algorithmic ability to adapt or compensate for sources of variability.

For example, systems that are inclusive of children should consider behavioral variability due to individual differences in age, gender, sociocognitive level, and language ability. Additional contextual factors that need to be accounted for include the nature of interactions—how many people are involved, who they are (e.g., peers, parents, teachers), how free or structured the interaction is—as well as the interaction environment (indoor/outdoor, home/school/clinic) and data capture constraints (wearable or environmental sensors, frequency and quality of sensing).

Opportunities for Creating and Using Inclusive Machine Intelligence

Some of the UN Sustainable Development Goals[2]—good health and wellbeing, quality education, gender equality, reduced inequalities—indicate opportunities where inclusive machine intelligence can, and should, contribute. The following examples illustrate the breadth of needs and possibilities as well as applications addressing the NAE's Grand Challenges for Engineering.[3]

Personalized Learning

Child-centered MI can help engineering systems personalize learning. Children make up over a quarter of the world's population, but their physical, cognitive, emotional, and social developmental differences and changes challenge the design of inclusive MI technologies (e.g., enabling broad interactivity through automatic speech, language, and vision technologies).

But an engineering system that attempts to personalize learning needs to also understand sources of individual differences, such as cognitive (confusion) and emotional (frustration) states. Additional factors such as health state and neurocognitive differences (e.g., attention deficit) may add further challenges.

Health Informatics

MI engineering can help advance informatics for behavioral and mental health. With over 10 percent of the world's population affected by mental health challenges (Ritchie and Roser 2018), and with clinical research and practice heavily dependent on (relatively scarce) human expertise in diagnosing, managing, and treating conditions, opportunities for engineering to offer access at scale and tools to support care are immense.

The right data and an engineering approach that adequately accounts for individual variability are paramount.

For example, to determine whether a child is on the autism spectrum, a clinician would engage and observe the child in a series of interactive activities targeting relevant cognitive, communicative, and socioemotional aspects, observe the resulting behavior cues, and codify specific patterns of interest (e.g., vocal intonation, facial expressions, joint attention behavior) (Bone et al. 2017; Guha et al. 2016). MI advances in both processing speech, language, and visual data and combining them with other clinical data enable novel and objective ways of supporting and scaling up these diagnostics.

Likewise, tracking psychotherapy can enhance understanding of the quality of care and of causal factors of outcomes. Engineering systems can automate analysis of a psychotherapy session through computing quality assurance measures that, for example, rate a therapist's expressed empathy (Xiao et al. 2015). And technology can go beyond clinics to patients in their natural settings. For example, remote sensing of biobehavioral cues and secure computing can enable new ways to screen and track response to treatment and offer just-in-time support (Arevian et al. 2020).

[2] https://unfoundation.org/what-we-do/issues/sustainable-development-goals/

[3] www.engineeringchallenges.org/

Looking Forward

Inclusive machine intelligence holds great promise for many human-centered societal realms. But there are many challenges. Research and development are needed to

- enable the collection of relevant data;
- design algorithms that handle human aspects such as data variability, heterogeneity, and uncertainty;
- specify and derive targets for modeling that reflects diverse human perspectives and subjectivity and affords interpretability; and
- create an ecosystem of trusted partnerships between the designers and users of engineered MI systems, including addressing data provenance, integrity, and, not least, the ethical use of technology.

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Reimagining Government and Markets

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"A victory small enough to be organized is too small to be decisive," wrote Eliot Janeway (1951, p. 16) in his history of the mobilization of American industry during World War II. A great victory required an upwelling of energy from all parts of society. That energy could not be organized, but it had to be summoned forth. And it had to be led.

During the war President Franklin Roosevelt set an urgent agenda, but, with a few exceptions such as the forced conversion from automobile production to airplanes, the government did not command. It *created the conditions for success* by establishing priorities and making them stick, providing expansion capital where necessary, and making commitments to buy the resulting products. But it was the genius and initiative of American industry that increased the production of airplanes from 3000 to 300,000 over the course of the war, and got the production of each Liberty ship down from a year to a single day.

That history is a powerful demonstration of the way decentralized markets can be harnessed by centralized leadership that directs them toward overcoming great challenges. Government and markets are both ways of coordinating human effort at scale, and at their best they work together. As Doris Kearns Goodwin (2001) observed,

> One almost totally forgotten lesson of the [Second World War] is that deep government involvement doesn't have to mean a command economy.… The things we revere about capitalism, the parts that spur energy, efficiency, and entrepreneurial skill, were still in place. What the war did was tap that energy, not constrain it.…
>
> Throughout our nation's history, there have been critical moments when the government's relationship to private enterprise had to change, allowing both economic expansion and the flourishing of democracy. Now is one of those times. The World War II experience shows just how bold that effort has to be.

Now is indeed one of those times! The entire thrust of the global economy must be redirected—as is happening today in response to the coronavirus pandemic, but even more urgently in years to come to stave off the ills attendant on climate change. Societies must

- unwind dependence on fossil fuels while simultaneously preparing for sea level rise, crop failures, and mass migrations as some parts of the world become uninhabitable;
- stop propping up the stock market by pouring capital into phantom paper assets held by a small fraction of the population; and
- invest instead in upgrading and reinventing real-world infrastructure and in more evenly distributing prosperity through higher wages and robust employment.

A fully electrified economy would create millions of jobs, save consumers billions of dollars, and require half as much total energy as today's fossil-fueled economy.

Roadmap to Improve Energy Efficiency

The work of Saul Griffith, Sam Calisch, and others, including data studies with the US Department of Energy,[1] which produced the energy and economic policy plan *Rewiring America* (Griffith et al. 2020), outlines a comprehensive government plan to shape one sector of the economy.

Rather than suggesting scattershot market interventions like the loans that kickstarted Tesla and the electric vehicle market, it lays out a detailed information roadmap that shows how and where energy is used and how a fully electrified economy would create tens of millions of jobs, save consumers billions of dollars, and require only half as much total energy as today's fossil-fueled economy. And it specifies interventions that will spur the market to reach those goals, much as Roosevelt did during World War II. For example, it proposes that the government create a guaranteed market for insured, low-interest loans for electrifying the privately owned, de facto electric infrastructure represented by cars and homes, much as it spurred home ownership with guaranteed mortgages after World War II.

Too many people think addressing climate change requires miracles and that the answer is technological moonshots. This wasn't true for WWII nor is it true for climate. Technological innovation is certainly needed but it is far from sufficient. These are challenges of industrial policy and infrastructure, and most importantly of scale and urgency.

Management of the Market

Economic leadership to spur the market is not only necessary, it is achievable, thanks to advantages that were not available to Roosevelt and his team. For all their flaws, the algorithmically managed platforms of the internet have demonstrated new ways to manage markets at a scale and speed exceeding those of many real-world economies.

In many ways, companies such as Google, Amazon, and Facebook can be thought of as centrally planned economies that exercise control not by managing production but by managing demand. They build systems for understanding in detail what consumers want using signals not only from the content itself (or in the case of Amazon, from product descriptions and other metadata such as availability) but also from the collective preferences of millions of other consumers. Uber and Lyft apply similar techniques to transportation and logistics. Each of these companies runs its own "invisible hand," directing markets to satisfy those needs, shaping production by making consumer preferences visible, and ultimately deciding who gets what and why.

The struggles of social media companies notwithstanding, the information management capabilities of

[1] www.energyliteracy.com

the Silicon Valley giants are truly staggering. What if these capabilities could be put to work on stuff that matters more than getting people to click on provocative content and the ads that accompany it? What if government had the kind of capabilities, information flows, and partnerships between humans and machines that distinguish the best of technology companies? What if government thought of itself as the enabler and manager of its markets, rather than a reluctant participant?

In the naïve economic thinking promoted by free market fundamentalists, "the market" operates as if by magic, with self-interested negotiation by independent parties the invisible hand that coordinates it. Any attempt by government to intervene is seen as a departure from the ideal. In reality, government's essential role goes far beyond ensuring the rule of law, national defense, and providing shared infrastructure. Even in ordinary times, the market is profoundly shaped by government and central bank policy.

Tax rates, interest rates, and regulatory policy play much the same role in shaping the direction of the economy as Google's or Facebook's algorithms play in shaping their marketplaces. And when those algorithms fail to produce the desired results, quicker and more robust action is needed to correct them.

Facebook's engineers believed that showing people more of what they wanted would bring people together. They were wrong. Instead, Facebook's algorithms have driven us apart.

Economists told policymakers that encouraging businesses to put profit before people would spur growth and spread prosperity. They were wrong. Instead, these economic algorithms produced extreme inequality in income and wealth and dire consequences for social mobility.

Why do we cry out for social media platforms to rein in their algorithms run wild, yet fail to do the same for government tax incentives and rules of corporate governance that are so clearly not yielding the expected or desired results?

Government Responsibility in the Digital Economy

Public health challenges like covid-19; repairing the fractured US marketplace for health care, riven by rent seeking and plagued with inefficiency; building a truly distributed electric grid able to incorporate a variety of renewables and accelerate the transition away from fossil fuels; improving distribution systems for increasingly scarce water; helping immigrants find the most productive place to move and find jobs; managing the insurance risks associated with wildfires and rising seas—all of these are information problems as much as they are matters of physical infrastructure.

The US government has long set a gold standard for data collection. Where it falls down is in making the data usable. That is left to the private sector, which often adds little value but instead sees private exploitation of government data as an opportunity for rent extraction.

What if government had the capabilities, information flows, and partnerships between humans and machines that distinguish the best technology companies?

As Michael Lewis (2018) warned so presciently, the current US administration has drastically reduced state capacity, including on the data-gathering side. Even since before the Trump administration, the IRS, SEC, DOJ Antitrust Division, and FTC have been persistently and cumulatively underfunded. Basic state capacity to execute needs to be rebuilt (Lewis 2018). And government needs to use data to actively manage national priorities, not simply to observe and intervene only in a few egregious cases long after the damage has been done.

The US government is taking halting steps into the 21st century digital economy. The United States Digital Service (part of the White House) and 18F (part of the General Services Administration), as well as public sector–facing nonprofits like Code for America and US Digital Response, are staffed with Silicon Valley veterans who are bringing digital thinking to bear on an increasing variety of public interest problems, much as Roosevelt brought auto industry veterans like William Knudsen into government as "dollar-a-year men."[2]

[2] https://en.wikipedia.org/wiki/One-dollar_salary

But these groups are just nibbling around the edges. Policymakers and government agencies are still largely using slow 20th century tools and processes for understanding and managing the impact of fiscal and monetary policy, taxes, and market-shaping regulations.

If civilization is to survive the challenges of the 21st century, we need a robust government that builds state-of-the-art real-time information capabilities for purposes other than surveillance, understands itself as the custodian of the public interest, and sets clear priorities for the market in areas that are essential to that interest.

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Confronting the Societal Implications of AI Systems: Leading Questions

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Lisa A. Parks

As a media scholar interested in technology's relationship to society, I think about the ethical challenges brought about by computing and artificial intelligence (AI) tools in shaping global media culture. Three fundamental societal challenges have emerged from the use of AI.

Technological Knowledge and Literacy

Who has the power to know how AI tools work, and who does not? Issues of technological knowledge and literacy are increasingly important given digital corporations' proprietary claims to information about their data collection and algorithms. The concealment or "black boxing" (Pasquale 2015) of such information by social media companies such as Facebook, for instance, keeps users naïve about AI tools and the ways those tools shape social media experiences and the information economy.

Most users learn about the AI tools used in social media platforms only inferentially or when information is leaked, as in the Facebook/Cambridge Analytica matter (Granville 2018). Digital companies protect their intellectual property to compete in the marketplace, but cordoning off technical information has huge stakes. It presents challenges not only for users who want to understand what data are being collected from them and what is done with the data, but also for researchers and policymakers who seek to explore the "back ends" of these platforms and their industrial, behavioral, and juridical implications.

In the United States, digital corporations' intellectual property rights supersede consumers' right to know about the AI tools they encounter online every day. In Europe, the General Data Protection Regulation has attempted to address these issues obliquely by defining "data subject rights," yet to defend these rights it is essential for regulators and the public to know how AI tools are designed to work and to understand any potential for them to act autonomously. In fact, some inventors of AI tools do not even understand how their own systems work.

AI in International Relations and Globalization

How do AI tools intersect with international relations and the dynamics of globalization? As AI tools are operationalized across borders, they can be used to destabilize national sovereignty and compromise human rights. Concerns about this have emerged, for instance, in the contexts of US drone wars (Braithwaite 2018) and Russian interference in the 2016 US presidential election (Jamieson 2018).

Without considering questions of social justice, AI products are likely to implicitly reproduce the values and worldviews of those with privilege.

Meanwhile, think tanks and nonprofits celebrate the potential of AI tools to accelerate global development. The Global Algorithmic Institute (https://global-ai.org) is dedicated to developing algorithms that "serve the international public good," focusing on "global financial stability through implementation of big data and dynamic algorithms." And AI Global (https://ai-global.org) suggests that there are "limitless opportunities to provide better access to critical services like healthcare, banking, and communication."

Given these contradictions, this area of concern might be addressed by specifying which countries or regions have the resources to innovate and contribute to AI technologies and industries, and which are positioned as recipients, subjects, or beneficiaries. What do the vectors of the global AI economy look like? Who are the dominant players? Where are their workforces located and what labor tasks are they performing? What are the top-selling AI tools, and how do their supply chains correlate with historical trade patterns, geopolitics, or conditions of disenfranchisement?

Given the power of AI tools to impact human behavior and shape international relations, it is vital to conduct political and economic analysis of the technology's relation to global trade, governance, natural environments, and culture. This involves adopting an infrastructural disposition and specifying AI's constitutive parts, processes, and effects as they take shape across diverse world contexts. Only then can the public understand the technology well enough to democratically deliberate its relation to ethics and policy.

AI and Social Justice

What is the relationship between AI and social justice? Will new AI and computing technologies reinforce or challenge power hierarchies organized around social differences such as race/ethnicity, gender/sexuality, national identity, and so on?

Researchers are advancing important projects in this area (e.g., Joy Buolamwini's Algorithmic Justice League, https://www.ajl.org; Costanza-Chock 2020), exploring how social power and bias are coded into computational systems, and challenging people to confront structural inequalities, such as racism and sexism, when using or designing AI systems. Their work suggests that social justice should be core to AI innovation.

If AI tools are designed in the United States—whether in Silicon Valley or in Cambridge, Massachusetts—by predominantly white, middle-class people who approach technical innovation as separate from questions of social justice, then AI products are likely to implicitly reproduce the values and worldviews of those with privilege.

Algorithmic bias occurs when the design process is divorced from critical reflection on the ways social hierarchies impact technological development and use. Arguably, all algorithms are biased to a certain degree, but as AI tools proliferate, it is important to consider who or what is best equipped to detect and remedy bias, particularly given the potential of these tools to reinforce, intensify, or create new inequalities or injustices.

Given ongoing demonstrations against systemic racism in the United States and other countries, there is a need for technology design workshops that foster candid discussions of the ways power hierarchies and social inequalities shape pathways into computing and engineering as well as the technology design process. Designers need a more robust understanding of social justice challenges, including the struggles against systemic racism and sexism, to be able to build AI systems that resonate with diverse users.

Requiring technology developers to do some of their work beyond the lab context, where they can engage with highly variable socioeconomic conditions across diverse international contexts, may generate more equitable and ethical AI systems.

Looking into the Future

If economic models are any indication, artificial intelligence is on a fast growth path and is projected to add $13 trillion in global economic activity by 2030 (Bughin et al. 2018). For AI design to support principles of technological literacy, international relations, human rights, and social justice, engineers and computer scientists can ensure the inclusion of humanists and social scientists from diverse backgrounds in AI research and development, and recognize the value of multidisciplinary perspectives when designing and building machines with such profound impacts. The most important guiding principle may be to work toward an AI future that prioritizes social bonds and public interests over profit, expansion, and influence.

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Moving Toward 20/20 Foresight

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Every new year prompts past reflections and new expectations, but some feel more significant than others. As the year 2000 arrived, the world anxiously waited to see whether a seamless conversion of global data systems from two- to four-digit representation would avert a "Y2K" disaster. It did, and the technological world continued its march, confident in the progress and potential of science and engineering to reliably introduce new solutions to problems both known and unknown (social media, anyone?).

Twenty years later, there were no worries about the possibility of inoperable telephone lines or inaccessible bank accounts, but the symmetry of the year 2020 was hard to ignore. The connection between the numerical year and the standard for visual acuity prompted many to ponder what could be foreseen. If we imagined a future along any of multiple dimensions, what would we see?

It seems safe to say that few would have envisioned what this year has brought forth. A global pandemic persists. The American West experienced destruction from wildfires on an unprecedented scale. For only the second time ever—and for the second time since the turn of this century—the list of named tropical storms extended into the Greek alphabet. And these disasters have been accompanied by economic distress, highlighting the inextricable links between the natural world and societal wellbeing, particularly with respect to the inequitable distribution of negative impacts.

Never has it been more clear that global challenges require coordinated, aggressively realized global solutions. Undoubtedly, advances in scientific knowledge and engineering know-how will bring new technological revolutions, enabling society to make progress against these and other, yet-to-be-identified threats. After all, it's almost easy to immediately turn to science and engineering to solve the most pressing problems, including those emerging from medical crises and climate change.

Promises and Limitations of Scientific and Technical Innovation

Exciting Possibilities

Through my own lens of metabolic engineering and synthetic biology, I see new products being brought to market from the transformation of renewable substrates, products that will dramatically reduce reliance on fossil carbon for fuels and chemicals. In addition, novel bio-based materials will reduce the environmental burden of unrecycled and unsustainable plastics by incorporating end-of-life biodegradability at the design stage. Harnessing the exquisite diversity of biological metabolism will enable a reduction in waste, as discarded organic matter becomes the feedstock from which sustainable materials are produced.

The leveraging of natural and synthetic biological sensing systems will enable new modes of assessing water quality, reducing the burden of waterborne disease. Further advances in complex biological systems design and engineering will generate mimics of natural microbial ecosystems that will remediate contaminated water—perhaps using distributed purification systems powered by locally produced energy.

New manufacturing modalities for point-of-care therapeutics, tied to POC diagnostics, will transform the practice of medicine and, more importantly, the quality of life. It's even conceivable that engineered implantable devices—whether mechanical, biological, or hybrid—will dynamically detect and treat disease without intervention from a provider.

Persistent Challenges and Wicked Problems

History, however, has shown that technological advancement is not enough to solve society's most serious problems.

The mass shift toward remote work and school shone a spotlight on disparities in access to technology. How can the college student learn effectively when her internet access is too unstable to enable meaningful engagement from 3000 miles away? How much does the achievement gap expand when the parents of an elementary-age child do not have the luxury to dedicate time to home schooling and the child is unable to "self-direct" at the age of 9 (or younger)? What if neither has access to a laptop with sufficient computing power to even attempt a remote connection?

In addition, substantial racial disparities in health outcomes among those infected with SARS-CoV-2 point to much deeper tragedies masquerading as "underlying health conditions." What does it say about equal access and opportunity when those most likely to become infected with a pandemic virus are those who are also both most essential to the continued operation of a productive society and most likely to suffer high mortality rates from infection?

History has shown that technological advancement is not enough to solve society's most serious problems.

The inability or unwillingness of a significant fraction of citizens to accept and adhere to the public health recommendations that are most likely to enable a return to economic activity while also reducing infection rates may indicate a broader lack of trust in science. How can a society wage a successful battle against an insidious pathogenic foe in the face of persistent reluctance and even refusal to accept that it exists?

Questions to Guide the Way Forward

Hindsight is 20/20. Considering ways in which engineering will change the world over the next 50 years, perhaps it is time to reflect on the past as a way to understand the promise and the perils of advancing engineering into the future.

The biggest obstacles in addressing current and future global challenges are unlikely to arise from limits on transformation efficiency of microbial hosts being constructed to produce novel chemicals, or from limits on oxygen transfer rates in reactors designed to manufacture novel vaccines. For certain, there will be stumbling blocks and two steps forward may be followed by one step back. But this, to the researcher, is normal; it is expected. Rather, the questions that must be answered include the following:

- How can we engineers encourage full and inclusive participation in the process of defining problems and developing solutions?
- How can we identify and mitigate the implicit biases that may skew these solutions to be impractical or undesirable for populations at risk?
- How can solutions be deployed in the most equitable and therefore most effective manner, to maximize benefit to all?
- How can we scientists and engineers engage in effective and productive dialogue with our citizen neighbors? How do we acknowledge that predictive science comes with uncertainty, while communicating that this does not mean scientific conclusions are unknowable?
- And to invoke the famous phrase from the film *Field of Dreams*, what if we build it and they don't come? What if we develop technologies that are accessible and have real potential to have significantly positive impacts on the health of both humans and the planet we inhabit, but they are ignored or rejected or even denigrated?

These are not questions that most engineers, including myself, are trained to answer. But they are ones that I hope will increasingly motivate all of us to approach our work with an eye toward making the most positive and lasting impact we can. The future is what we make it.

Lessons Future Technologies Should Heed from the Past

Ainissa Ramirez

Ainissa Ramirez is a materials scientist and author. Photo credit: Bruce Fizzell.

When thinking about how technologies will impact life decades from now, the past holds many lessons and warnings. I have come to this realization after spending several years examining old inventions for my book *The Alchemy of Us: How Humans and Matter Transformed One Another* (Ramirez 2020).

Surprising Outcomes and Unintended Consequences

Technologies are generally made to solve specific problems. Sometimes, though, they generate surprising outcomes, as well as unintended consequences. As such, it is my hope that those who have a hand in building the future consider whether what they produce will indeed create a future that benefits all of us.

The Telegraph

Inventions are often built from necessity, but they always recreate society. Take the telegraph, for example. Samuel F.B. Morse would have loved for information to travel faster than a letter carried by stagecoach in his time, for he would have gotten the news to return home to see his ailing wife before it was too late. After he created the telegraph, it connected the country, with news zipping to all parts of the nation.

But the telegraph also had an unusual offspring. The early machine's inability to send more than a few messages at a time compelled telegraph

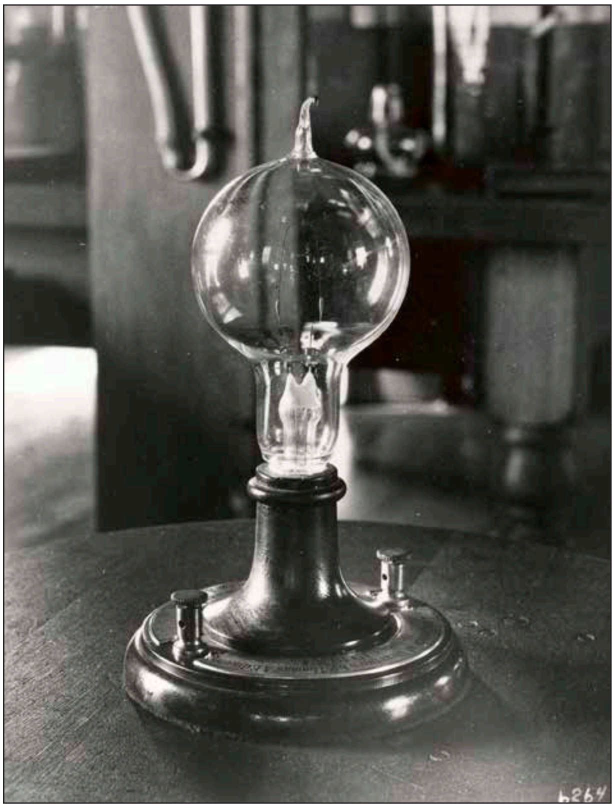

FIGURE 1 Edison's early lamp was created to push back the darkness, but its progeny has been linked to a range of human health issues, illustrating the unintended consequences of technology. Photo credit: US Department of the Interior, National Park Service, Thomas Edison Historical Park.

operators to make messages brief. When newspapers adopted the telegraph in their newsrooms, editors would tell their reporters to be succinct. The writing style of short, declarative sentences was embraced by one former reporter named Ernest Hemingway.

Morse may not have been able to predict that his 19th century invention would shape language as it did. Technologists of the 21st century must consider that their inventions will likely shape culture in unexpected ways, too.

The Light Bulb

When Edison made his improvements to the incandescent bulb (figure 1), he put society on a path that would never fall dark again. But he did not know that the human body responds to light. More than a century after the invention of the light bulb, scientists found that constant exposure to artificial light has health ramifications.

The human body has a daytime mode and a nighttime mode. In daytime mode, the body's metabolism, temperature, and levels of growth hormone are high. In nighttime mode, these all decrease. The body enters daytime mode when it detects blue light (Brainard et al. 1997). In modern life, unlike Edison's day, people spend most of their waking hours under artificial lights, which often give off blue light, causing the body to swim in growth hormones.

The impact has been documented (Ramirez 2020; Stevens et al. 2007). Epidemiologists have found that off-hours shift workers have an increase in the risk of heart disease and some forms of cancer, attributed to being continuously exposed to artificial light.[1]

Looking Out for Blind Spots in Engineering the Future

Edison and other 19th century inventors were trying to solve one problem with electric lights, but by fixing one issue, they inadvertently created others. It is hoped that 21st century engineers, scientists, and technologists consider that their innovations will likely lead to unintended consequences, too.

Unintended outcomes may be difficult to predict, but they're important to consider so that inventions can be modified, whenever feasible, to create the best possible solution. Such an analysis requires that scientists, engineers, and inventors do something new: They must reach out to experts in other fields, like the humanities and social sciences, and look at their innovations through the lens of history and culture.

Creating the best possible future also requires acknowledging, probing, and exploring our cultural blind spots. A case study to illustrate this is Carl Sagan's efforts to select music for the 1977 Voyager Golden Record. The 90 minutes of playtime were supposed to encapsulate the entire planet, yet initially most of the selections were classical music, originating from one small region in Europe. When Sagan received music suggestions from the younger members of his team as well as experts from other fields, like Alan Lomax, a collector of the world's songs, the record started to resemble the sounds of the entire world as was its mission.

Modern technologies exhibit a few more of these blind spots, and I have personally experienced them. When I wash my hands in a certain East Coast airport, the water does not come on unless I outstretch my hands so that the lighter part of my palm is under the light sensor. My brown skin absorbs more light, so the sensor does

[1] "Blue light has a dark side," Harvard Health Letter, May 2012 (updated Jul 7, 2020).

not detect that I am in front of the faucet otherwise. It seems that the designers of this faucet tested it only on lighter skin. As a result, this technology now contains a bias, operating properly for one group of people and not all. Had a diverse teamed worked on the design, this faucet mishap would not have happened.

More troubling than an irritating water faucet is the racial bias recently found in healthcare algorithms, which disproportionately recommend less care for Black patients, as reported in *Science* (Obermeyer et al. 2019).

Conclusion

Let us look at past technologies and learn the lessons they have to offer. The past tells us that technology is a cultural force that needs to be continuously examined. Technology is not innocuous, it is not unbiased, and it is not neutral. Our inventions mirror the culture from which they are born.

To make the best possible world for all in the future, technology development requires oversight, inclusive input, and informed citizens. This way we will together create a future that we all want to live in and a world where everyone will have a place in it.

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Living, Sensing, Learning: Next-Generation Bioinspired Building Materials

Jenny E. Sabin

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According to the World Green Building Council (WGBC 2017), building and construction account for 39 percent of annual global carbon emissions. The heating, lighting, and cooling of buildings accounts for 28 percent of this total and the remaining 11 percent comes from what is known as embodied emissions or “upfront” carbon associated with materials, construction, and building processes throughout the building lifecycle. The energy intensity per square meter of the global buildings sector must improve on average by 30 percent by 2030 to meet international climate ambitions set in the Paris Agreement[1] (WGBC 2017).

The covid-19 crisis is forcing a reconsideration of workspaces, residences, and other occupied structures. Radical new models are needed for design research and collaboration across disciplines. One approach entails the hybridization of labs and studios to fuse innovations across science and design to generate next-generation building materials and structures that are adaptive, efficient, smart, and resilient.

This essay describes three ongoing projects in my lab at Cornell University that integrate bioinspired design processes and the dynamics of light and energy to innovate responsive nonstandard photovoltaic building skins, biobricks and -tiles, and sentient spaces.

[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Transdisciplinary Collaboration to Innovate Design and Function

We couple architectural designers with engineers and scientists in a research-based laboratory-studio to develop new ways of thinking, seeing, and working in each of our fields (Sabin and Jones 2017). These transdisciplinary collaborations are working to develop adaptive materials that are not just elements and things in buildings: they will generate immersive spaces, both acting on and responding to inhabitants and dynamic conditions in the built environment (Sabin 2015).

Like the cells in human bodies, sensors and materials 50 years hence will learn and adapt, making buildings not only smart but also healthy, aware, and sensate. To evolve buildings and their materials to reduce their carbon emissions and better serve people and the planet, the anthropocentric paradigm of resource consumption must shift to resource renewal, circular economies, adaptive reuse, and resiliency (Armstrong 2012; Sabin 2015).

Most contemporary sustainable approaches to reduce CO_2 emissions offer various technological solutions through sanctioned rating systems. These measures address resource consumption in buildings, but not the systemic ecology of the built environment over the long term.

Sustainable building practices should move beyond energy conservation and technical performance to new models that inspire sociocultural change and innovation across disciplines (Sabin 2015). Such a transformation will require transdisciplinary collaborations that explore how adaptive processes in nature can be leveraged and applied, through the integration of emerging technologies and design, in the development of new materials and healthy building products. In addition, aesthetics play a role in exciting the public about the importance of using sustainable building materials and practices in private and public domains.

Heliotropic Solar Panels

One such collaboration grew out of a conversation at the NAE's 2017 US Frontiers of Engineering Symposium, where I met Mariana Bertoni, associate professor in the School of Electrical, Computer, and Energy Engineering at Arizona State University. We talked about the role of design and aesthetics in the context of sustainable architecture, high-performance engineering systems, and the potential for widespread adoption of alternative energy—especially, active power systems such as solar panels in residential and industrial sectors.

We have collaboratively innovated the design and engineering of building-integrated photovoltaics through computational design and 3D printing for highly customized nonstandard filters and panels that result in site-specific nonmechanical tracking solar collection systems. Beginning with biological adaptations such as heliotropic mechanisms in sunflowers and the light-scattering structures in lithops plants, we investigate nonconventional configurations of solar panels as a means of integrating aesthetics while maximizing energy conversion efficiency.

Heliotropic mechanisms in sunflowers and light-scattering structures in lithops plants inform nonconventional configurations of solar panels.

Our prototype structure (figure 1) demonstrates an adaptable system with extremely low greenhouse gas emissions in comparison to PV systems that have not considered the temperature dependence of cell performance and solar tracking structures (Leccisi et al. 2016). This project innovates the design and engineering of PV cells through advances in computation and 3D printing, for highly customized bioinspired filters and panel assemblies that leverage the phenomena, beauty, and performance of light absorption for energy generation.

The PolyBrick: A DNA-Steered Building Material

In a collaboration of the Sabin and Luo labs at Cornell we are exploring the potential of designing with light and energy through living programmable matter or DNA-steered materials. Our PolyBrick research investigates the possibilities of living building tiles and bricks through the integration of DNA and programmable materials (Rosenwasser et al. 2018), building on

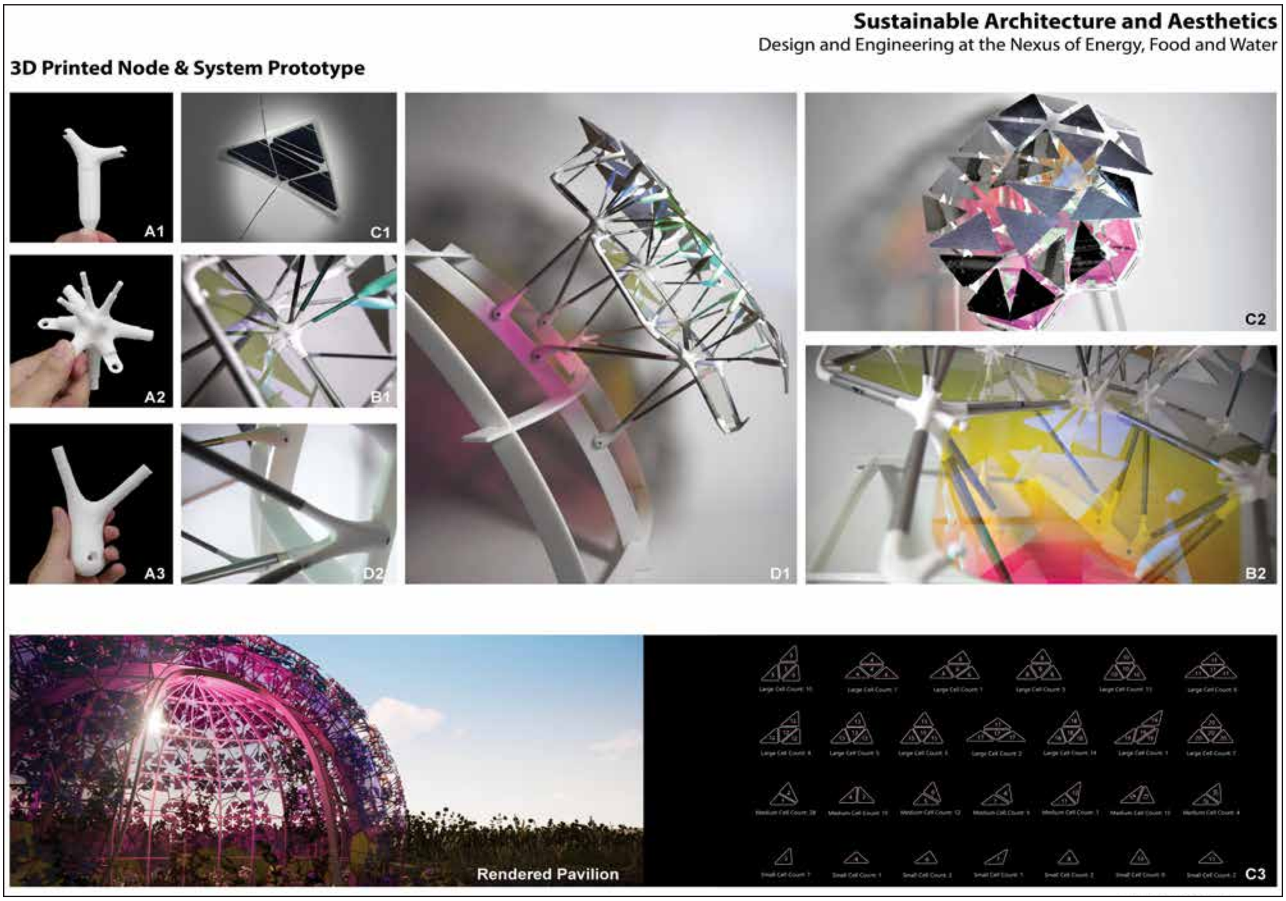

FIGURE 1 Image compilation of the heliotropic solar panel system featuring 3D-printed nodes (A1–3), nonstandard dichroic filters (B1–2), custom photovoltaic panels (C1–3), and a digitally fabricated frame (D1–2). The prototype and rendered pavilion are demonstrators for site-specific nonmechanical tracking solar collection systems. Figure courtesy Sabin Lab at Cornell University and DEfECT Lab at Arizona State University.

11 years of design research on 3D-printed nonstandard clay components and digitally designed ceramic bricks and assemblies.

PolyBrick 3.0 explores programmable biofunctionalities in constructed architectural environments through the development of advanced ceramic biotiles. These tiles use cutting-edge 3D-printed patterning techniques and novel bioengineered hydrogel materials to tune surface conditions and effects at the micro- and macroscales.

Using DNA as building blocks, varieties of structures have been designed and constructed from nano- to macroscale, including efforts to mimic and recreate structural components seen in architecture and mechanical engineering (Rosenwasser et al. 2018). Synthetically designed with advanced bioengineering, the first phase of this research uses DNA to design with light so that unique signatures fluoresce in the PolyBrick clay body. Imagine if the walls in your immediate surroundings glowed to alert you to contaminants in the air! The second phase will focus on adaptations to the local environment, including proteins and particulate matter, with the aim of cleaning the surrounding air and reducing pollution.

DNA nanotechnology will open up new possibilities for creating nano- to macroscale materials and architectural elements that can dynamically react to environmental cues and interact with biochemical reactions. With our unique DNA stamps and glaze, we explore the possibility of living matter and dynamic surface techniques for new forms of adaptive architecture.

Personalized Architecture

In conjunction with this work, we are exploring how artificial intelligence (AI) can personalize rooms and buildings—the spaces and environments that people inhabit influence how they feel (and act). Ada[2] is the first architectural pavilion project to incorporate AI. Through the integration of responsive materials and emerging technologies, it has the capacity to promote and increase wellbeing and healthy environments through people's direct engagement with the architecture.

The lightweight pavilion is composed of responsive and data-driven tubular and cellular components held in continuous tension via a 3D-printed semirigid exoskeleton. The lighting system and materials of the cyberphysical architecture respond to human participation as individual and collective facial pattern data are collected through a network of cameras, processed by AI algorithms, and transmitted as sentiment through light and color.

"An important aim of the project [is] to expand and inspire [architectural] engagement with humans. While artificial intelligence powers the project through the precise narrowing and statistical averaging of data collected from individual and collective facial patterns and voice tones, the architecture of Ada augments emotion through aesthetic experience, thereby opening the range of possible human emotional engagement" (Sabin et al. 2020, p. 246).

For example, personalized architecture may sense subtle changes in human emotion through sensors and interfaces that detect changes in facial patterns and voice tones (McDuff et al. 2019), and respond in ways that increase wellbeing and promote healthier environments. Such architectural responses might include adaptations to building temperature and windows that respond to daylight and UV energy by shifting from transparent to opaque.

Conclusion

Through the integration of biological adaptations, DNA-steered materials, and emerging technologies such as artificial intelligence, the future will bring building tiles that emit light, rooms that sense and respond to the wellbeing of their occupants, and cellular building skins that collect and store energy.

In my lab we are leveraging the context-driven processes of biological systems with AI and other advanced technologies to design and fabricate material and spatial structures that don't simply mimic nature but integrate the dynamics and specificity of material with environmental feedback. This approach enhances both technical and conceptual understanding of nature's inner workings for the design and fabrication of bioinspired material systems and a new model for adaptive architecture.

Using the resulting knowledge, design, and materials, buildings of the future will actively reduce carbon emissions and contribute to the health of both their occupants and the planet.

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[2] Ada was a project by Jenny Sabin Studio for the Artists in Residence Program at Microsoft Research, 2018–19.

Entering the Solar Era: The Next 50 Years of Energy Generation

Rebecca Saive

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It would be absurd today if anyone attempted to launch a product using chlorofluorocarbons (CFCs). Yet less than 50 years ago, the use of CFCs was entrenched in industry standards for numerous products, such as aerosols and refrigerants. With the 1987 Montreal Protocol, 197 countries agreed to phase out CFCs to halt the growing destruction of the ozone layer (EPA 2020), and the atmosphere is recovering from this human activity fallout (Merzdorf 2020).

This story suggests that it *is* possible to overcome environmental problems on a global level and bring Earth back to a healthier state.

Moving Away from Fossil Fuels

As happened with CFCs, the next 50 years will see a shift of mindset regarding fossil fuels, although their phaseout poses a greater challenge than CFCs, as fossil fuels have long been perceived as the foundation of modern prosperity. However, the commercial technology is already available to transition to a fossil-fuel-free society, with economic drivers favoring renewable energy sources in a multitude of use cases (e.g., Pyper 2019). One recent analysis finds that "it is already cheaper to *build* new renewables including battery storage than to *continue operating* 39 percent of the world's existing coal fleet" (Bodnar et al. 2020, p. 6).

The future energy grid will be a mix of renewables—solar, wind, hydro, and geothermal—heavily dependent on the major local resource. Five countries already boast at or near 100 percent renewable electricity generation: Albania, Costa Rica, Iceland, Norway, and Paraguay, leveraging their advantageous geography of highlands, mountains, and rivers to generate electricity from hydropower.[1]

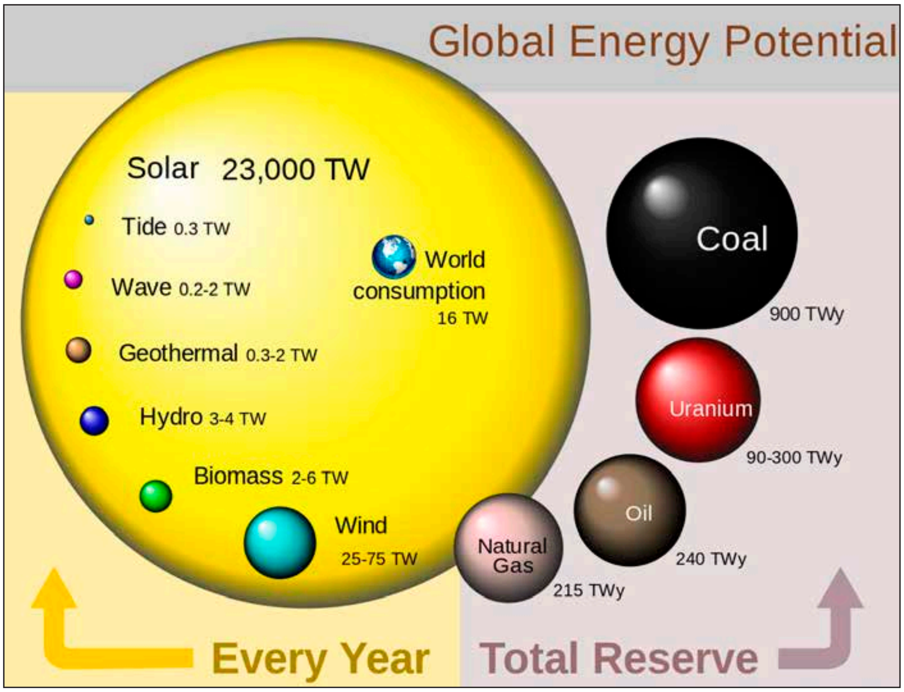

FIGURE 1 Comparison of renewable and fossil global energy potential. For renewables, the amount of energy is shown per year; for fossil sources the total reserve is displayed. Solar energy received by emerged continents only, assuming 65% losses by atmosphere and clouds. TWy = terawatt-year. Adapted from Perez and Perez (2009).

The abundance of solar outstrips all other resources by many orders of magnitude (figure 1; Perez and Perez 2009), and, combined with its ubiquity, will position it as the dominant global energy source, particularly as electrification spreads.

In many countries, the cost of solar-generated electricity is already on par with the cost of traditional electricity generation. This has led to several decades of global, exponentially increasing solar power production per year. However, maintaining current adoption rates will not displace enough fossil fuel use to stay below catastrophic CO_2 emission levels. To enhance the solar adoption rate, breakthrough technologies are required to catapult us into the era of solar energy.

Implementation

Direct power will be possible through high-performance solar cells that capture available irradiance almost lossfree. This will be accomplished through advanced engineering of the solar-harvesting device itself and of the microenvironments surrounding the device.

One possibility for direct power is a combination of microconcentrators (Domínguez et al. 2017) with multijunction solar cells (Geisz et al. 2020) and effectively transparent contacts (ETCs) (Saive et al. 2016). As shown for a solar-powered electric car in figure 2, multijunction solar cells (C) capture nearly all wavelengths with optimal efficiency by employing different absorber layers optimized for different parts of the irradiance spectrum. Triangular cross-section silver front electrodes (e.g., ETCs) ensure optimal light capture and electric current extraction (D). External to the device, microconcentrators (B) funnel light to microscale solar cells.

Through light concentration, solar cells work more efficiently, to some extent analogous to any thermodynamic process that runs more efficiently given a higher temperature difference between the hot and cold reservoirs. As an added benefit of such micro- or nanostructures, antisoiling properties can be readily integrated (Quan and Zhang 2017), keeping solar-powered vehicles clean.

Impacts

For individual use, portable items such as mobile phones, computers, and most importantly automobiles (figure 2) will be powered both directly and indirectly by solar cells.

Buildings can be fully integrated with solar cells (Meinardi et al. 2017; Peng et al. 2011) and smart

[1] Data and statistics, International Energy Agency (https://www.iea.org/data-and-statistics?country=WORLD&fuel=Energy%20supply&indicator=Total%20primary%20energy%20supply%20(TPES)%20by%20source)

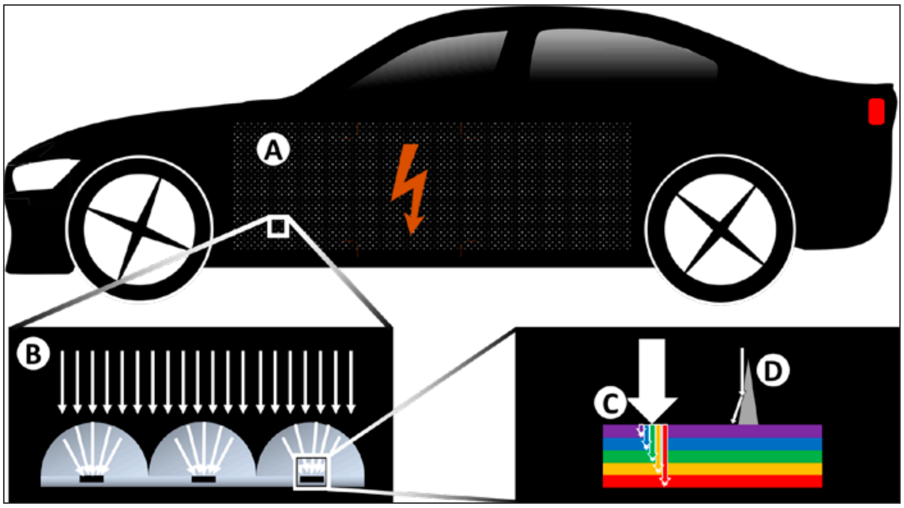

FIGURE 2 Schematic of future solar-powered electric cars. (A) Solar cells are seamlessly integrated with car exterior. (B) Schematic of microconcentrators funneling light (top arrows) onto microsolar cells. (C) Principle of multijunction solar cells: layers optimized for a narrow-wavelength regime converting sunlight efficiently into electricity. The rainbow colors denote the different parts of the solar spectrum. (D) Triangular cross-section microscale silver contacts (effectively transparent contacts) allow for low-loss light capturing and electricity extraction.

energy monitors, allowing them to be a net energy source rather than a sink most of the year. Semi-transparent and colorful solar cells integrated into smart windows and façades can transform any building surface into aesthetically pleasing solar power plants, and luminescent solar concentrators offer additional freedom for novel designs and functionality (Aghaei et al. 2020; Einhaus and Saive 2020; Needell et al. 2018).

Around the world, massive solar power plants providing gigawatts of energy will become widespread. Densely populated countries will integrate solar with agriculture, optimizing both crop and electricity yield (Dinesh and Pearce 2016; Dupraz et al. 2011; Weselek et al. 2019). New power plants will increasingly employ bifacial solar cells that capture light on front and rear surfaces (Guerrero-Lemus et al. 2016), capitalizing on the power in ground-reflected (albedo) light (Russell et al. 2017).

Moreover, with the emergence of privatized space travel, solar harvesting need not remain terrestrial. Prototypes of space solar power projects have been demonstrated[2] (Kelzenberg et al. 2018) and likely will be employed within the next 50 years.

When the Sun Doesn't Shine and the Wind Doesn't Blow

But the sun does not shine during the night, nor provide enough energy during the winter in all areas of the world. Solar and wind energy often complement each other, but what Germans call *Dunkelflaute*—the simultaneous absence of wind and sun—poses a risk to electricity supply.

If space solar generation does not become a viable workaround, several solutions are available:

- energy storage,
- smart appliances, and
- internationally interconnected electric grids.

Nowadays, batteries easily buffer daily electricity variations, and their steadily increasing performance has led to commercially available electric cars with a 400-mile range (Crider 2020). Further developments will allow electric cars to provide stability to the grid by offering decentralized storage through their batteries. With smart software and electricity pricing—and perhaps autonomous driving protocols—electric cars will recharge when renewably generated electricity is abundant and cheap, and discharge during demand peaks. A car owner might even profit if instantaneous electricity trading prices are applied—although the likelihood of individually owned and operated vehicles 50 years from now will strongly diminish (indeed, as autonomous, community-owned cars become more prevalent, individual driving may be viewed the same way we now regard horseback riding).

Smart appliances would also both augment the electric grid and help buffer fluctuations on a timescale of seconds to hours: refrigerators, laundry machines, air conditioners, and others could easily run whenever there is an oversupply of electricity, thus abating curtailment concerns.

Nevertheless, pervasive smart grids do not solve the issue of seasonal variations of solar resources and the needs of energy-dense industrial processes. These will

[2] Caltech Space Solar Power Project, https://www.spacesolar.caltech.edu/

require either long-term storage—ideally in the form of energy-dense chemical fuels—or intercontinentally connected electric grids.[3] The sun is always shining and the wind is always blowing somewhere.

Conclusion

Solar energy breakthroughs will occur at every level of society, seamlessly integrated and perfectly normal to the next generations. Optimistically, renewables may even eventually enhance international peace and stability. Diminishing the necessity of fossil fuels might settle at least some territorial conflicts, enabling most countries to become energy-independent. Moreover, the indiscriminate way the sun distributes its power to both developed and less developed countries may lead to increased wealth and independence in third world countries.

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Catalysis and the Future of Transportation Fuels

José Santiesteban

Thomas Degnan

José G. Santiesteban and Thomas F. Degnan Jr.

Transportation is a large and diverse sector that encompasses road (passenger and freight vehicles), aviation, marine, and rail transport. In 2018 this sector accounted for nearly a quarter of global anthropogenic carbon dioxide emissions,[1] so efforts to decarbonize it are critical to achieving the goals of the Paris Agreement.[2]

But the transition to a net-zero-emission transportation sector will take decades, cost hundreds of billions of dollars, and may never be complete (Ogden et al. 2016). Decarbonization of the sector will depend on advances in technology, policies, incentives, investment in infrastructure, and the manufacture of low-carbon and zero-emission vehicles.

There is no single energy carrier that, in the foreseeable future, can satisfy requirements across all aspects of the transportation sector. For example, the

[1] Of the total 8 billion tons of CO_2 emitted by transportation in 2018, 45% came from passenger vehicles, 29% from road freight vehicles, 12% from aviation, 11% from shipping, 1% from rail, and the remaining 2% from other sources. (International Energy Agency, https://www.iea.org/topics/transport).

[2] https://ec.europa.eu/clima/policies/international/negotiations/paris_en

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prospects for battery-powered supersonic aircraft remain quite distant (Epstein 2020; Langford and Hall 2020). In the interim, a "bridging" low-carbon energy transition strategy will rely on the combined increased use of energy carriers such as electrons, hydrogen, and lower-emission liquid fuels (advanced biofuels and synthetic liquid fuels).

Catalytic Challenges

Catalyst technologies have played an essential role in the economic and energy-efficient conversion of crude oil into liquid energy carriers that meet the demands of the current transportation sector (Rostrup-Nielsen 2004). Catalytic breakthroughs have also played a crucial role in onboard abatement systems to eliminate emissions of environmental pollutants such as SOx and NOx (Farrauto et al. 2019). Novel catalyst technologies are needed to enable the low-carbon energy transition for the transportation sector.

The fuel and vehicle industries must focus their catalytic expertise on improving the sustainability of and reducing the nonrenewable carbon footprint of liquid fuels. Significant advances are needed in three areas:

1. improving the yield and quality of biofuels,
2. increasing the amount of both "green" and "blue" hydrogen[3] produced and incorporated in hydrocarbon fuels, and
3. reducing the cost and improving the robustness of fuel cells.

Biofuels

A major obstacle in the direct substitution of biofuels (e.g., biodiesel) for conventional hydrocarbons is the ubiquitous presence of chemically bonded oxygen in biomass. The substitution of biomass-derived diesel and gasoline for conventional liquid fuels requires the near-complete removal of oxygen (oxygenates can lead to the formation of gum and engine deposits and they lessen the energy content per unit volume or mass). Oxygen can be catalytically removed through the selective addition of hydrogen to biomass in a process known as *hydrodeoxygenation*; the process is analogous to the methods used in the petroleum industry for sulfur and nitrogen removal. However, for deoxygenated fuels to be economical, more selective catalysts must be identified and developed.

Biodiesel is composed of long-chain hydrocarbons, whose fluidity often has to be improved by modifying the chemical structure. Improved catalysts that both optimally rearrange the hydrocarbon structure and simultaneously remove oxygen would constitute a significant advance.

Hydrogen

The concept of using hydrogen as a transportation fuel has always been environmentally attractive, but economically challenged—and likely to remain so. The high pressures (and low temperatures) required for onboard H_2 storage are daunting, as are the prospects for setting up a national—or even statewide—distribution system.

Liquid fuels with higher hydrogen content derive more of their energy from the production of H_2O than from CO_2, thereby creating more energy per unit mass of CO_2 produced. Cheaper hydrogen would enable a more hydrogen-rich fuel supply.

Improved catalysts that both optimally rearrange the hydrocarbon structure and simultaneously remove oxygen would constitute a significant advance.

About 95 percent of all hydrogen is produced by steam methane reforming (SMR). SMR ($CH_4 + H_2O \rightarrow CO + 3H_2$), when coupled with the water gas shift process ($CO + H_2O \rightarrow CO_2 + H_2$), produces 5.5 tonnes of CO_2 for every tonne of hydrogen (not counting the CO_2 generated by the heat required for the net endothermic process). Thus, CO_2 needs to be captured and sequestered to enable low-carbon (blue) hydrogen (van Hulst 2019). New catalytic systems may make it possible to use biomass (e.g., cellulose and/or municipal solid waste gasification) rather than natural gas–derived methane as the hydrogen source.

Electrolysis is less economically attractive than SMR. However, some companies are constructing green

[3] Blue hydrogen is made from natural gas through the process of steam methane reforming coupled with carbon capture and storage; green hydrogen is produced from water using renewable power.

hydrogen plants based on large-scale electrolysis using wind and solar (Parnell 2020). Catalysts used either in electrolysis or for the purification of SMR hydrogen are both expensive and susceptible to poisoning by a number of contaminants in the feed streams. Identifying improved catalysts that allow the design and economical manufacture of small modular SMR, with carbon capture, or electrolysis units would open up many new possibilities for further reducing greenhouse gases.

Fuel Cells

New catalysts and catalytic systems are needed to improve the economics of fuel cells suitable for vehicles. Fuel cells can use a range of sources for hydrogen, including methanol (direct methanol fuel cells), ethanol, and even gasoline.

Proton-exchange membrane fuel cells (PEMFCs) are approximately three times more efficient than internal combustion engines in converting chemical energy to power, but they require an expensive noble metal catalyst, platinum (Pt), that is particularly sensitive to impurities in the hydrogen-rich fuel. Identification of a substitute for the Pt catalyst would reduce the cost of fuel cells by as much as 25 percent (Mitchem 2020).

A potentially more economically attractive alternative to the PEMFC is the anion exchange membrane fuel cell, which does not require Pt and uses less expensive metal catalysts thanks to the high pH of the electrolyte. The performance and durability of anion exchange membrane fuel cells have recently been significantly improved through the development of new catalytic materials, improved systems design, and refinement of operating conditions (Gottesfeld et al. 2017).

Finally, several academic research groups around the world are advancing the science and technology to fabricate systems that combine solar energy–gathering semiconductors and photocatalytic materials to drive chemical reactions to produce sustainable liquid fuels (Wadsworth et al. 2019). Of particular interest is the use of semiconductor photoelectrodes for water splitting. This area of photoelectrochemistry for solar energy conversion dates back at least 40 years, but has garnered a tremendous amount of attention in the last decade (e.g., Lee et al. 2019).

Summary

The pathway to a net-zero-emission transportation sector must capitalize both on liquid fuels that produce less CO_2 from nonrenewable sources and on CO_2 capture and sequestration. This strategy translates into greater reliance on biomass, green and blue hydrogen, and improved fuel cells. The identification and development of improved catalysts is the critical enabler for advances in all three of these areas.

The road to a more sustainable transportation sector involves research on more product-selective catalysts incorporating earth-abundant elements (e.g., iron, copper, nickel, molybdenum). Particularly attractive will be catalysts that are designed around the use of photons or electrons rather than heat to drive the desired chemical transformations.

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Understanding Uncertainty, Context, and Human Cognition:
Necessary Conditions for Safe Autonomy


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Autonomous vehicles are still "baffled" by unpredictable human actions such as wrong-way driving, emergency vehicles, and human-guided traffic diversions. Yet this unpredictability gives people an edge in unknown or dangerous situations. Therefore remote supervision by a human and safety intervention by a remote human driver are necessary for such vehicles to be deployed safely and effectively in real-world situations. Developing human supervision for autonomous vehicles will provide the necessary safeguards to deploy these vehicles quickly and effectively.

Self-Driving Shuttles at TAMU

At Texas A&M University (TAMU) we are developing human supervision for autonomous vehicles in a state-of-the-art teleoperation center. In our efforts to develop self-driving shuttles in the city of Bryan, TAMU is deploying and testing autonomous shuttles that do not have a safety driver behind the wheel (but always have a safety navigator in the front passenger seat). We have outfitted our self-driving shuttles with a teleoperation system.

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Our proof-of-concept project includes the integration of teleoperation hardware and software in connected self-driving shuttles. We are specifically interested in (i) quantifying when the human teleoperator takes over the vehicles, (ii) developing higher-level actions for the teleoperator to interact with the vehicles, and (iii) quantifying the behavior of such high-level actions.

Risks of Partial Autonomy

As researchers and manufacturers move rapidly toward achieving full autonomy, human operators and passengers become increasingly disconnected. To the extent that an autonomous vehicle's situational awareness increases, that of the human operator or passenger decreases, meaning they are less likely to efficiently take over manual control when needed if an anomaly occurs.

This trade-off has been called *the automation conundrum*; because the goal of full system autonomy is quite difficult, most systems will exist at some level of semiautonomy for the foreseeable future (Endsley 2017). The automation conundrum may be a fundamental barrier to full autonomy in safety-critical systems such as driving.

Humans fare poorly with increased automation: it results in automation complacency and overreliance, loss of situational awareness, and skill loss.

While recent system autonomy efforts are beginning to leverage artificial intelligence and learning algorithms to allow the platforms to better adapt to unanticipated and changing situations, it is clear that the design and inclusion of human autonomy interfaces are needed.

There has been much research demonstrating that humans fare poorly with increased automation: it results in automation complacency, overreliance on automation, loss of situational awareness and spatial orientation, and skill loss. These contribute to human errors, accidents, and loss of trust in the automation. Modern autonomous systems are, and will remain, dependent on the development of successful approaches to human-autonomy teaming.

For these reasons, companies have started working on human supervision of autonomous vehicles. Such supervision ranges from simple remote operation (when the vehicle doesn't know what to do, a remote driver takes over and drives) to remote supervision (the vehicle gets high-level commands such as "stop," "slow down," or "overtake" from the remote driver). While this human involvement solves some problems, it creates new ones: What happens if the remote driver makes a wrong decision? Who is responsible? How should one deal with delays associated with sending information to the remote driver and commands from the remote driver back to the vehicle?

Cognitive Engagement in Autonomy

Human supervision of autonomous vehicles is not a new concept, but several areas require development. Humans are very good at understanding context, a capacity that is lacking in current autonomous vehicles, and it remains an open question whether context can be inferred by a remote driver.

Augmented/virtual reality, along with sound and haptic sensations, will play a key role for the remote driver to understand context. Similarly, understanding human emotions is important. The emotional state of the passenger determines how s/he reacts and behaves in an autonomous vehicle.

When humans act as passive monitors of autonomous driving, it is inherently difficult for them to fully understand what is going on because of their lower level of cognitive engagement. There is a clear need to understand the features that influence the human cognitive processes involved in successful oversight, intervention, and interaction with automated systems.

Transitions may be ineffective, even dangerous, if the automation suddenly passes control to the human operator who cognitively may not be ready to take over. This means that in addition to situational awareness of the environment, the vehicle requires situational awareness of the passengers. This demands a real-time assessment of human cognition, accounting for the difference between discrete cognitive tasks associated with human intervention, which require more conscious attention sporadically, and continuous manual control, which generally requires lower attention over an extended period.

Quantum Probability to Model Human Cognition

The general mathematical structure of quantum probability and artificial intelligence provides an engineering approach that not only is applicable to any domain that has a need to formalize uncertainty and probability but also can be formally applied to human cognition. Quantum probability theory provides a method to consistently convey contextuality between any combination of autonomous system components and operational environments. In addition, the mathematics of quantum probability may be relevant to the contextual phenomenon of trust.

In applying the well-structured machinery of quantum probability to human cognition we do not wish to imply that the human brain and psychological processes have a quantum nature. We simply suggest that engineers may take a quantum-like modeling approach to assessing human cognition: context can be modeled to a great extent, and quantum probability may better describe and explain the human cognitive state.

Conclusion

Autonomous vehicles will save lives and change the way people work and live. But for these and other autonomous systems to truly and safely succeed, they need to "understand" the context of the situation in which they operate, recognize the emotions of the passengers, and safely work alongside other vehicles and humans. Without these, a fully autonomous system will never be safe and effective.

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Space Launch in 50 Years: Abundance at Last?

Gwynne E. Shotwell and
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Space travel is the next necessary step in human evolution. Ensuring that humans can live on multiple planets and be out among the stars, exploring the universe, is both key to human survival and a magnificent source of inspiration.

But current single-use rockets make getting to orbit prohibitively expensive, and the maximum transportable payload becomes vanishingly small with increasing distance. In the next 50 years, fully reusable rockets that can be refueled in space will remove these constraints, accelerating the space economy and making space travel accessible to a large sector of the population.

With launch abundance, entirely new classes of space missions will become possible, including colonization of the Moon and eventually Mars. These colonies will provide waypoints for humans to explore deep space, at first for science and industry and eventually for leisure. Learning how to live and work for long periods in space will lead to the exciting possibility of reaching other habitable planets. Perhaps one day humans will even make contact with other lifeforms that share the vast galaxy that we are just beginning to explore.

Reducing the Costs of Space Travel

Since the US Space Shuttle program's last mission in 2011, China and Russia had been the only countries carrying humans to low Earth orbit

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(LEO) and back. But this year the United States once again became capable of human space transportation under the NASA commercial crew program.

Yet getting to orbit, let alone beyond, is still extraordinarily expensive. A seat for a single person to fly to LEO on a Soyuz rocket costs more than $80 million (NASA IG 2016). The Space Launch System, NASA's newest rocket intended for spaceflight beyond LEO, is projected to cost between $876 million and $2 billion per launch (NASA IG 2019; Vought 2019).

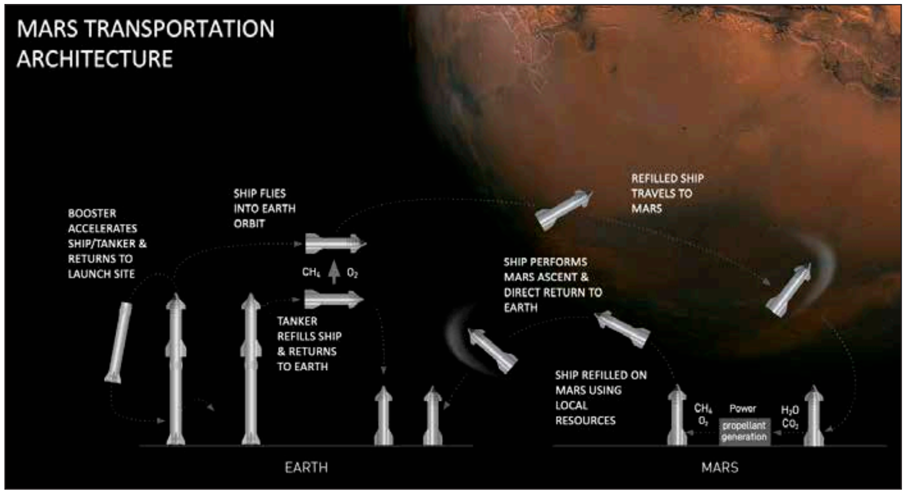

FIGURE 1 Example of in-space refueling, in situ propellant generation on Mars, and controlled landing of upper and booster stages to send unprecedented payloads to and from Mars. Source: SpaceX.

From Expendability to Reuse

One of the primary reasons for the staggering cost of space travel is that these rockets are expendable. The entire skyscraper-sized rocket is discarded after a single flight, and only the tiny capsule at the top of the stack survives launch to go on to complete a mission. Imagine what air travel would be like if the aircraft were thrown away after each flight! If it were possible to land, refuel, and refly rockets just like airplanes, the cost of the launch could theoretically be as low as the propellant cost—a 200X reduction.

In the past 5 years, spaceflight companies have spurred a renewed interest in reusable launchers. Virgin Galactic and Blue Origin are developing reusable suborbital launchers that reach the edge of the atmosphere, providing a few minutes of weightlessness. In 2015 SpaceX achieved the world's first landing of an orbital-class rocket, Falcon 9. The company has also achieved landing and reuse of the payload fairing. With over 50 successful landings, as well as 35 booster and 6 fairing reflights, SpaceX has made reuse a normal part of its business, significantly reducing the cost of spaceflight for its customers.

Breakthroughs Needed

Reusability is not enough. Space vehicles must achieve aircraft-like operations with costs approaching the lower bound of just the propellant. Five breakthroughs are needed:

1. Propulsive, precision landing of the booster stage (already demonstrated with Falcon)
2. High-performance engines that run on methane and oxygen, which can be relatively easily generated (compared to fossil fuel–based propellants) on planetary bodies (such as Mars) with the right elements (carbon, hydrogen, and oxygen)
3. In-space refueling, to "reset the rocket equation" and dramatically increase the payload that can be sent to distant planets
4. Controlled entry and propulsive landing of the upper stage, whether on a planet with a thick atmosphere (Earth), no atmosphere (the Moon), or something in between (Mars)
5. Sufficient payload volume to carry cargo and crew for long-haul flights.

SpaceX is creating a vehicle, Starship, to meet all five criteria. It will be 100 percent reusable with a payload compartment 8 m across and 17 m high, more than double that of current rockets. It will lift 100 metric tons to LEO, the surface of Mars, or Jupiter, dwarfing the capacity of today's most powerful (expendable) rockets.

Beyond Launch Scarcity

Completely reusable rockets will create a world of launch abundance rather than launch scarcity, which has been top of mind for anyone seeking to explore outer space. When every kilogram in orbit costs an astronomical sum, and when the maximum transportable payload plummets with distance, it is no surprise that spacecraft designers have been obsessed with minimizing mass and volume. Efforts to shrink payload necessarily contribute to the high cost of space missions, whose budgets exceed initial estimates as much as tenfold (Billings 2010; GAO 2019).

Relaxing or removing the constraints of launch scarcity could radically reduce mission costs:

- Exotic, ultralightweight materials can be avoided, instead using common metals such as steel.
- Off-the-shelf components can be used more readily without size and mass constraints.
- Complex or structurally intricate designs such as folding mechanisms will no longer be needed.
- Cheaper, riskier space missions can be tolerated with a reduced financial barrier to entry.

Further Options

Vehicles that meet the above criteria will make possible entirely new classes of space missions:

- Larger space telescopes that see farther with greater resolution, enabling new observations of exoplanets and the beginnings of this universe; stationing such telescopes in higher-energy orbits further improves observations by removing Earth's brightness (Gaskin et al. 2019; Mennesson et al. 2016; NASA 2019)
- Missions that travel directly to the outer planets, reducing the travel time by years compared to complex trajectories that require gravity assists from planets (Lam et al. 2015)
- Huge constellations of cheap Earth-orbiting satellites (Gristey et al. 2017)
- Long-haul transportation that leverages spaceship technology to allow the standard business or pleasure traveler to touch space en route to their earthbound destination
- Development of permanent human bases on the Moon or Mars.

The last of these is the ultimate goal: the establishment of a self-sustaining civilization off Earth. This monumental undertaking will be possible only in a future of launch abundance—which will become reality in the next 50 years.

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Predicted Advances in the Design of New Materials

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The prehistory and protohistory of humanity are divided into three ages in terms of materials: the Stone Age (~3.4 million years, until 8700–2000 BC), based on raw materials from nature; the Bronze Age (3500–300 BC), based on human-made copper (alloyed with 12 wt% tin); and the Iron Age (1200 BC–800 AD), derived from human-made iron-carbon alloys.

In the 21st century the functionality of society relies on digital technology built on silicon-based electronics. Digitization through the integration of cyberphysical systems with many autonomous subsystems will demand increasingly more efficient development of materials with emergent performance under extreme conditions, such as those required for the human colonization of other planets (Lambert 2018).

While knowledge of materials among engineers has improved steadily over the last few hundred years and especially since the start of the Industrial Revolution, most materials development has occurred through the intuition of experts, trial and error, or serendipitous discovery. The logical next step is the computational design of materials, first systemized in 1997 (Olson 1997) and given a big boost in 2011 with the launch of the Materials Genome Initiative by the US government (NSTC 2011).

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The key enabler of this approach is the digitization of knowledge on materials stability in terms of thermodynamic information (Gibbs 1873) stored in digital databases developed by the calculation of phase diagram (CALPHAD) method (Kaufman and Bernstein 1970), capabilities separated from each other by about 100 years. Fifty years have passed since the creation of CALPHAD, and we imagine here developments that will take place over the next 50 years.

Materials 4.0

After steam power, electricity, and computerization, the process of digitization—often referred to as Industry 4.0—is now ushering in Materials 4.0 (Liu 2020). Digitization of materials knowledge progressed significantly in the 20th century, from the Schrödinger (1926) equation in quantum mechanics to its solutions based on the density functional theory (DFT; Kohn and Sham 1965), resulting in massive digital databases of materials properties predicted using high-performance computers. Known weaknesses in the DFT, such as consistent underestimation of band gaps in semiconductors, were addressed through theoretical improvements that were implemented in a computationally efficient manner.

Deep neural network machine learning models can be continuously improved with new input data in a manner analogous to the way humans learn from experience.

Data, empirical models, and mechanistic correlations (Cordero et al. 2016) are now leading to an era where artificial intelligence (AI) will be used to (i) interpret the knowledge that connects the data through machine learning (ML) algorithms and (ii) develop deep neural networks (DNNs) to predict new data and knowledge (Gubernatis and Lookman 2018).

Generation of data from experiments takes weeks and months, whereas DFT-based calculations reduce the time to hours and days, and DNN ML models can produce results in seconds to minutes. The models can also be continuously improved with new input data from computation and experiments in a manner that is analogous to the way humans learn from experience, capturing more and more fundamental building blocks of materials (Liu 2014).

The expected technical advances of this current trajectory include the design of materials with emergent properties (Liu et al. 2019), fulfilling the decades-long goal of "materials by design" (Gillespie 2019). In addition, the development of new experimental methods, such as the cold-sintering approach for producing complex metal oxides at very low temperatures (Guo et al. 2019), will further accelerate new material discovery and manufacturing.

Impacts and Applications

The transformative development will be the full integration of DNN methods into experimental and computational approaches used in materials synthesis and structure-property relationship determination. The integration of computational methods such as DFT, CALPHAD, and DNN in materials synthesis will continue to evolve to the point that human involvement will be greatly reduced. For example, optimizing the microstructure of materials may be achieved by rapidly analyzing many microstructures in multiple samples using a combination of electron microscopy with image recognition algorithms.

The biggest impact of these developments will be the speed with which new materials may be available for specific applications. More compositions and microstructures may emerge very rapidly, including pervasive applications of today's nanotechnology, future quantum-scale manipulations, polymer materials that exist in nonequilibrium states across multiple scales (de Pablo et al. 2019), and metallic alloys optimized for new space applications (Lambert 2018).

It is further expected that experimental characterization, artificial intelligence, and ML will be seamlessly integrated with each other such that the line between computational methods and experimental characterization disappears.

Computational materials design will encompass the recycling of materials as the physical ecosystem interfaces with the data/cyber ecosystem throughout the materials lifecycle (Liu 2018). Initially, it is anticipated that this physical/cyber integration will result in efficient DNN ML models so that each step in a complex manufacturing process can be optimized according to the prior steps, starting from the inevitable fluctuations in the raw materials properties. This AI-guided interactive manufacturing system will be able to self-balance every subsequent step to ensure that materials remain on optimal pathways to final products with desired microstructures and properties, thus leading to zero-scrap manufacturing.

Ultimately, when this integrated system is fully implemented, the residuals from the design, manufacturing, service, and recycling of materials can be drastically reduced, thus lessening the impact of materials use on the environment.

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The Role of Engineering and Technology in Agriculture

Michael Steinwand

Pamela Ronald

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By 2050, the global population is predicted to reach 9.7 billion. If consumption practices do not change and food continues to be wasted at alarming rates, farmers around the world will need to increase production 25–100 percent to meet the associated increase in food demand (Hunter et al. 2017).

At the same time, crop yield is stagnating in many parts of the world (Ray et al. 2012), and climate change threatens the yields and nutritional content of major crops (Myers et al. 2014; Rosenzweig et al. 2014). Additionally, the range of crop pathogens and insect pests is expanding toward the global poles (Bebber et al. 2013).

These challenges to sustained food security require multiple solutions encompassing social, scientific, and economic change. In this essay we highlight the current and future role of genetic technologies in advancing sustainable agriculture, reducing food insecurity around the world, diversifying the global diet, and enhancing health through the decreased use of pesticides.

This essay was adapted from Steinwand and Ronald (2020).

Michael Steinwand is a postdoctoral researcher and Pamela Ronald (NAS) is a distinguished professor in the Department of Plant Pathology and the Genome Center at the University of California, Davis.

Technological Advances in Crop Engineering

Humans have manipulated plant genomes for millennia, long before understanding the DNA underlying heritable genetics. Early domestication of wild species involved selection of characteristics such as upright vegetative structure, uniform flowering, seed retention on the plant for easier harvest, and reductions in seed dormancy and toxic chemicals in edible tissues. Geographic dispersal established locally adapted landrace cultivars.

The rise in molecular genetic tools has ushered in the era of genomic breeding, wherein molecular breeding and genetic engineering have gained prominence. Crop species can now be developed in a fraction of the time and with a broader array of changes than could be achieved with conventional breeding.

Crop Diversity

Genetic diversity is a crucial resource for crop improvement. It can be introduced via mutagenesis using irradiation or chemical treatment, crossbreeding with related or wild populations, genetic engineering (introducing a gene from a distantly related species such as another plant species or a microbe), or gene editing (mutation or insertion of a gene at a specific locus).

Plant breeding techniques may introduce valuable agronomic traits such as enhanced environmental and biotic stress tolerance to minimize yield losses and improve food nutrition and quality. Underutilized and regionally important crops, often adapted to grow on marginal lands, can be improved and grown more widely to diversify the global diet.

Genomics, Proteomics, and Other "Omics"

Recent technological advances and reduced costs have led to molecular "omics" studies in plant science, profiling the total complement of a biological unit such as genes (the genome) or proteins (the proteome). Whereas producing the first plant genome (of *Arabidopsis thaliana*) required 10 years and $100 million, a new *Arabidopsis* genome can now be sequenced for a few thousand dollars (Li and Harkess 2018).

With modern high-throughput genome sequencing technology more economically accessible, the breadth of species with genomic data is expanding to include regionally important staple crops (e.g., cassava and finger millet) historically neglected in breeding programs of developed economies (Hendre et al. 2019). Computational correlative association studies synthesize the information in agronomic, proteomic, transcriptomic, and/or metabolomic data to reveal the genetic profiles underpinning complex traits such as flavor, drought tolerance, disease resistance, and yield.

The discovery and refinement of targetable site-directed nuclease (SDN) enzymes enables precision manipulation of crop genomes (gene editing), deleting or changing DNA base pairs at specific sites to introduce genetic mutations. The RNA-guided SDN called *CRISPR-Cas* has become a dominant tool since 2013, when its use in gene editing was demonstrated in plant cells (e.g., Shan et al. 2013).

Enhanced Disease Resistance to Address Food Insecurity

Plant diseases and pests (e.g., fungi, bacteria, nematodes) reduce the annual global yield of major crops by an estimated 17–30 percent (Savary et al. 2019), with higher losses in food-insecure regions. Among many ways to address this problem are genetic engineering to add genetic material that confers resistance and mutation of the plant genes that facilitate disease susceptibility (because they either suppress plant immune responses or are required by the plant pathogen for its growth and proliferation).

Underutilized and regionally important crops, adapted to grow on marginal lands, can be grown more widely to diversify the global diet.

Disease susceptibility genes have been identified widely in crop species of agronomic importance and are often conserved between species. For example, breeders have used a naturally occurring mutant allele of the mildew resistance locus O (MLO) gene to confer heritable broad-spectrum immunity against powdery mildew races in susceptible barley cultivars for decades. Researchers used SDNs to edit the corresponding MLO genes in wheat (Wang et al. 2014) to generate similar resistance to the powdery mildew species infecting these crops.

Reduced Use of Chemical Insecticides

One of the most prevalent engineered traits across many crops, including maize, soybean, cotton, and eggplant, is insect resistance conferred by genes originating from the soil bacterium *Bacillus thuringiensis* (Bt). Bt insecticidal sprays have been used in organic agriculture for many years because they are specific to pests and nontoxic to humans and wildlife. Although useful, in many cases the sprays are expensive and do not prevent the insect from getting inside the plant.

As an alternative to sprays, geneticists have engineered the Bt gene directly into the crop genome. On average, use of Bt maize, soybean, and cotton crops has resulted in 37 percent less insecticide use (Klümper and Qaim 2014). Recent analysis finds that widespread planting of Bt field corn also has regional insect pest-suppressive benefits to nearby non-Bt vegetable crops, which translates into fewer chemical insecticide sprays and less damage from corn borer insects (Dively et al. 2018).

Plant genetic material can be added or mutated to enhance disease resistance.

The cultivation of Bt-resistant crops has reduced both the use of chemical insecticides by 50 percent in India and acute pesticide poisonings in cotton growers (Kouser and Qaim 2011). In neighboring Bangladesh, the introduction of four varieties of Bt eggplant in 2014 led to a sixfold increase in net returns for farmers, in part due to a 61 percent reduction in insecticide costs (Shelton et al. 2019).

Going Forward

Crop genetic improvement ranges from the deletion of a few small DNA regions to the introduction of new genes or entire genetic pathways to produce new chemical compounds or agronomic traits. These genetic alterations will facilitate crop trait improvement programs.

Modern biotechnologies enable scientists to introduce genetic changes that enhance disease resistance, increase yield, or enable growth on marginal lands. One exciting application is the potential to rapidly accelerate the domestication of wild plant species. A recent proof-of-concept study used a genome editing approach to increase the size and number of the ancestor of the modern tomato, so that it resembles commercial tomatoes but retains the stress tolerance traits of the wild parent (Li et al. 2018). Such efforts will likely broaden and diversify the food supply of the human diet.

The targeted DNA breakages caused by SDNs may also serve as insertion points for transgenic gene clusters that enhance the nutritional content of a crop. For example, the Golden Rice trait introduces vitamin A precursor betacarotene in rice grain and has recently been approved for consumption in many countries. Production and consumption of Golden Rice will save the lives of thousands of children and young mothers suffering from vitamin A deficiency (golden rice.org). We recently demonstrated that an SDN technology can be used to insert this trait in a precise genomic target (Dong et al. 2020). Further refinement of the technique would allow for multiple traits to be stacked at targeted genomic regions, facilitating subsequent breeding.

Adoption of these new biotechnology products remains limited. In 2017, 26 countries cultivated 191.7 million hectares of genetically engineered crops, with only five countries—the United States, Brazil, Argentina, Canada, and India—collectively representing 91 percent of the global transgenic crop area (ISAAA 2018). In many countries governmental frameworks for regulating genetically engineered crops are well established, whereas those governing the techniques of gene editing in crops are rapidly evolving. For example, in the European Union the EU court of justice decision stating that crops developed through genome editing must be regulated as strictly as genetically engineered products complicates EU scientific field trials of genome-edited crops and restricts farmer adoption (Faure and Napier 2019). In contrast, under its biotechnology regulations, the USDA does not regulate or have any plans to regulate genome-edited crops as long as they are not plant pests or developed using plant pests (USDA 2018).

Challenges

The process for commercialization of transgenic technologies and crop varieties is affected by political and socioeconomic concerns and can span decades, making it difficult to address urgent agricultural needs. Consequently, in many parts of the world, breeders and farmers do not have ready access to some genetically engineered crops. For example, while farmers in Bangladesh cultivate Bt eggplant, it is prohibited in neighboring India despite farmer demand and its clear benefits in reducing insecticide use. Similarly, organic farmers do not have access to genetically engineered crops because genetic engineering techniques are excluded from use in certified organic production (even though other types of genetic alteration such as chemical and radiation mutagenesis are permitted).

There remains a need for ongoing engagement of the scientific community with diverse stakeholders, including consumers and politicians, on the challenges faced by farmers and the use of plant biotechnologies to address these challenges. Increasingly polarized political environments and fundamental changes in how information is shared have given new urgency to the problem of the disconnect between public opinion and scientific consensus on scientific topics.

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Beyond Engineering for Sustainable Global Development

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About 5 years ago the number of mobile phone accounts in the world exceeded the total human population (ITU 2019). Nomadic pastoralists in East Africa and tribal communities in South Asia make fluent use of cellphones, even where life is otherwise preindustrial, even preagrarian. As measured by the speed and extent of its market penetration, the mobile phone is the most successful consumer product in the history of human civilization.

But what has been its impact on global socioeconomic development, and what can we expect of its technological descendants? An interdisciplinary research community focused on information and communication technologies and development has found mixed outcomes.

Benefits, Shortcomings, Lessons Learned

On the positive side, mobile phones have a range of benefits. They offer portable, real-time communication at a remarkably low cost, connecting communities that, just a decade ago, were largely isolated. Migrant workers stay in touch with their families. Smallholder farmers receive text-message weather alerts. Shopkeepers accept mobile payments in lieu of cash. In the south Indian state of Kerala, the arrival of cellular towers improved fishing markets, leading to a 5 percent decline in the price of sardines for consumers and a 9 percent increase in profits for fishermen, who used their mobile phones to call ahead to find the best market on shore at which to sell, flattening prices across the coastline and eliminating wasteful gluts (Jensen 2007).

Smartphones and 3G appear to have augmented these effects, putting the power of internet-enabled supercomputers in purses and pockets everywhere. Thanks to Chinese low-cost handsets, local markets for secondhand (and third- and fourth-hand…) devices, and fierce competition among mobile operators, day laborers in the developing world now have access to goods and services that wealthy 20th century elites never had: movies anywhere on demand, instant money transfer, political protest by swiping a screen.

The same technologies, however, have caused their share of problems. Mobile payments and cryptocurrencies have facilitated international money laundering. In the world's poorest households, meager income is sometimes diverted from nutrition and education to keep mobile phones topped up. And every country appears to be wrestling with the problem of fast-flying fake news about politics, public figures, personal health, and myriad other topics.

Even focused attempts to apply digital technologies toward positive ends rarely succeed. Efforts to improve education with laptops and smartphones consistently fail to show results. Making corruption visible through online reporting changes little where citizens always knew it was happening. Just as previous generations of development engineers promoted innovative cookstoves that no one used and sent medical devices to rural clinics ill equipped to maintain them, today's technological do-gooders often fail to appreciate the nonengineering challenges that must be addressed for innovation to have positive impacts.

Fortunately, interest in engineering for development and its poor track record of success has led to reflection among engineers and development practitioners, and to a search for more effective ways to design and apply technology. Some engineers recommend that technologies be codesigned in collaboration with the communities they are meant to benefit (Brewer et al. 2005). Others suggest an emphasis on training and partnership to ensure that users have and know what they need to take advantage of a technology (Chib and Zhao 2009). Still others emphasize that systems are sociotechnical; good outcomes require a combination of design decisions and institutional choices that account for each other (Dearden and Rizvi 2009). Almost everyone agrees that that the social context in which a technology is used is as important as the technology itself.

One way to encapsulate these insights is to see that technology does not add a fixed benefit wherever it is adopted; rather, it amplifies underlying human forces (Toyama 2015). Where those forces—social, political, cultural, economic—are capable and well intentioned, technology can make things better, but where they are ineffective or dysfunctional, even the best-engineered technology cannot turn things around. Where human forces are corrupt or repressive, adding powerful tools can even make things worse.

The Next 50 Years: Reconsidering Assumptions

What will the next 50 years bring? On the one hand, technological advances will continue, with improvements in artificial intelligence, robotics, device affordability, and miniaturization, among others. It is less clear whether there will be nanorobots that hunt down malarial mosquitoes, embedded chips that allow direct brain-to-brain communication, or learning machines that "teach" mathematics through noncontact synaptic induction.

Technology does not add a fixed benefit wherever it is adopted; rather, it amplifies underlying human forces.

But if future technologies are difficult to predict, the law of amplification allows some prediction about their societal impact. If global politics and economic institutions continue largely as they are, no technology in the future will eliminate poverty, heal the rifts of inequality, rein in climate change, or ensure sustainability.

In fact, each new technology may exacerbate existing problems. Technologies of productivity will be appropriated by wealthy capitalists, even if some trickle down to the masses. Technologies of sustainability will be restrained for their perceived harm to existing businesses, even if they could reverse the ravages of the Anthropocene. And technologies of entertainment and consumption will provide an opiate for all as the world lurches from crisis to crisis.

Those projections, of course, assume current politics and capitalism. Beginning in the 1940s, the scientists who ushered in the nuclear age foresaw the threat of a world armed with atomic weapons. Adding their collective voice to those of activists, they lobbied national governments to contain the technology; their efforts culminated in the Nuclear Non-Proliferation Treaty of 1970. A half-century later, only nine countries have nuclear weapons—an astonishing political feat.

Another half-century from now, what technologies will be available are anyone's guess. But for the products of engineering ingenuity to contribute to sustainable development, underlying human forces must be righted. For that, engineers will need to engage in their capacity not only as designers, architects, and scientists but as global citizens and activists.

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Building the Nexus Between Electronics and the Human Body for Enhanced Health

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Over the past few decades information technology (IT) has suffused every corner of society and reshaped the way people live, communicate, work, and entertain themselves. The next 50 years are likely to yield another generational change in electronics, and corresponding changes in people's lives.

A major recent trend is the creation of electronics, including stretchable microchips, that can be integrated, even merged, with the human body (Chu et al. 2017; Kim et al. 2011; Wang et al. 2018a), expanding the role of IT from obtaining information for human use to obtaining information from the human body.

A nexus between electronics and the body, with its rich quantity and diversity of information, will significantly enrich technological approaches that can benefit people's life and health (figure 1). To achieve this, the conventional silicon electronics in planar and rigid form factors need to give way to a new generation that possesses multiaspect similarity and compatibility with the human body (Ray et al. 2019; Someya et al. 2016; Wang et al. 2018b).

Projected Benefits

The ability to easily obtain different types of information from the human body—from movements and vital signs to organ conditions and brain

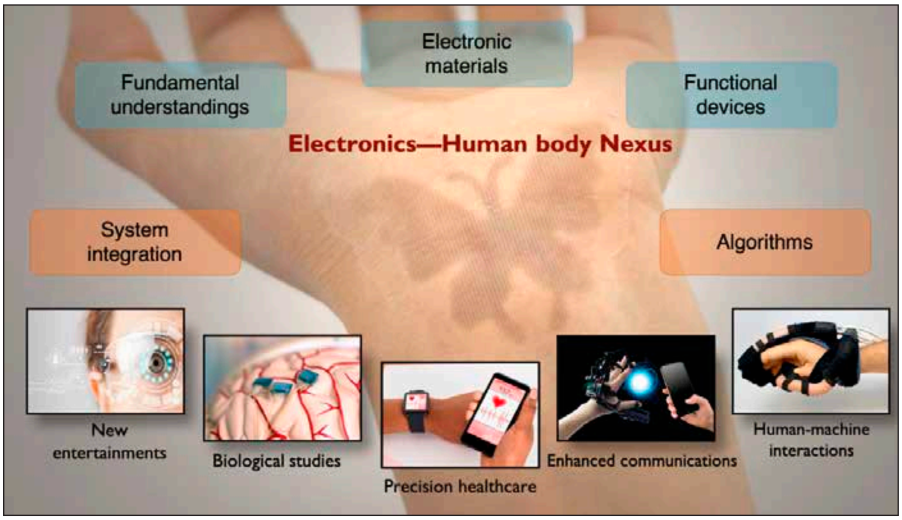

FIGURE 1 Building the nexus between electronics and the human body, as the technological basis for the future of information technology: areas of technological challenges and application impacts.

activity—could enable a number of improvements in people's life and health.

Ubiquitous and Precision Health Care

Continuous access to complex and rapidly changing health data (e.g., body temperature, blood pressure, breathing rate, perspiration composition) can enable constant monitoring of health conditions, early diagnosis of diseases, and preventive and point-of-care treatments. Moreover, the accumulated big data of an individual's health history can provide a record and understanding of health characteristics to support precision medicine.

Deeper Understanding of Human Biology

With the technological feasibility of high spatiotemporal resolutions, it will be possible to decipher mysterious biological mechanisms of the body in both healthy and diseased states. In particular, important discoveries can be made about pathogenic causes of complicated diseases to guide the development of more effective treatment methods.

Remote Physical Interactions

The major challenge in current remote communication approaches and face-to-face interactions is the lack of direct physical interaction. In the future, the development of electronics for collecting physical information in real time could add this missing piece to communication technology, so that a "handshake" can happen between two persons at different locations and physical therapies can be carried out remotely.

Technological Challenges

To achieve the collection of high-fidelity, stable, and multi-type information about an individual's physical health over a long period, electronic devices need to have a suite of properties that enable conformable attachment, minimal side effects, and long-term function. Notwithstanding some groundbreaking efforts, significant research and development progress are needed in the following areas.

Fundamental Understanding of Material-Biology Interfaces

For the relatively simple scenario of interfacing electronics on the body (i.e., on the skin), it is generally understood that the matching of mechanical properties is the primary requirement for electronics. However, for the more complicated case of implanted electronics, systematic studies and knowledge are still largely lacking about the relationships between electronic materials' physicochemical properties and long-term biocompatibility.

Generation of New Electronic Materials

The large variety of electronic devices (e.g., transistors, light-emitting diodes, biosensors, actuators) are built on different functional properties of materials. Although some successes have been achieved for combining certain electronic functions (e.g., semiconducting and conducting properties) with biocompatible form factors (Kayser and Lipomi 2019; Xu et al. 2017), new material designs must be created for the effective integration of the rest of the functional properties.

Because biological tissues are primarily composed of biopolymers, polymers are the most favorable material family for achieving the desired biocompatibility. To realize advanced functions, polymers with biocompatible designs will have to provide functional properties on par with their rigid counterparts.

New Device Designs and Fabrication Methods

Operations on or in the human body and uses of new classes of materials may exclude the use of many existing device designs for certain applications. Thus, new device designs—and even new working principles—are needed to ensure desired performance with the simplest device and system architectures possible.

Devices need to be designed to perform reliably, undistorted by the body's mechanical and chemical conditions. And for the new class of electronic materials, fabrication methods (Kaltenbrunner et al. 2013; Wang et al. 2018a) need to move away from microfabrication for silicon electronics and to confer large-area scalability, low cost, and batch-to-batch uniformity.

Sustainable and Biocompatible Power Sources

As an integral part of electronic systems, power sources must have biocompatible properties. Batteries (Liu et al. 2017; Xu et al. 2013) need to be stretchable and made of nontoxic chemicals, while still providing enough energy density.

With the very limited options of recharging or replacing batteries, on-body generation of electricity through energy harvesting will be needed (Jiang et al. 2020). Efficiencies and power outputs need to satisfy power requirements by functional modules.

The possible impacts of energy harvesting on biological processes over the long term need to be carefully studied as well.

High-Throughput and Trainable Data Processing

To make full use of continuously produced, large-quantity health data from each individual, artificial intelligence (AI) needs to be built into data-processing algorithms. For faster speed and better reliability, such AI algorithms should be implemented by human-compatible computational chips, which require development based on emerging architectures (e.g., neuromorphics) that are especially efficient for AI (Burr et al. 2017; van de Burgt et al. 2018).

System-Level Integration Strategies

For different functional modules (e.g., sensing, data conditioning and computation, wireless communications) in fully integrated electronics for acquiring information from the body, application-specific requirements for the performance parameters (e.g., speed, bandwidth, energy consumption) must be clearly defined. In particular, notwithstanding substantial research progress in the use of both conventional inorganic materials and emerging functional polymers to build human-integrated electronics, their overall suitableness for different functions is still unclear.

Societal and Cultural Challenges

It won't be trivial to persuade people to accept the long-term attachment or implantation of electronics to or in their body to acquire information. It will be essential to clearly communicate the benefits of accessing the information.

Protocols for protecting the privacy and security of personal physical data will be critically important.

In addition, the best approaches for using this previously unavailable health data need to be studied and guidelines established for the use of these data. Protocols for protecting the privacy and security of the data will be critically important. Not least, the public needs to be better informed about science and technology, to allay fears and misconceptions about technology.

Perspective for the Future

Human-integrated electronics are likely to become an important part of the electronics and health industries over the next 50 years. Wearable electronics alone are projected to have a market value of about $150 billion by 2026 (Hayward et al. 2016).

The successful commercialization of new types of electronics with novel applications for the human body can be expected to significantly enhance quality of life and increase lifespan. The path to get there requires deep collaborations between academia, industry, and government.

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Desalination Innovations Needed to Ensure Clean Water for the Next 50 Years

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In stark contrast to progress on almost all the UN Sustainable Development Goals, clean water supply and safety issues are worsening globally, threatened by groundwater depletion, shrinking glacial melt, major rivers running dry, increasing salinity of soils and groundwater, more dangerous and tenacious waterborne pathogens, worsening water pollution with new emerging contaminants, and more frequent conflicts around water (Boretti and Rosa 2019; Gunasekara et al. 2014; Mekonnen and Hoekstra 2016). And the challenges are widespread: today 3.6 billion people face water scarcity for at least part of the year (Mekonnen and Hoekstra 2016), and this number is expected to grow to ~5.6 billion by 2050 (Boretti and Rosa 2019).

To address this crisis, the global water supply must be substantially increased through the purification and reuse of water from large sources that have salts or small contaminants. This purification is called *desalination*, but the term applies to any water process that removes the smallest compounds.

Needed Technological Improvements

Although use of desalination has emerged rapidly in some parts of the world, there remain significant barriers. These vary by location, because water is typically a local resource (long-distance water transport is expensive and requires energy-intensive pumping), and by whether a system is inland or seaside and whether it is a large-scale grid-connected or remote off-grid system. Barriers to the widespread use of desalination must be overcome with new technological solutions.

High-Salinity Capabilities

Current desalination technologies are competitive for seawater and mild-salinity groundwater in many regions, but they are rarely economically viable for treating salinities beyond seawater brine (i.e., >7 percent salt by weight; Swaminathan et al. 2018). This challenge is particularly important for inland regions where there is no large body of water (such as the ocean) for disposal of the brine.

Current desalination technologies are rarely economically viable for treating salinities beyond seawater brine.

Technologies for inland application require extremely high recovery of the pure water and, ideally, the ability to dispose of the solutes as solid waste (so-called *zero-liquid discharge*, ZLD) (Tong and Elimelech 2016). To achieve ZLD, technologies need to have much better prediction and control of salt crystallization to avoid forming blocking layers on membranes (Warsinger et al. 2015) or heat exchangers (Tong and Elimelech 2016), depending on the technology. Unfortunately, the energy requirements of these high-salinity technologies dominate costs and must decrease dramatically through efficiency improvements.

Resource Recovery

The byproduct streams of high-concentration desalination are not just another waste product: with proper approaches they can be used to recover valuable salts and resources from saline sources. Such resources would include not only specific salts such as easier-to-extract magnesium but also, potentially, highly sought elements like gold and lithium. Selective removal of these compounds will require new and improved versions of technologies such as crystallization, electrodialysis, and ion-selective membranes (Tong and Elimelech 2016).

While today resource recovery from desalination is minimally used, to be sustainable and widely cost competitive, large or inland desalination must capitalize on this option to extract resources while minimizing potential contaminants (Du et al. 2018).

Renewable Integration and Time-Varying Capabilities

A major challenge for desalination technologies is their integration in a changing and more renewable electric grid while minimizing their CO_2 production. Current large-scale desalination plants run as steady-state baseload power electricity users. However, as grids become more dependent on renewable energy sources, it may become uneconomical to run desalination plants during peak demand (in Israel some plants idle operation in those scenarios; Dreizin 2006).

Desalination must switch to adaptive, time-varying technology to improve efficiency and meet the needs of renewable power through, for example, demand response and salinity-gradient power using desalination system components for peak prices. Approaches will include process innovations, such as novel components for batch desalination (Warsinger et al. 2016), as well as modified and new control methods and other components (e.g., pumps and energy recovery devices) to run in varied operating conditions (Khiari et al. 2019).

The control and optimization of time-varying desalination will be a major target for innovations in artificial intelligence (Dudchenko and Mauter 2020).

Better Membrane Technology

Current membranes for some desalination technologies, such as reverse osmosis, as well as pretreatment steps are highly effective. However, membranes still need further research and development.

Reverse osmosis membranes don't block small uncharged solutes well, such as boron (in the form of boric acid) and disinfection byproducts like NDMA (N-nitrosodimethylamine; Al-Obaidi et al. 2018; Warsinger et al. 2018). Other membrane-based technologies, such as membrane distillation or forward osmosis, require significant improvement before full-scale deployment.

Most membrane technologies also need further chemical modification and surface design to minimize membrane fouling (She et al. 2016), more resistance to destructive cleaning chemicals, and they may benefit somewhat from increases in permeability. Resilience to high pressures remains a challenge for reverse osmosis membranes in particular (Davenport et al. 2018).

Other Innovations

Widespread adoption of desalination will depend on a variety of additional innovations in pre- and post-treatment and in the operation of these systems. For example,

- Better control of biological and other types of membrane fouling is needed; innovative areas include novel cleaning compounds, backwashing processes, phage-based technologies, and reactive nanoswimmers.
- Novel catalytic processes may destroy emerging contaminants and provide safe reject brine (Hodges et al. 2018; Warsinger et al. 2018).
- Substantial process intensification will improve performance by combining different driving forces (e.g., pressure, heat, electric fields) with reactive systems.
- New manufacturing techniques, including additive manufacturing, will be key in making membrane modules that minimize concentration gradients, pressure losses, and fouling.

The Future

As water supplies decline in quantity and quality, demand is increasing because of population growth, shifts to meat-based diets, population concentrations in cities, and economic growth. The need for safer water, water reuse (Warsinger et al. 2018), and expanded water supplies means that much of the world's water treatment will need to include desalination membranes. Although it is a scarce technology today, desalination will one day be a ubiquitous cornerstone of the world's clean water.

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Future Directions for Cybersecurity Policy

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Fifty years feels almost unimaginably long in internet time. Fifty years ago, the ARPANET was barely a year old; Ray Tomlinson had not yet sent the first email, Vinton Cerf and Robert Kahn had not yet published their seminal paper on the protocol that would become TCP/IP, Tim Berners-Lee had not yet invented the World Wide Web—the online world looked nothing like the one we know today, and the word "cybersecurity" wouldn't be introduced for nearly another 20 years.

Viewed in that light, trying to predict the technological landscape of the internet and cybersecurity a half-century from now is an almost impossible task. But 50 years is not nearly so long when it comes to considering the policy landscape for cybersecurity and the ways that regulators around the world will define, solidify, and implement approaches to securing the internet in their respective countries in the coming decades.

The Case for Reduced Connectivity

Even if the precise technology underlying how computer networks will work in the future is difficult to predict, certain trends seem inescapable, such as the increasing internet connectivity of existing infrastructure, from cars to personal home electronics to industrial manufacturing machinery. Networking these devices will enable tremendous efficiency, convenience, and safety—but it will also create new opportunities for cyberattacks and vastly raise the stakes of accidental technological failures.

To strengthen cybersecurity over the next several decades, technology designers will have to focus on segmenting the networks connecting different devices and think seriously about which of the ever growing number of interconnected devices actually need to be able to communicate with each other. Ideally, 50 years from now, those connections will be much more restricted, so that an adversary who compromises one device is not then able to easily compromise thousands of others.

This approach of restricting the connections between different types of devices will appear, at times, to go against current trends toward greater interconnectivity and convenience, such as being able to turn on your car from your smartphone. But a future in which every new device that comes online can communicate with every other device will create much greater risks for all of those machines and their users than will isolating device connections according to their functions.

How and when technology developers begin to set boundaries on which types of devices can interconnect with each other and how effectively they implement those borders will be one of the crucial determinants of the future of cybersecurity. Thinking about cybersecurity will have to shift from a focus on preventing breaches and eliminating vulnerabilities to limiting the spread of breaches and minimizing the negative impact of any individual vulnerability beyond the borders of its own system.

Role of Regulation

Artificial intelligence (AI) will also play a significant role in what cybersecurity looks like 50 years from now. AI can be both an adversarial technology, when algorithms are used to identify vulnerabilities and circumvent defensive technologies, and a target for adversaries trying to undermine or alter sophisticated machine learning algorithms, such as those used by cars to detect traffic signs.

To secure AI, it is essential to be able to identify when algorithms are being tampered with in ways that will provide incorrect recommendations or results. This ability will require significant advances not just in explainable AI technology but also in regulatory requirements to implement and audit that technology. The more decision making is outsourced to computer systems, the more cybersecurity efforts will come to focus on safeguarding those systems and the integrity of the decisions they make rather than protecting individuals' money or companies' stores of sensitive or proprietary data.

Both of these trends, toward more networked devices and more automated decision making, will require regulators to think seriously about the question of who is responsible when security compromises occur, as they inevitably will.

The goal of policymakers in the coming decades should be to establish a liability regime that both makes clear who is responsible for which elements of negative cybersecurity incidents and aligns penalties with the stakeholders who are in the best position to mitigate the consequences of those incidents. Clarity about these responsibilities will create stronger incentives for all stakeholders—from software developers and hardware manufacturers to internet service providers and Domain Name System (DNS) server operators—to secure their respective components of the internet ecosystem.

Ideally, future device connections will be much more restricted, so that an adversary who compromises one cannot do so to thousands of others.

A liability regime will also enable insurers to provide clearer coverage for cybersecurity incidents tailored to the roles and responsibilities of individual customers, and help individuals harmed by such incidents to pursue legal remedies against the appropriate parties.

Different countries may define liability for cybersecurity incidents in different ways, as is beginning to happen even in the absence of very clear responsibilities in most places. Despite the current push for global norms and standards for cyberspace, it seems unlikely that the future of cybersecurity lies in defining globally accepted norms, but rather in countries getting better at leveraging their own domestic laws to have outsized, international impacts on the internet through the regulation of global intermediaries and service providers.

International Fragmentation of the Internet

The fragmentation or balkanization of the internet that has been heralded for years seems less likely to arrive through a definitive fracturing of the internet's technical infrastructure—the globally used protocols for transmitting information, for instance, or the DNS root zone—than through a gradual, steady divergence in the ways that different countries regulate and restrict online services.

In many ways, fragmentation should be the goal in the future:

- fragmentation of the current internet into many internets that each serve particular, segmented purposes
- fragmentation of sophisticated AI algorithms into explainable and auditable components
- fragmentation of responsibility for complex cybersecurity breaches into many smaller subresponsibilities for the different involved stakeholders
- fragmentation of global cybersecurity regulations according to different countries' priorities and ideas about what a secure internet should look like.

Fundamentally, the future of cybersecurity will involve recognizing that there are multiple visions and finding a way for them to coexist on the global internet.

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