Spring 2018

INTERNATIONAL FRONTIERS OF ENGINEERING

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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

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The BRIDGE

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LINKING ENGINEERING AND SOCIETY

Editor's Note

Features

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Editor's Note

Janet Hunziker directs the NAE's Frontiers of Engineering program.

Expanding the Frontiers Internationally

After the winter issue of *The Bridge* featured papers from the 2017 US Frontiers of Engineering (FOE) symposium, the FOE program gets another turn in the spotlight with this issue featuring papers primarily from the bilateral FOE meetings.

The NAE has five bilateral FOE programs: with Germany, Japan, India (currently on hiatus), China, and the EU. These meetings are held biennially, with the exception of the EU-US FOE, which is held twice every three years. The NAE works with a number of wonderful partner organizations to carry out these events: the Alexander von Humboldt Foundation, the Engineering Academy of Japan, the Indo-US Science and Technology Foundation, the Chinese Academy of Engineering, and the European Council of Applied Sciences, Technologies, and Engineering.

Each 2½-day symposium covers four topics of mutual interest determined by the symposium cochairs and an organizing committee composed of early-career engineers from both sides plans the program. To facilitate cross-cultural exchange, the bilateral FOEs are smaller than the US event, with 60 (instead of 100) attendees, 30 from each side, but the format is similar, with four topic sessions, poster sessions, technical or cultural tours, and many opportunities for informal interactions. Locations alternate between the United States and the partner countries.

It was only a few years after the first US FOE symposium in 1995 that the NAE received an inquiry from the German-American Academic Council Foundation (GAAC) about starting a joint FOE program, resulting in the launch of the German-American FOE (GAFOE) symposium series in 1998. When the GAAC was disbanded a few years later, the Alexander von Humboldt Foundation assumed partnership responsibilities, making GAFOE the bilateral FOE program with the longest history. Additional bilateral FOE programs were started in subsequent years: with Japan (2000), India (2008), China (2009), and the European Union (2010).

There are over 4,000 alumni of the Frontiers of Engineering program worldwide. The 95 FOE alumni elected to the NAE since the Frontiers program's inception include 12 speakers at bilateral FOEs. Other outcomes reported by bilateral FOE alumni include exchange visits and joint projects. In fact, a US attendee of the 2003 GAFOE recently informed us that she is still collaborating with a German researcher she met at the meeting.

Furthermore, based on their experience working with the NAE, some of our partner organizations have started their own Frontiers programs with other countries. For example, the Humboldt Foundation has Frontiers of Research programs with Brazil, Great Britain, Israel, India, Japan, and China. And the Royal Academy of Engineering has a Frontiers of Engineering for Development with participants from developing countries.

The primary US sponsors for the bilateral FOE meetings are The Grainger Foundation and the National Science Foundation. In addition, the US programs could not have continued without the support of the Department of Defense, DARPA, Microsoft, Cummins, individual donors, and US companies and institutions that have stepped up to host the meetings. For example, GE Aviation and the University of California, Davis, hosted the 2017 GAFOE and 2017 EU-US FOE, respectively.

The six papers in this issue reflect the breadth of topics covered at Frontiers of Engineering meetings. At the 2017 GAFOE symposium, in a session on gene editing and its applications, Luisa Bortesi (Maastricht University) gave a presentation on tailor-made plants using next-generation molecular scissors. In her paper she describes site-specific nucleases, which can be thought of as "molecular scissors" that can be programmed to cut DNA at a predetermined site on the genome. The CRISPR/Cas system is the most promising of these. When the technology is applied to plants, it can introduce mutations that enlarge grain size to increase crop productivity, change flower color, or make a plant pathogen-resistant. Bortesi's article introduces the applications, drawbacks, and future outlook of this technology, with an emphasis on use in plants.

The next paper, by Gabrielle Gaustad (Golisano Institute for Sustainability, Rochester Institute of Technology), was delivered in a session on energy storage at the 2017 China-America FOE. Her presentation covered end-of-life and recycling issues related to energy storage devices—lithium ion batteries (LIBs), in particular—from a sustainability perspective. She notes that since their introduction for commercial use in the 1990s, LIBs are now used in a variety of consumer electronic devices such as laptops, cell phones, digital cameras, e-readers, and electric vehicles. As a result, sustainability challenges such as depletion of critical metals and minerals and end-of-life waste management have emerged. Her paper identifies options for reuse, remanufacturing, and recycling in order to distribute costs and reduce overall environmental impacts.

Branko Kerkez (University of Michigan) also presented at the 2017 GAFOE meeting, in the session titled Streams of Water and Information: Managing Water Supply, Treatment, and Delivery in the 21st Century. In his paper he describes how the Internet of Things in the form of real-time monitoring and data analytics can reshape the management of water systems. For example, information technology can play an important role in monitoring and maintaining drinking water treatment and conveyance systems, which account for nearly 2 percent of the US energy budget. Managing pollutants in storm water is another critical issue. In lieu of replacing aging infrastructure, technologies utilizing wireless nodes, sensors, and valves can be deployed to existing systems to remotely control water flow. Embedding intelligence in the management of water systems will be an important factor in meeting the NAE Grand Challenge for Engineering of restoring and improving urban infrastructure.

What if travel through the solar system could be made faster and more affordable by a revolutionary propulsion method? Sini Merikallio (with the Finnish Meterological Institute at the time of her presentation), described such a possibility in the 2017 EU-US FOE session on technologies for space exploration. In her paper (coauthored for this issue with Pekka Janhunen), she explains the electric solar wind sail, or E-sail, which is based on Coulomb repulsion between a positively charged sail interacting with solar wind protons. She highlights several possibilities that could be realized with this new propulsion method, such as supporting manned flights to Mars, towing away an asteroid on a collision course with Earth, and traveling to and from near-Earth asteroids for mining operations or to gather samples for scientific study. One spin-off from the E-sail technology, the "plasma brake," could be used to deorbit satellites at the end of their lifetime. With an E-sail payload currently waiting to be tested, this technology may be deployed for solar system research within a decade.

The final paper in this issue is by Michael Ramage (University of Cambridge) and was presented at the 2017 US FOE session on megatall buildings. As more of the world's population moves to urban areas, high-rise and megatall buildings will become a growing part of the built environment. Ramage discusses the use of engineered timber as a substitute for steel and concrete in structures higher than previously thought possible. He notes that the first generation of these buildings demonstrates that it is possible to envision a future where the built environment is synergistic with nature and a high quality of life.

NAE president Dan Mote refers to Frontiers of Engineering as an "evergreen" program. Because the topics and attendees of each meeting are different, the engineering areas that are covered reflect emerging fields and changing societal priorities. Now in its 24th year, the FOE program retains its relevance as a mechanism for bringing people together to facilitate collaboration across engineering fields and national boundaries. And of course, as with most things, the vitality of the program is due to people—the NAE members, many of whom are FOE alumni themselves, who chair the symposium organizing committees, and the early-career engineers who plan and participate in the meetings, then integrate that experience and the connections they've made into their research and technical work.

Plant genome editing represents an invaluable tool to rapidly and effectively address sustainability challenges.

Tailor-Made Plants Using Next-Generation Molecular Scissors

Luisa Bortesi

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When people hear the words "mutation" or "mutant," they usually associate them with something negative (e.g., a disease) or even evil (as in a science fiction movie). But mutations are simply changes or variations, which are not inherently positive or negative. As a matter of fact, mutations are the basis of evolution and biodiversity and are often favorable. And mutations are the essence of agriculture.

The variety of traits found in nature reflects random genetic changes that are often the result of mistakes in the repair mechanism initiated after DNA damage. Mutations effected through genome editing can confer resistance to pests, increase biomass, remove allergens, and enhance adaptability to changing environmental conditions such as drought. Such mutations can help improve product quality and yield, reduce costs, and protect the environment.

Background

Since the practice of agriculture began about 10,000 years ago, humans have tried to adapt plants to their convenience, identifying and crossing varieties with traits that were beneficial or advantageous. For a long time, adaptations were achieved only by observing and selecting plants that were naturally available, collecting the seeds of those that looked best and propagating them over generations of seedlings. This practice came to be called plant breeding, and in this paper is referred to as conventional breeding.

In the late 1920s it was discovered that the occurrence of "natural" variability could be increased by exposing plants to radiation or chemicals that cause extensive DNA damage and thus mutations (Stadler 1928). This process was called mutation breeding. The findings both considerably expanded the range of useful traits available for breeding and accelerated the establishment and release of new, improved plant varieties, many of which now show up on the dinner table every day.

However, with mutation breeding many genetic changes are induced randomly, which means that it is still necessary to screen a large number of individual plants to identify those (if any) carrying the mutation in the gene of interest. Furthermore, it may not be clear what alterations might result from all the other randomly induced mutations.

The long-sought solution to these problems came about in the 1990s with the discovery of site-specific nucleases (SSNs), a sort of sophisticated "molecular scissors" that can be programmed to cut DNA precisely at a predetermined site (Kim et al. 1996), enabling the directed introduction of changes (mutations) in the target gene. This technology is called genome (or gene) editing.

"Molecular scissors" can be programmed to cut DNA at a precise site to create specific changes in the target gene.

CRISPR/Cas9: First the Gene Is Cut…

The first programmable molecular scissors had limited applicability because protein engineering was required to "program" them, a capacity available in only a few specialized laboratories. The real breakthrough came in 2012 with the development of a particularly efficient SSN based on the clustered regularly interspaced short palindromic repeats (CRISPR) and CRISPR-associated protein 9 (Cas9) system (for a review of this technology, see Bortesi and Fischer 2015).

The principle behind the CRISPR/Cas9 system is quite simple. The system works like a vaccination for bacteria: when a bacterium is infected by a virus, it retains a short piece of the viral sequence and uses it to recognize and destroy the virus by efficiently and quickly cleaving its DNA.

What makes the CRISPR/Cas9 system such an exceptional and interesting tool for genome editing is that no complex protein engineering is necessary to change the specificity: all one needs is the Cas9 protein, which is activated upon interaction and binding with a short piece of RNA called the single guide RNA (sgRNA). The activated Cas9/sgRNA complex locates the target site by scanning genomic DNA for sequences complementary to a short stretch in the sgRNA. With changes to just 20 nucleotides (or bases) in the sgRNA, the system can be "programmed" to cleave any sequence of choice and only that sequence (figure 1). In other words, scientists now have a simple instrument that makes it possible to identify and cut precisely 20 base pairs among, for example, the approximately 840 million that make up the potato genome.

Since nowadays one can order 20-base-long nucleic acids for a few dollars and get them the next day, it becomes clear what a simple yet potent tool the CRISPR/Cas9 system represents. Part of its power comes from the fact that, because it's so easy and cheap to change the specificity, one can test several sequences at the same time and select only the most efficient one for study. This is why researchers worldwide jumped on this technology and many even approached genome editing for the first time.

A further advantage of the CRISPR/Cas9 system over other SSNs is that it allows researchers to easily target multiple loci at the same time, a concept called multiplexing, by using multiple sgRNAs with different sequences for each target (figure 1). This feature is especially important for crop improvement, because most of the relevant agronomic traits, such as yield, quality, and stress response, are jointly regulated by many genes.

…Then It's Repaired

Once the DNA is cut it has to be repaired, and the different possible outcomes of the repair process can be exploited for various applications (figure 2).

Plants mostly repair a DNA break by "stitching" the loose ends together via an error-prone process called nonhomologous end joining, which frequently results in the modification (mutation) of one or several random base pairs at the cut site (figure 2a). The nature of these modifications cannot be predicted and often destroys

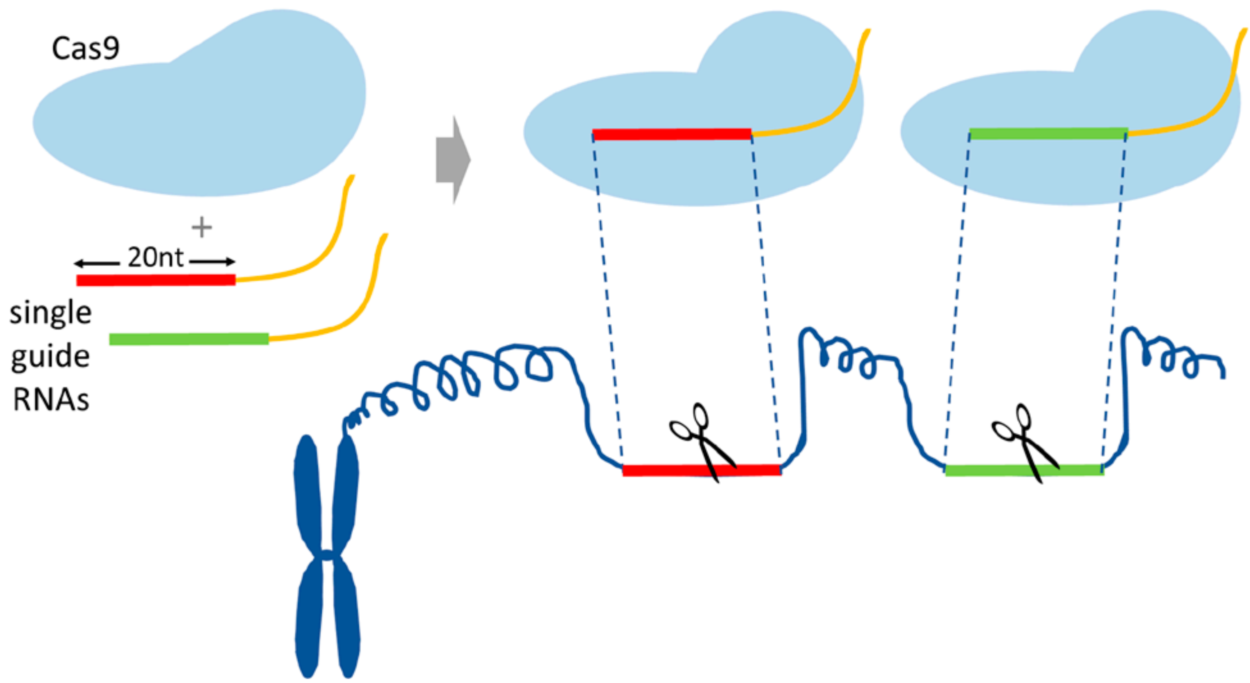

FIGURE 1 The CRISPR/Cas9 system for genome editing requires one type of protein (Cas9) and one or more single guide RNAs (sgRNAs) that determine the 20-nucleotide (nt) sequence to be cut (red and green lines). When Cas9 and an sgRNA assemble together they form an active complex, which scans the whole genome to recognize and cut the target sequence determined by the 20 nucleotides in the sgRNA. With the use of several different sgRNAs, the CRISPR/Cas9 system can cleave multiple targets simultaneously in a process known as multiplexing. To reprogram the scissors for a different site, one simply changes the 20 nt sequence in the sgRNA, which costs only a few dollars and can be done in a couple of days. Not drawn to scale.

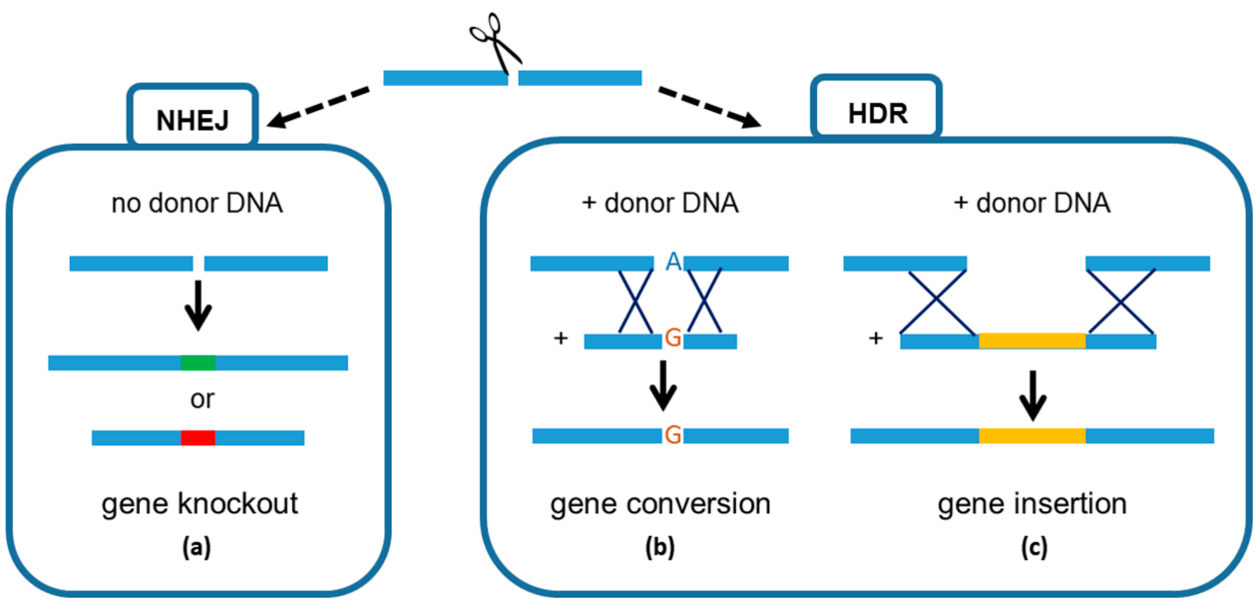

FIGURE 2 Genome editing with molecular scissors. When programmable molecular scissors such as the CRISPR/Cas9 system are used to cut DNA at a specific site, it can be repaired by either nonhomologous end joining (NHEJ; left) or homology-directed recombination (HDR; right). Repair by NHEJ is the most frequent and usually results in the insertion (green) or deletion (red) of random base pairs, abolishing the gene's function and generating a gene knockout **(a)**. With HDR, a short donor DNA template, differing for only one or a few nucleotides, can be used to introduce precise mutations through gene conversion **(b)**. With a large DNA donor (>1,000 bases) it is possible to achieve targeted gene insertion **(c)**. Homology regions involved in the recombination are indicated with large Xes.

the function of the gene, generating a gene knockout (KO).

When DNA is cut in the presence of a small piece of exogenously supplied ("donor") DNA that matches the sequence around the break but for a few mutations, the plant can (but doesn't necessarily) use it as a patch to repair the break. Through this process, called gene conversion, researchers can determine not only the position but also the nature of the resulting mutation (figure 2b). Such homology-dependent repair is technically more difficult, but it affords control of the outcome and can be useful to, for example, change or fine-tune the expression of a gene instead of completely destroying it.

Under certain conditions one can even induce a plant to use a much larger piece of DNA as a patch to repair the break, thereby introducing a new gene (or a whole new metabolic pathway) at a precise location (figure 2c). This offers an unprecedented way of controlling the insertion of foreign DNA, in contrast to the usual way of generating transgenic plants, which, relying on random integration in one or multiple genomic locations, risks compromising some essential functions of the plant or altering its metabolism in unpredictable ways.

Why Are Programmable Molecular Scissors Needed?

Conventional breeding is limited by the fact that it relies on existing genetic variation and requires lengthy backcrossing to introduce selected traits into elite lines (these are the best lines, with many positive features—especially, among agronomic traits, high yield). Mutation breeding using radiation or chemicals increases genetic variation but requires extensive screening and, again, lengthy backcrossing.

Using the SSN approach, both drawbacks can be overcome by expanding and explicitly controlling the genetic variation. The outstanding advantages of this technology are not only high efficiency and relative simplicity but also the remarkable precision and speed with which desired mutations can be achieved compared to conventional or mutation breeding (table 1).

Genome editing for crop improvement mostly aims to increase biomass, boost uptake of soil nutrients such as phosphorus and nitrogen to reduce both the costs (of purchase quantities and application) and environmental pollution associated with the use of fertilizers, or confer resistance to pests to improve product quality and yield while limiting the use of toxic pesticides.

Knockouts are the simplest and most frequent outcome of genome editing in plants. They are very useful for studying the function of a gene and can also have important practical applications. For instance, by simply knocking out a plant gene essential to a particular viral infection it has been possible to generate a resistant cucumber variety (Chandrasekaran et al. 2016), and a significant increase in rice yield was achieved by the simultaneous KO of three genes that restricted grain weight (Xu et al. 2016). The latter is an example in which speed of mutation and multiplexing are striking advantages, because several genes had to be modified to obtain an appreciable trait improvement.

The use of SSNs such as the CRISPR/Cas9 system also enables targeted molecular trait stacking, the combination of multiple, otherwise segregating traits at a specific position in the plant genome. For example, maize genes that confer greater drought tolerance, dis-

TABLE 1 Pros and cons of conventional breeding, mutation breeding, and site-specific nuclease–mediated genome editing

	Conventional breeding	Mutation breeding	SSN-mediated genome editing
PROs	• Established practice	• Expanded genetic variability • Long history of safe use • Clear regulatory framework	• Expanded genetic variability • Targeted mutations • Speed • Multiplexing
CONs	• Limited by existing genetic variation • Lengthy backcrossing	• Random mutations • Selection required • Lengthy backcrossing	• Off-target mutations (low risk) • Inadequate regulatory framework • Uncertain patent landscape

ease resistance, and yield could be stacked in an elite variety either simultaneously or in subsequent rounds of targeted integration. And the entire array of genes could thus be mobilized into another germplasm by simple crossing because it would behave as a single locus. This would eliminate the need to introduce one trait at a time via conventional breeding and would avoid excessively lengthy timescales and severe downstream breeding challenges (e.g., from extended backcrossing to eliminate unwanted genomes while ensuring inheritance of desired trait[s]).

Besides conventional agriculture for food, feed, or fuel, plants can be used for molecular farming (as production platforms for biopharmaceuticals, technical proteins, or small molecules; Arora and Narula 2017; Tschofen et al. 2016) or as a source of bio-based materials, such as rubber, starch, cellulose, and lignin. In this context, SSN-mediated genome editing is a valuable tool to rapidly optimize plants and plant cell cultures by, for example, eliminating potentially immunogenic plant-specific glycans for the production of pharmaceuticals (Hanania et al. 2017; Mercx et al. 2016), improving the composition of starch for industrial applications (Andersson et al. 2017), or diverting a metabolic pathway to boost the accumulation of valuable natural compounds (Alagoz et al. 2016; Li et al. 2017).

Last but not least, the ability to control integration of new genetic material in a so-called "safe harbor" (a site in the genome where a transgene is consistently and stably expressed with no adverse effects on the plant's fitness) via SSN-mediated targeted insertion may accelerate the development and possibly the approval of new transgenic lines for recombinant protein production.

Off-Target Effects

The use of SSNs and especially the CRISPR/Cas9 system may be accompanied by off-target effects, mutations that occur in sequences other than those intended to be modified. They are basically the only, albeit major, criticism of this technology.

While it is true that off-target mutations can happen and measures have to be taken to eliminate or reduce as much as possible their occurrence, it is also true that since the first use of CRISPR/Cas9, knowledge of the system has increased so much that in many cases it is possible to predict and prevent such mutations (Zischewski et al. 2017). Improvements in experimental design and protein engineering, for example, have substantially increased the fidelity of the CRISPR/Cas9 system. And recently identified anti-CRISPR proteins of viral origin can be used to switch off the system after it has done its job, to prevent random off-target cutting (Shin et al. 2017). In addition, plants as a whole have the following advantages:

1. Off-target effects are very rare in plants (Bortesi et al. 2016). Even without the application of high-fidelity approaches such as the use of improved Cas9 versions (Kleinstiver et al. 2016; Slaymaker et al. 2016), in all studies reported in the literature it was always possible to identify lines bearing the desired mutation(s) and no off-target effects.
2. Researchers can evaluate the outcome of genome editing in several plant lines and select only those that do not show unintended modifications.
3. Off-target effects can be eliminated by backcrossing, as is regularly done in mutation breeding with radiation or chemicals. The difference is that off-target effects are substantially fewer (if any) when the CRISPR/Cas9 system is used.

Improvements in experimental design and protein engineering have substantially increased the fidelity of the CRISPR/Cas9 system.

GMO Regulation

As highlighted above, SSNs such as the CRISPR/Cas9 system can be used for a variety of applications. Some are clearly transgenic, such as the targeted introduction of a new gene to produce a pharmaceutical protein. In other cases, the resulting plant may carry only mutations that are indistinguishable from naturally occurring ones or from changes induced through mutation breeding. These plants may or may not be regulated as genetically modified organisms (GMOs), depending on the country.

When GMO regulations were first conceived, the types of genetic modifications that researchers were able to perform were limited and transgenic plants constituted a clear and defined class of GMOs involving the stable introduction of foreign DNA. Now, with the advent of SSNs and the rapid evolution of genome editing technologies, it is possible not only to perform a great variety of modifications but to do so in multiple ways, transcending a single definition. For example, one can perform genome editing via an intermediate transgenic approach (i.e., introducing the transgenes to produce SSNs in a plant and then removing them through crossing once the desired modification has been achieved), or even do the whole procedure without introducing DNA at all (i.e., using the SSNs as proteins or RNA/protein complexes; Liang et al. 2017; Svitashev et al. 2016).

Product- rather than process-based classification of genome-edited plants would lower the prohibitive costs of regulatory approval.

Every jurisdiction that has considered the regulation of genetically modified products has had to choose whether to adopt a product- or process-based approach (Marchant and Stevens 2015). For example,

- Canada has adopted a strictly product-based evaluation of plants with novel traits, so it is the characteristics of the product that are scrutinized, not the process.
- The United States has a hybrid system: the regulatory trigger is process-based, but the risk assessment is product-based. Applications involving genome-edited plants are reviewed on a case-by-case basis.
- The European Union uses a process-based approach: products generated using recombinant DNA are subject to burdensome premarket risk assessment and approval, labelling, and traceability requirements (which do not apply to other products such as those created by mutagenesis), even if in the final product there remains no trace of foreign DNA and the modification is indistinguishable from naturally occurring mutations.

Given the importance of the topic and the challenges of applying the existing binary transgenic/conventional regulatory framework to products modified using these new genome editing techniques, the European Commission is evaluating the legal classification of "new plant breeding techniques," including SSN-mediated genome editing. Many academic scientists as well as seed and crop companies are urging a shift toward product- rather than process-based classification of genome-edited plants. This would lower the currently prohibitive costs of regulatory approval and could bring the commercialization of improved plant varieties within the reach of entities other than big multinational corporations.

Conclusions and Outlook

Given worldwide dependence on agriculture for food, feed, and fuel, and the increasingly urgent need to reduce dependence on petroleum, plant genome editing represents an invaluable tool to improve selected traits in elite cultivars, offering a rapid and effective means to address sustainability challenges. With the global population expected to top 9 billion by 2050, it is projected that the world's food production will need to increase by 60–110 percent. Worryingly, most of the land used to grow wheat, maize, and rice is endangered by the effects of climate change (Pugh et al. 2016).

The SSN-mediated genome editing technology is already mature and safe enough to be used in plants, with the possibility of selecting and backcrossing to eliminate unwanted mutations if needed. As a matter of fact, the CRISPR/Cas9 system has been successfully used for genome editing of single or multiple genes in a wide range of plant species, including not only model plants used for research but also important crops such as rice, maize, and wheat (Bortesi and Fischer 2015).

Since CRISPR/Cas9 was first used for genome editing, variants of the system have been discovered with features that may be desirable for different applications (Steinert et al. 2015). Recently developed hybrids use the flexibility and ability of the CRISPR/Cas9 system to guide an enzyme that can modify a nucleotide without causing a break in the DNA (Gaudelli et al. 2017).

While research is rapidly moving forward to optimize the technology and its implementation in plants, the main limitations to its widespread application beyond the lab seem to lie elsewhere (Brinegar et al. 2017). Inadequate regulatory policies in some countries may limit commercialization of genome-edited crops to the few large corporations profitable enough to afford the costs for regulatory approval. Negative public perceptions of genetic engineering may influence policymakers and pressure governments to ban cultivation of even approved crops, as happens in Europe. Last, uncertain intellectual property protection, due to a long-running legal battle over patents for CRISPR/Cas9 genome editing (Ledford 2017), may discourage companies to invest in this technology.

Given the ease and speed of creating new mutations, SSN-mediated genome editing has the potential to effectively and rapidly generate a quantum leap in crop yields. Importantly, the use of genome editing to improve the adaptability of plants to new environmental conditions could help to maintain the biosphere and even prevent the extinction of certain plant species.

The question is not whether the use of programmable molecular scissors and other methods of genome editing to modify plants will have an impact on society, but when and where.

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The dynamic variety and growing use of lithium-ion batteries call for research and policy measures to ensure their safe disposition.

Lifecycles of Lithium-Ion Batteries:

Understanding Impacts from Material Extraction to End of Life

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Since lithium-ion batteries (LIBs) were introduced for commercial use decades ago, they have quickly become the most popular power source for a wide variety of products. Their comparatively high power and energy densities make them an excellent source of power for consumer electronic devices and mobile applications in particular, including laptops, cellphones, digital cameras, electronic readers, and portable power tools.

More recently, the demand for LIBs has increased significantly with their use in electric vehicles (EVs). This rapidly growing demand may bring sustainability challenges throughout the battery lifecycle, from supply risks for critical metals and minerals to end-of-life waste management concerns.

This article reviews the sustainability challenges of LIBs, with a focus on both resource constraints and end-of-life economic and environmental tradeoffs, specifically for secondary life and recycling.

Introduction

The rapid technology trajectory of lithium-based energy storage introduces a great deal of uncertainty in quantifying not only demand and supply but also environmental and economic impacts.

For one, commercial products come in a variety of sizes and shapes (their form factor), as shown in table 1. Most portable consumer electronics, like laptops, use an 18650 cylindrical cell, which refers to its 18 mm diameter

TABLE 1 Form factors for common lithium-ion batteries. EV = electric vehicle

Form factor	Characteristics	Type	Applications
Cylindrical	Small cylinder, lowest cost to manufacture	18650 (65mmL,18mmD)	Portable consumer electronics, some EVs
		26650 (65mmL, 26mmD)	Power tools
Button	Can be very small, long lifespan	C, B, and G	Hearing aids, medical implants, key fobs
Pouch	Laminated structure, best packing efficiency, can swell		EVs, stationary storage, drones
Prismatic	Aluminum or steel case for safety/stability, good packing efficiency, more expensive	Small format	Mobile phones
		Large format	EVs, stationary storage

and 65 mm length. A rectangular laptop battery typically contains 8–12 of these form factor batteries. Small applications use a button cell for its long lifespan and size. Most larger applications, including EVs, use either prismatic or pouch form factor batteries, which are more expensive to manufacture than cylindrical but typically have a higher energy density due to improved packing efficiency.

In addition, LIB cathodes have significantly divergent compositions; table 2 lists the five most common. Lithium cobalt oxide (LCO) is by far the most common type of LIB, but with EV production ramping up other chemistries may dominate in the near future. Many automotive batteries are a blend of the cathode types shown in table 2. It should be noted that there are stoichiometrically different versions of lithium nickel manganese cobalt oxide (NMC). The one listed in table 2 is NMC-111, which has the same amount of nickel, manganese, and cobalt on a mole fraction basis; other variations in development commercially are NMC-622 and NMC-811. The type is important because the materials in the cathode significantly influence supply (Olivetti et al. 2017), economics (Sakti et al. 2015), and environmental impacts (Wang et al. 2014a).

Potential Resource Constraints

With the potential for widespread adoption of EVs, concerns about resource constraints in the LIB supply chain have emerged. Lithium, natural graphite, cobalt, nickel, and manganese are all critical, with little opportunity for material substitution. The need to import them from a select few locations may also be a problem—the lack of supply diversity introduces risks to both individual firms and national interests.

There is little concern about a scarcity of lithium as it has a high crustal abundance and is present in a variety of concentrated sources. It has two main production routes: (1) evaporation from brines to precipitate lithium carbonate and (2) mining from the ore spodumene (pegmatites) to produce lithium carbonate or lithium hydroxide. The challenge with lithium is in ramping up battery-grade production to meet the current aggressive targets of some countries and auto manufacturers to go "all-electric" within the next decade (Kushnir and Sandén 2012; Olivetti et al. 2017).

Supply and demand vary for the other resources. Most graphite, which is used prevalently in anodes, is supplied by China, and this lack of supply diversity can create vulnerabilities to supply disruption (e.g., from sociopolitical issues, natural disasters, or changes in regulations; Yang et al. 2017). Manufactured graphite might be an option, although it is significantly more expensive than mined natural graphite (Robinson et al. 2017), but the high diversity of other graphite demand sectors will likely ensure the supply for LIBs (Olivetti et al. 2017).

TABLE 2 Common lithium-ion battery cathodes. EV = electric vehicle

Type	Acronym	Notation	Use
lithium cobalt oxide	LCO	$LiCoO_2$	portable electronics
lithium manganese oxide	LMO	$LiMn_2O_4$	power tools, EVs (e.g., early Chevy Volt and Nissan Leaf)
lithium nickel manganese cobalt oxide	NMC	$LiNiMnCoO_2$	EVs
lithium nickel cobalt aluminum oxide	NCA	$LiNi_{0.8}Co_{.15}Al_{.05}$	EVs (e.g., Tesla)
lithium iron phosphate	LFP	$LiFePO_4$	e-bikes, e-bus, some EVs

Challenges in the supply of cobalt lie mainly in its status as a byproduct of copper and nickel mining: its availability is tightly linked to the supply and demand dynamics of its parent materials. Furthermore, the location of most of the cobalt supply chain in the Democratic Republic of the Congo poses potential sociopolitical risks for disruption. Short-term supply bottlenecks have caused massive price spikes in the past that were debilitating to manufacturers (e.g., civil unrest in the 1970s; Alonso et al. 2007). Transitions from cobalt to more nickel-heavy cathode chemistries like NMC-811 may help alleviate demand pressures for cobalt.

Both nickel and manganese enjoy diversity of supply and other major demand markets, so constraints in demand for their use in lithium-ion batteries do not seem probable (Olivetti et al. 2017).

End-of-Life Management

Lithium-ion batteries are generally significantly less toxic compared to lead-acid and nickel-cadmium batteries (Pistoia et al. 2001), but they are nonetheless associated with environmental impacts. These include resource depletion (Notter et al. 2010), energy waste, and risks of land and groundwater pollution leading to ecotoxicity and human health impacts (Kang 2012).

Concerns about these impacts have motivated a patchwork of domestic and international legislation. In the United States, for example, California and New York ban and impose fines for the deposit of lithium-ion batteries in landfills (Richa et al. 2017a). In the European Union, the Battery Directive provides recycling targets for LIBs although its effectiveness is difficult to quantify (Kierkegaard 2007). Battery directives in other countries often target the heavy metals contained in metal hydride batteries and do not include LIBs (e.g., Brazil; Espinosa et al. 2004).

Determining the appropriate end-of-life disposition of lithium ion batteries is complex given the many options available; these include reuse in the original application, cascaded use in other applications, remanufacturing or refurbishment, refunctionalization, recycling, and ultimately disposal (figure 1).

The variety of disposition options combined with the rapid technology trajectory of LIBs (resulting in changing form factors) and dynamic cathode chemistries (e.g., listed in table 1) further complicate this determination.

Reuse, Remanufacturing, and Refurbishment

Restrictions limit the reuse of EV batteries, but cascaded use, or use in another application, has some promise. The remaining life of EV batteries (often as high as 80 percent capacity because of the high-demand nature of automotive consumption) has inspired examination of secondary use applications such as stationary power and grid load leveling (Neubauer et al. 2012). Any reuse route will require some testing and processing to prepare end-of-life batteries for use in another application. During these processes, often called remanufacturing or refurbishment, it is necessary to assess the functional properties of end-of-life LIBs and access information from the embedded battery management systems (Foster et al. 2014; Standridge and Corneal 2014). Remanufacturing processes for LIBs likely also require some degree of disassembly to access and replace underperforming cells or modules.

Cascaded use can lower costs of the battery system (Cready et al. 2003; Heymans et al. 2014) and reduce environmental impacts of LIBs (Cicconi et al. 2012). For example, one study found that lifecycle cumulative energy demand could be reduced by 15 percent for LIBs when used for stationary storage under base case assumptions and up to 70 percent under optimistic scenarios when compared to lead-acid batteries (Richa et al. 2017b).

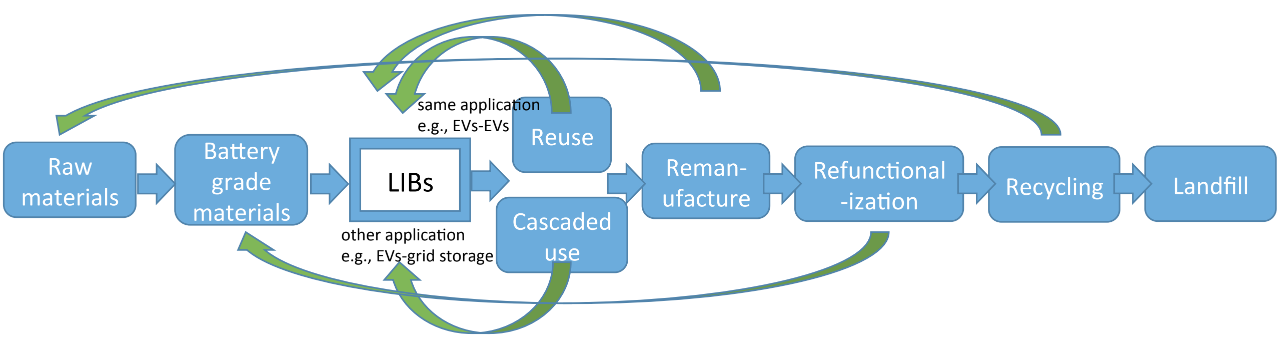

FIGURE 1 Lifecycle of the lithium-ion battery, showing variety of end-of-life routes.

But despite environmental and economic savings, significant barriers to reuse remain. One challenge is to match supply to demand in terms of both volume and properties (e.g., remaining lifespan, past life C-rates, minimum energy density). Quality control and consistent sourcing are concerns for users of second-life batteries. And those who provide such batteries—namely automotive manufacturers (original equipment manufacturers, OEMs)—cite liability, corporate policy, and collection and distribution costs as barriers. Recent incidents (e.g., the Samsung Galaxy Note 7 cellphone, hoverboards) involving explosions and thermal runaway of LIBs have increased concerns about the safety of secondary use applications.

Secondary use applications such as stationary power and grid load leveling can lower costs and reduce environmental impacts of LIBs.

Refunctionalization

Between reuse and recycling, a step that maintains some of the energy input in battery-grade cathode and anode materials is refunctionalization, the treatment of active battery materials to reestablish the electrochemical performance that degraded during use. Such techniques have been demonstrated using a variety of technologies (Liu et al. 2016; Sa et al. 2015; Senćanski et al. 2017; Zou et al. 2013).

Most of the techniques for refunctionalization involve some type of relithiation. For example, a method using lithium carbonate as a treatment for LMO cathode EV batteries has been demonstrated (Dunn et al. 2012). For LFP cathode batteries, it is possible to restore the original capacity of 150–155 mAh/g through chemical relithiation, a method that results in about half the embodied energy required to make the same cathode material from virgin inputs (Ganter et al. 2014).

Laser radiation techniques have also been shown to be successful in removing solielectrolyte interface layers, a key cause of performance degradation, thus providing other routes to refunctionalization by restoring capacity (Liu et al. 2016).

Recycling

When reuse or refunctionalization of active materials is not possible or economically favorable, recycling is a clear path to resource recovery for LIBs and is generally preferred over disposal. Studies have found resource savings (Dewulf et al. 2010) and also show that LIB recycling can greatly reduce environmental impacts of EVs (Gaines et al. 2011; Notter et al. 2010; Sullivan et al. 2011).

Recycling processes for LIBs need to find a balance between low-cost, high-throughput methods that have low yields of some of the metals and labor- and reagent-intensive approaches to maximize metal yields. Current recycling processes for other battery systems provide examples at both extremes.

Infrastructure and Methods

The well-developed infrastructure for lead-acid automotive battery recycling has been mainly motivated by toxicity and disposal concerns associated with lead as well as favorable economics. Lead-acid recycling is generally a high-throughput smelting process. In contrast, many nickel–metal hydride batteries need to be hand sorted for hydrometallurgical recycling, a very labor-intensive process (Gaines 2014). And disassembling large-scale EV batteries is complex, challenging, and potentially dangerous work (Dorella and Mansur 2007). Most of the recoverable value resides in the base metals in the cathode, increasing disassembly cost and time as this is the last portion of the battery taken apart.

Research into preprocessing has found that high-throughput methods used for other primary and secondary streams may have promise for economic recycling of LIBs (Al-Thyabat et al. 2013). Shredding and size-based separation could successfully segregate valuable metals like cobalt and copper into different size fractions (Wang et al. 2016). For example, for LCO batteries, cobalt content has been improved from 35 percent by weight in the metallic portion before prerecycling to 82 percent in the ultrafine (<0.5 mm) fraction and 68 percent in the fine (0.5–1 mm) fraction, and excluded in the larger pieces (>6 mm). Such segregation may increase yields in further processing steps. However, because of safety concerns LIBs may be a poor match for traditional preprocessing technologies.

Economic Considerations

The economic impetus for recycling LIBs is mainly in the recovery of cobalt, by far the most valuable metal in them. As batteries transition away from cobalt-based chemistries, the potential profits for LIB secondary processors will go down significantly, unless other commodities in the batteries have significant price spikes (Wang et al. 2014a).

Compared to other electronic wastes, significantly more volume of spent LIBs is required to ensure profitability (Wang et al. 2014b), meaning that collection costs may play a role. The result may be more centralized processing facilities for LIBs as opposed to the distributed type used for other electronic wastes. Only a handful of companies handle LIB collection in the United States (e.g., Call2Recycle) and they must typically ship the batteries quite far for processing because of a lack of infrastructure.

Recovery of Materials

Most successful extraction technologies are hydrometallurgical in nature, requiring low temperatures and strong acids to leach out the metals of interest into metals, salts, or hydroxides. These leaching approaches have shown excellent yields at the lab scale (Chagnes and Pospiech 2013). Researchers are working to optimize extraction from more environmentally friendly organic acids as well (Li et al. 2010, 2013). Pyrometallurgical routes, like that employed at the Umicore battery recycling facility in Belgium, use high temperatures to melt mixtures of batteries to recover cobalt, nickel, and copper, but the lithium and aluminum typically end up as a waste byproduct in the slag.

One of the biggest challenges, which affects both reuse and particularly recycling, is the diversity of lithium-ion batteries, which makes for a dynamic scrap stream that can be difficult to manage. Even among batteries with the same cathode chemistry and form factor, the metallic composition can vary dramatically by manufacturer (Wang et al. 2014a). As the amount of valuable metals is crucial in ensuring profitability for secondary processors, such variability can negatively impact recyclers.

Furthermore, lithium-ion batteries commingled with the lead-acid input stream can cause dangerous conditions during smelting. Although the lead-acid battery recycling industry has advocated for labelling, there are no LIB labelling standards, so at this point even the development of sorting and segregation technologies may not be able to improve the process.

Disposal

Disposal of LIBs in municipal solid waste is the least desirable option as it can cause sanitation truck and landfill fires (Foss-Smith 2010), soil contamination from the organic electrolyte (Shin et al. 2005), and groundwater pollution from landfill leachate (Kszos and Stewart 2003). It also excludes opportunities for resource and energy savings.

Outlook

Demand for lithium-ion batteries will continue to grow over the next decade, especially with greater use of electric vehicles, and the LIB waste stream will increase exponentially over the next two to three decades (Richa et al. 2014). In the near term, the rising demand will cause pressures on the supply systems for lithium, cobalt, and natural graphite, with lesser effects on manganese and nickel.

Only a handful of companies handle LIB collection in the US and they must typically ship the batteries quite far for processing.

The pressures of supply and demand may help to incentivize secondary routes like reuse, remanufacturing, refunctionalization, and recycling. Reuse, remanufacturing, or recycling of LIBs at their end of life can distribute costs over multiple lifespans and reduce environmental impacts, but the reuse or recycling infrastructure will need to be responsive to the stream of diverse and continually changing materials.

To pave the way for reuse opportunities in grid storage, load leveling, and stationary energy storage, removal of barriers may require strategic intervention at the firm or policy level. As the economics improve, opportunities exist for firms to emerge to serve as matchmakers between the supply of end-of-life LIBs and cascaded use demand.

In addition, research and development opportunities are plentiful across a variety of disciplines. In battery R&D, manufacturing scale-up of new chemistries and cells is needed to reduce costs; next-generation chemistries and form factors are needed to increase energy density and lifespan; and basic science research is needed to improve safety and stability.

Improved waste management will depend on infrastructure that optimizes resource recovery and economics. Secondary processors will need to ensure profitability with a dynamic input stream of LIBs. Policy initiatives will be important to promote standardization and incentivize collection.

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Instead of costly construction, new technologies may make it possible to use existing water systems much more effectively.

Building Smarter Water Systems

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Branko Kerkez

In the era of self-driving cars, digital assistants, and other smart things, can the same level of autonomy and "intelligence" be embedded in water systems? Such technologies have the potential to dramatically reshape adaptation to some of the greatest water challenges, such as floods and droughts. Software-updatable water systems are well within reach, promising to enable highly cost-effective water infrastructure that dynamically redesigns itself in response to changing needs and uncertain inputs.

Background

Recent news coverage has concerned droughts in the American West, contaminated tap water in the Midwestern United States, and floods in California, New England, and the southeastern coastal states. In fact, flooding is the leading cause of extreme weather fatalities in the United States (Vörösmarty et al. 2010).

At the same time, dry regions struggle to find new and clean sources of water. By many estimates, the capture of stormwater in Los Angeles could offset 10 billion gallons per storm (Monte 2015), a large portion of the city's annual water budget. Unfortunately, most of this water is washed into the Pacific Ocean within hours after a storm. Capturing it requires distributed storage and treatment, both of which are limited.

The scarcity of water in the West and other parts of the United States is not helped by the age of the infrastructure that conveys it. By many estimates, nearly 20 percent of treated water is lost through old and leaky pipes, some of which were constructed at the turn of the last century (US EPA 2013).

Aside from water losses, leaks present significant revenue and energy challenges—treatment and conveyance across water systems account for almost 2 percent of the US energy budget (US EPA 2017). Thus, the need to better track and address challenges to water supplies and water distribution is imperative to maintain safe, leak-free, and energy-efficient water systems.

Status of US Stormwater Systems

Recent flash floods (e.g., Hunter 2016) are an all too common, dramatic example that aging infrastructure is struggling to keep up with changing and increasingly severe weather patterns. In addition, nutrients, metals, and many other pollutants are washed from urban surfaces when it rains, eventually ending up in streams, lakes, and oceans (Barco et al. 2008; Finkebine et al. 2000; Wang et al. 2001). And many parts of the country are dealing with chronically impaired coastlines due to algal blooms, which are driven, in part, by urban stormwater runoff (Carey et al. 2014; Doughton 2015; Wines 2014).

Infrastructure Challenges

To address flooding and water quality challenges, cities build and maintain complex networks of distributed stormwater assets such as pipes, canals, and basins. This infrastructure reduces flooding by moving water away from roads and buildings during storms. It also includes natural elements, such as wetlands and raingardens, to capture sediments and dissolved pollutants before they can be discharged to downstream ecosystems.

In some communities, however, stormwater and wastewater are combined, sharing the same pipes. With these systems, large storms can lead to sewer overflows into natural waterways, introducing viruses, bacteria, nutrients, pharmaceuticals, and other pollutants.

Many US stormwater systems were designed at times of less stringent regulations and for populations different from those they now serve. Most are approaching, or already exceed, their design life and face problems similar to those of America's other ailing infrastructure. The American Society of Civil Engineers (ASCE) report card has given US stormwater infrastructure a near failing grade (ASCE 2017), and the problem is echoed in the National Academy of Engineering's Grand Challenge to "restore and improve urban infrastructure" (NAE 2008).

Costly and Piecemeal Fixes

The distributed nature and massive size of most municipal stormwater infrastructure makes it impossible to dig up and resize the entire system. Instead, problems are often fixed one by one through expensive construction projects that are difficult to change afterward. As such, most stormwater systems comprise an amalgam of distributed fixes that have been constructed over decades and rarely add up to an optimized whole.

> *Most stormwater systems are an amalgam of distributed fixes over decades that rarely add up to an optimized whole.*

One of the country's largest stormwater and sewer tunnels was recently built in Chicago, and a few other cities are following this billion-dollar trend (Evans 2015). But these impressive, large construction projects are a luxury for most communities, many of which face challenges in simply maintaining their existing systems.

Even in small communities, stormwater systems can quickly add up to hundreds of linear miles of assets that must be maintained and repaired. In many US cities low or no fees are charged for stormwater services, in comparison to drinking water or sanitary sewer systems. With highly limited revenue streams, solutions that rely on new construction cannot keep pace with evolving community needs and uncertain weather. As cash-strapped communities seek more resilient infrastructure solutions, novel alternatives must be explored.

Technologies for Smarter Water Systems

The role of information technology in managing water supplies and drinking water distribution systems has been made evident in a number of applications. These include sensors for the management of large hydropower and agricultural basins (Kerkez et al. 2012; Rheinheimer et al. 2016), real-time pump optimization and leak localization systems (Stoianov et al. 2007; Whittle et al. 2010), drinking water contamination detection (Ostfeld and Salomons 2004; Storey et al. 2011), and even residential WiFi irrigation widgets.

A burgeoning smart water industry is beginning to fill the needs of modern water utilities and municipalities. The overall technology outlook for water supplies and drinking water systems is promising, notwithstanding much work that must still be done in the development of water quality sensors for important contaminants, such as lead, bacteria, and viruses.

Not all water sectors are embracing technology at the same pace. This is particularly true across stormwater systems, an often overlooked and possibly the most poorly funded subset of urban water infrastructure (Kea et al. 2016). Instead of relying on costly construction, new technologies may make it possible to use existing systems much more effectively.

Industrial and academic efforts are under way to demonstrate the benefits of real-time sensing, computation, and wireless connectivity for the management of urban watersheds. The driving hypothesis behind this work is that smart stormwater systems will vastly shrink the size of infrastructure required to manage runoff pollution and other impacts of changing weather. This approach will dynamically repurpose existing stormwater systems by adapting them on a storm-by-storm basis.

Researchers at the University of Michigan have been spearheading the development of open source technologies that enable watersheds to be retrofitted for sensing and real-time control (figure 1). These technologies and associated case studies are being shared through Open-Storm.org, an open source consortium of academic, industry, and municipal partners that seeks to provide a complete, "batteries included" template for the development of smart watersheds to combat flood-

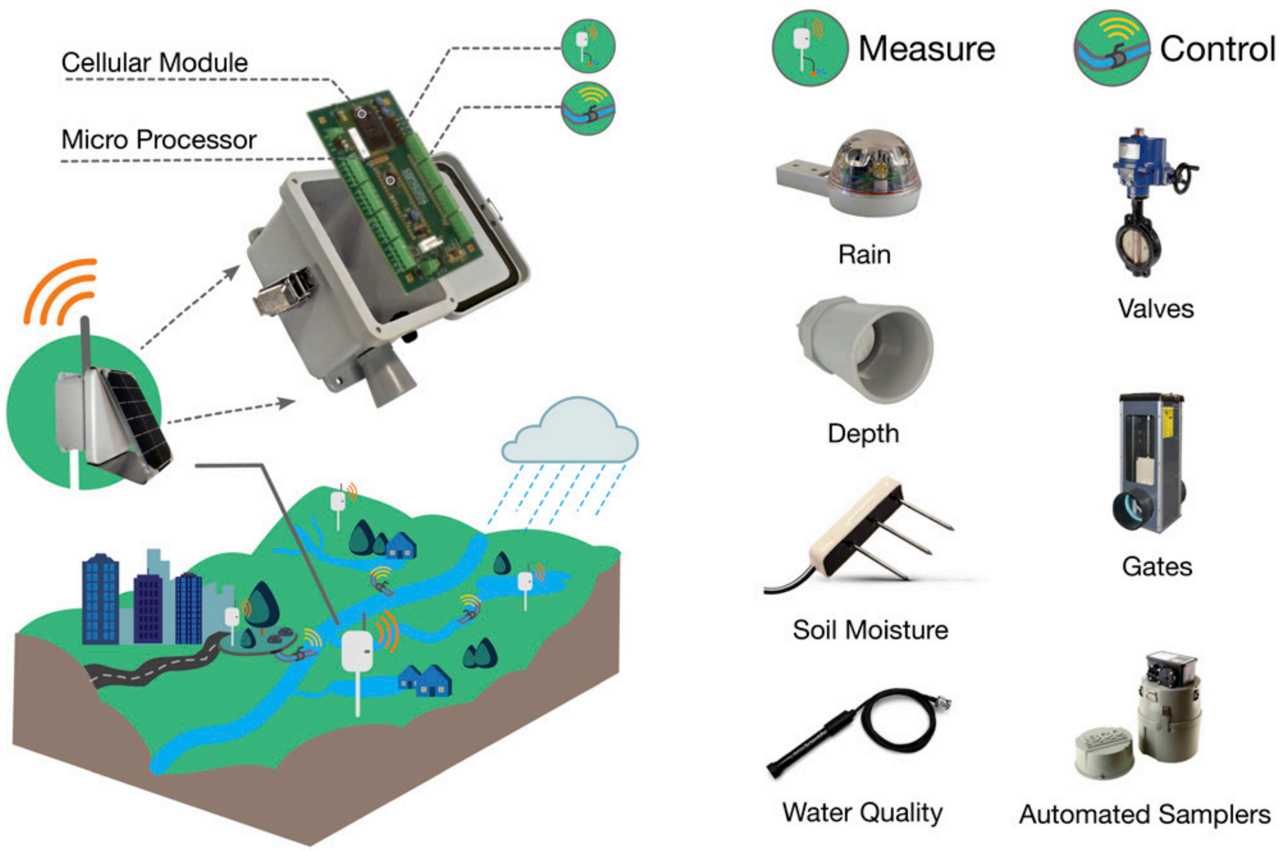

FIGURE 1 Technologies for the sensing and control of watersheds. A full wireless network is composed of many individual sensor nodes (left column) dispersed throughout a watershed, typically at least one per square mile. Each sensor node contains a low-power microprocessor, which collects measurements from a variety of connected sensors. The same unit can be used to control flows using gates, valves, or pumps (right column). A wireless radio, often a cellular module, allows sensor measurements or commands to be transmitted using cloud-hosted services in real time. Reprinted from Bartos et al. (2018) with permission from the Royal Society of Chemistry.

ing and improve urban water quality. The technologies include rapidly deployable wireless sensor nodes for the measurement of urban water flows, water quality, soils, and weather. These are complemented by cloud-hosted data services that allow measurements to be analyzed immediately, providing real-time information on the "health" of both the watershed and the infrastructure.

Commands can also be transmitted from the cloud to the watershed to change the configuration of infrastructure in real time. This is enabled by wirelessly controlled valves, gates, and pumps that can be quickly and easily attached to existing stormwater infrastructure, such as pipes, retention basins, or wetlands. Water levels at retrofitted sites can be safely controlled to release water based on sensor measurements or real-time weather forecasts. By dynamically controlling flows across sites, system-level storage can be adapted to the unique nature of any given storm. This allows infrastructure to be "redesigned" or updated in near real time without the need for new construction.

Even a single remotely controlled valve can provide major benefits. At a basin or pond, a valve can be used to control flooding and reduce stress on downstream systems—a simple control algorithm closes the valve during a storm and opens it before the next storm starts. Storing water locally during a storm temporarily removes it from downstream areas that may otherwise be prone to flooding. The captured water can be directly used for irrigation in adjacent neighborhoods or injected into underlying aquifers to replenish the groundwater table. Some level of treatment can even be achieved at the controlled site by promoting the capture of sediment-bound or dissolved pollutants through settling or natural treatment. Many of these benefits can already be explored by cities and stormwater utilities through commercial real-time control solutions.

Perhaps the biggest benefit of real-time control is the ability to coordinate flows across entire infrastructure systems. For example, the upgraded large combined sewer system in South Bend, Indiana, features over 100 sensors and 10 control points working in tandem to reduce sewer overflows over an area of some 40 square miles.

System-level control promises effective coordination of the many distributed parts of urban stormwater infrastructure at the scale of entire watersheds.

Testbed Implementation

Smart stormwater control networks are being deployed across the Midwestern United States as testbeds for system-level control. They were developed and deployed through the support of the Great Lakes Protection Fund, in partnership with the cities of Ann Arbor and Toledo, Washtenaw County, the Universities of Toledo and Michigan, and Michigan Aerospace.

By dynamically controlling flows across sites, system-level storage can be adapted on a storm-by-storm basis.

The largest Open Storm testbed is in Ann Arbor (figure 2). The sensor network covers a 10 square mile urban watershed, in which some portions have a density of over 15 sensors per square mile. Multiple basins and wetlands have been retrofitted for control, sometimes in just one day by a group of university and high school students. Now in its second year of operation, the relatively inexpensive testbed has demonstrated the following:

- Measurements of soil moisture, water flows, rain, and water quality are transmitted in real time, analyzed, and made available to researchers and city engineers. This provides continuous performance insights that can be used to maintain or upgrade the existing infrastructure.
- Some of the largest controlled basins can store nearly 5 million gallons per storm, making it possible to control the majority of flows across the watershed.
- Real-time coordination of multiple valves has reduced flooding risk. Controlling how long water is held in basins after a storm has also reduced the output of sediments and nutrients from the watershed.

All of these benefits were achieved without new construction, but rather by using existing infrastructure more effectively.

Many scientific questions must now be addressed, but the testbed has proven to be effective and can serve as a blueprint for future smart watersheds. Researchers are also engaging with residents, city managers, and regulators on the value of these technologies to the community.

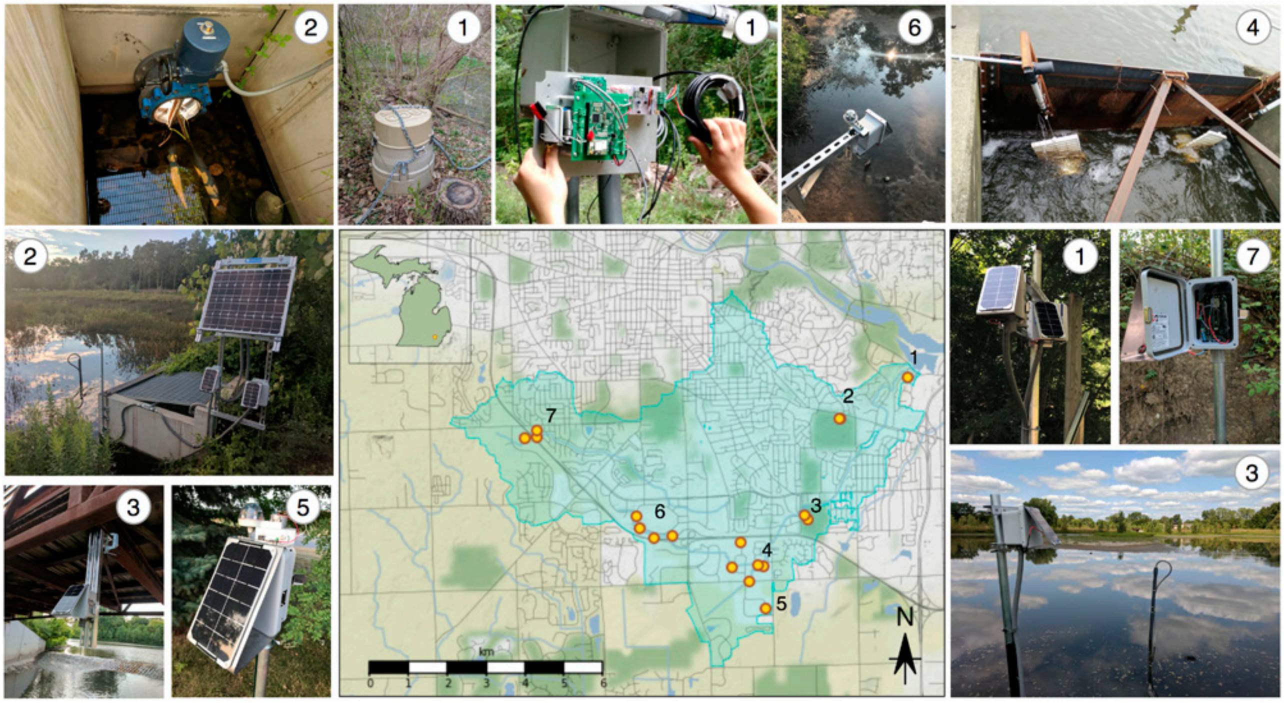

FIGURE 2 The real-time controlled watershed (blue region) in Ann Arbor, Michigan. Starting from the top right corner of the region, the numbers indicate water flow (in reverse order). (1) designates the outlet of the watershed, where urban stormwater flows enter the Huron River. Sensor nodes at each location measure multiple parameters: flows and water levels (locations 3, 4, 6, and 7), soil moisture and rainfall (location 5), and water quality (locations 1 and 3). The watershed is also controlled at a number of points using remotely controllable valves (locations 2 and 4). The current placement and density of sensors follow major infrastructure assets; the sensor network is continuously being expanded to capture the remaining parts of the watershed. Reprinted from Bartos et al. (2018) with permission from the Royal Society of Chemistry.

Simulating for Safety

Public safety demands that control algorithms be exhaustively validated and verified before control of watersheds is delegated to an autopilot. Efforts are focusing on achieving this through new simulation frameworks that allow large control networks to be modeled using state-of-the-art hydraulic solvers and control algorithms (Mullapudi et al. 2017).

Rather than running continuously, as is done in most water simulations, the water model can be halted after every step so that an external algorithm can "make decisions" on how to control valves or other assets. This allows a variety of algorithms to be evaluated in a physically realistic manner before being deployed on real-world systems (figure 3). These efforts are being freely shared through open source toolboxes to reach engineers in other disciplinary communities (e.g., control theory, machine learning) and encourage them to apply their own algorithms to combat flooding and improve water quality.

This simulation framework has already been used to begin investigating algorithms ranging across dynamical feedback control, market-based optimization, and reinforcement learning controllers. It can also help municipal managers decide on investments in real-time control.

Initial results obtained by University of Michigan researchers show that the addition of even a few control valves across urban watersheds allows the infrastructure to handle storms more than twice as large as those it was designed for. These findings also suggest that it may be possible to construct some new infrastructure at half the size when using real-time control, promising significant cost savings when compared to traditional methods.

Outlook

The adoption of smart water systems is no longer limited by technology (Kerkez et al. 2016), which has matured to the point that it can be ubiquitously deployed.

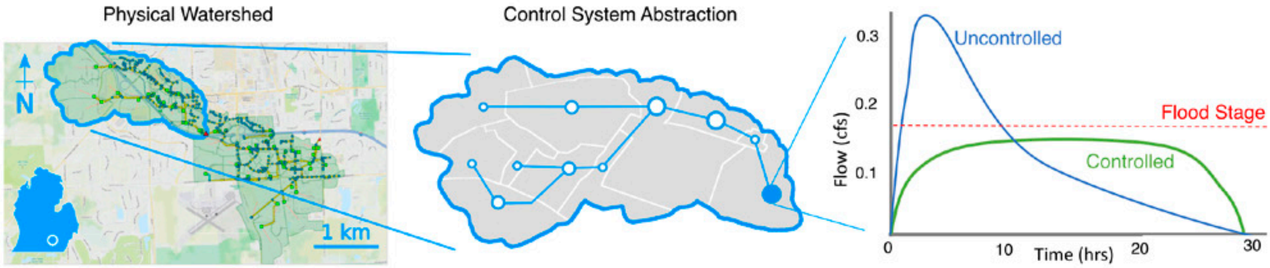

FIGURE 3 Control algorithms developed as part of the Open-Storm.org project allow watersheds to be abstracted into control models, which can then be used to simulate performance before the control systems are ported to the real world.

Rather, other barriers are becoming apparent and must be overcome to encourage and enable broader adoption:

- A new generation of control algorithms needs to be engineered, to ensure safe and autonomous operation at the scale of entire cities.
- More important, perhaps, social barriers to adoption need to be addressed. Doing so will require an understanding of how residents and decision makers perceive the benefits of smart versus traditional water systems.
- Finally, a new cross-disciplinary workforce needs to be trained and educated to be able to build, operate, and maintain this new generation of water systems.

New Control Algorithms

From a fundamental engineering perspective, there is a need to investigate how large water systems can be safely and autonomously controlled across the scales of entire cities and regions, requiring hundreds or thousands of control sites. To that end, extensive knowledge of water systems must be embedded in robust control algorithms.

While many control techniques for distributed systems have been successfully developed and applied in other engineering domains, an application-agnostic, one-size-fits-all approach may not be appropriate for water—what works for one type of water system may not work for another. For example, guidance on controlling flows across large spatial scales may come from research on reservoir operations (Wardlaw and Sharif 1999), water distribution systems (Cembrano et al. 2000), and control sewer systems (Marinaki and Papageorgiou 2005). However, the application of the same algorithms to stormwater may quickly reach limitations because of the need to account for challenges such as noisy sensor data, weather uncertainty, or the types of timescales, complexities, and feedbacks inherent in urban watersheds. Research is needed to determine which real-time control techniques will meet performance goals without risking the safety of nearby residents, property, and downstream ecosystems.

The need to solve these challenges presents an exciting opportunity for civil and environmental engineers to collaborate with colleagues in systems and computer science, electrical engineering, and other fields.

Public Buy-in

Even perfectly engineered smart systems may not be adopted if public trust is not secured. As autonomy moves into the sphere of residential and commercial water systems, it must be accompanied by a deep appreciation of how residents, decision makers, and regulators perceive its benefits and risks.

The vast majority of water utilities and districts in the United States are publicly owned. An understandable level of risk aversion has developed over the decades since even small changes in operations can have large implications. The close connection between water and public safety, health, and other local priorities means that decisions are not always based on economics or efficiency. Engineers' limited understanding of the perceptions of decision makers and the public regarding smart water technologies may be the biggest barrier to adoption.

The engineering disciplines must begin engaging with the social and economic sciences to develop a more holistic appreciation of the opportunities afforded by modern technologies for water management.

Workforce Development

Growing interest in smart cities promises exciting opportunities for a new workforce of engineers and technicians who will respond to a multitude of cross-disciplinary challenges. In the context of water, this will require educating a new generation of students whose knowledge of water systems will be combined with mastery of other disciplines, such as computer science and electrical engineering. Novel graduate and undergraduate educational initiatives are forming to fill this need, such as the University of Michigan's Intelligent Systems graduate program in the Department of Civil and Environmental Engineering.

This new generation of students must be embraced by an industry willing to value skills that have not traditionally been part of its core. The economic and efficiency gains resulting from smart water systems will need to be translated into commensurate salaries for appropriately educated, technologically savvy engineers, who may otherwise be lured into much higher-paying tech careers.

Economic and efficiency gains from smart water systems will need to translate to commensurate salaries for appropriately educated, tech-savvy engineers.

Similarly, there is an opportunity to begin training a new workforce of smart water technicians and maintenance experts, who will not need college degrees to benefit from a tech career. This new workforce of engineering technicians may also help to advance equity and inclusion (Kuehn 2017).

Conclusions

Smart and autonomous water systems are well within reach, driven by pioneering efforts in a growing number of US communities and utilities. Early implementation of these systems indicates that, before resorting to costly new construction, it may already be possible to use existing infrastructure much more effectively.

Lessons learned by early adopters are being shared through new cross-sector groups and consortiums of regulators, companies, utilities, and academics, such as the international Smart Water Networks Forum (SWAN), and initiatives of established water organizations, such as ASCE's Environmental Water Resources Institute (EWRI) and the Water Environment Foundation (WEF). In addition, the National Science Foundation, through its new Smart and Connected Communities program, is funding efforts to encourage fundamental discovery and meaningful engagement with cities and communities; one recently funded project will work across a number of US cities to investigate and overcome major barriers to adoption of smart stormwater systems (NSF 2017).

Anyone interested in efforts to enhance water management is encouraged to engage with these groups or to learn and contribute through open source efforts such as WaterAnalytics.org and Open-Storm.org.

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The E-sail will enable space travel and exploration with higher speed, better mass economy, and at less cost.

The Electric Solar Wind Sail (E-sail): Propulsion Innovation for Solar System Travel

Sini Merikallio and
Pekka Janhunen

Sini Merikallio

Pekka Janhunen

The electric solar wind sail (E-sail) is a novel propulsion concept that enables fast and economic space travel in the solar system. For propulsion it utilizes a continuous particle stream from the Sun (i.e., solar wind) by deploying long, electrically conductive charged tethers, which through electric force interaction are pushed by the charged solar wind particles, mainly protons (Janhunen et al. 2010). The E-sail thus provides constant thrust without fuel consumption, enabling more ambitious space missions than current technologies.

In this paper we explain how the E-sail works and review some advantages and challenges of the technology. We then describe some specific possibilities that it opens for solar system travel and exploration: asteroid mining of water and metal ores, support for a manned Mars presence, and the reduction of space debris.

The Electric Solar Wind Sail: Overview

The physical principle of the E-sail was discovered in 2004 (Janhunen 2004) and the technical concept in 2006 (Janhunen 2010a). The E-sail is currently

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under development by the Finnish Meteorological Institute (https://www.electricsailing.fi/), NASA (the Heliopause Electrostatic Rapid Transit System, HERTS), and the European Space Agency (ESA; unpublished information).

The possible applications of the E-sail are numerous and promising. It may be used to support manned Mars flight (Janhunen et al. 2015), tow an Earth-threatening 3 million ton asteroid to a more benign track (Merikallio and Janhunen 2010), or deliver a probe to Mercury within a year without any gravity assists (Quarta et al. 2010). It will be ideal for a cometary rendezvous (Quarta et al. 2016), fast planetary entry probe (Janhunen et al. 2014), or asteroid investigations and sample returns (Quarta and Mengali 2010a; Quarta et al. 2014). Travelling toward the edges of the Solar system, the E-sail will make it possible to reach the heliosheath in 15 years (Quarta and Mengali 2010b), a feat that took the Voyager spacecraft 27 and 30 years (Decker et al. 2008; Stone et al. 2005).

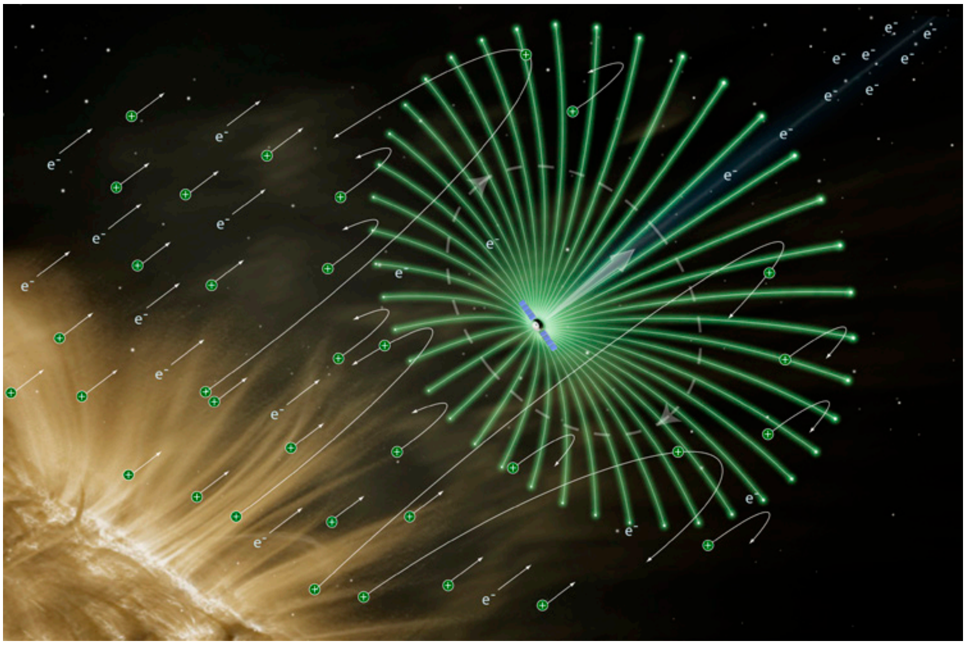

FIGURE 1 Artist's impression of an electric solar wind sail showing the spacecraft from which dozens of tethers (green) are deployed. The whole structure rotates in a cartwheel fashion around the spacecraft to keep the tethers centrifugally stretched. Also shown are solar wind particles (protons [+] and electrons [e−]) and their tracks affected by the electric charge of the tethers. The widths of the tethers and the size of the spacecraft are greatly exaggerated. Image by Alexandre Szames/Antigravite.

How It Works

Thrust for the E-sail is produced by the interaction of charged tethers with solar wind particles: deflected by the electric potential surrounding the tethers, the particles transfer some of their momentum to the E-sail. Solar wind consists mainly of hydrogen and helium nuclei, and a comparable number of electrons. All of these contribute to the thrust of the E-sail, although most of the wind's momentum is a function of the more massive positively charged particles.

Figure 1 shows an artist's impression of an E-sail design; the size of the solar wind particles and spacecraft is hugely exaggerated, and the numbers of tethers, protons, and electrons are not representative. Wire tethers are deployed from the spacecraft and their extension maintained by centrifugal force due to rotation of the whole system.

The produced thrust of an E-sail is inversely proportional to its distance from the Sun, $F \alpha (1/r)$ (Janhunen et al. 2010), in contrast to the traditional photonic solar sail, for which $F \alpha (1/r^2)$. The reason behind this is that, with greater distance from the Sun and a corresponding attenuation of the solar wind, the effective area around the charged E-sail wires increases. In other words, the impact of the wire potential extends farther from the sail as the plasma density dwindles, resulting in better performance than with photonic sails, for which the area of the sail stays constant.

Advantages and Challenges

The E-sail requires no propellant, and discharging of the wires by the solar wind thermal electrons can be counteracted by an electron gun powered by solar panels of a modest size. To enable maneuvering and trajectory control, the E-sail thrust can be steered by controlling the voltage of individual tethers and thus changing the plane of the E-sail's rotation. At 1 astronomical unit (au) of distance from the Sun, approximately 2,000 km of E-sail tether are required to produce 1 newton (N) of thrust. This can be achieved with, for example, 100 tethers, each 20 km long, spun out centrifugally from the spacecraft. There are no technological showstoppers in sight for producing an E-sail like this.

Space is dense with tiny dust particles that threaten the integrity of the E-sail. The risk of this micrometeorite impact is mitigated by weaving the E-sail tether into a 2–3 cm wide mesh-like structure of several wires so that isolated damages in constituent wires do not jeopardize the whole (Seppänen et al. 2011).

E-sail tethers need to be lightweight, conductive, resistant to micrometeoroid impacts, and able to withstand the tension and pull created by the centrifugal acceleration. The number and lengths of the tethers can vary. Their diameter is restricted by the need to limit surface area so as not to generate excessive thermal electron current. Such current would need to be cast off by the electron gun, the use of which decreases performance by increasing power system energy consumption.

Given mechanical (tensile strength, surface area, and weight) and availability (workability and industrial supply) requirements, the material currently under consideration for the tethers is 25–50 μm diameter aluminum alloy wire. Each kilometer of the tether weighs 10 g (Seppänen et al. 2013), resulting in a total tether mass of just 20 kg for a 2,000 km E-sail. The whole propulsion unit—including supporting structures, electron guns, power systems, and design margins—weighs 50–200 kg (Janhunen et al. 2013), far less than the weight of currently used propellant technologies. These features give the E-sail a significant advantage, especially in sample return missions and campaigns with many targets.

In the future, carbon nanotube technology might further enhance the E-sail by allowing the manufacture of longer, more lightweight yet durable and conductive tethers (Lee and Ramakrishna 2017; Monthioux et al. 2017).

Asteroid Mining: Rocket Fuel from Water

The E-sail will permit very low cost freight carriage in the solar system and thus enable affordable asteroid mining operations. It can be used for the transportation of mining equipment to asteroids and return of the mined products. One E-sail can make several trips to and from asteroids during its estimated 10 years of life. The technology can be easily multiplied and operations could proceed on several asteroids simultaneously.

In addition to relatively rich heavy metal ores in asteroids, our interest was raised by another reserve: an abundant number of water-bearing asteroids on near-Earth orbits (Elvis 2014) that can be readily accessed by the E-sail (Quarta 2014). The water can be separated from the asteroid material by using a two-part container (figure 2) in which the water is evaporated from the asteroid regolith in the first chamber and then pressure driven into the other chamber to condense into ice (Janhunen et al. 2015). The temperatures of the containers can be controlled by their surface albedos and infrared emissivities (i.e., coating by colored metal or white paint) or by using additional shades, heat pumps, or solar-powered heat elements. Once filled, the second container can be separated and hauled to the orbit of the Earth or anywhere else.

The resulting water can be split into hydrogen and oxygen, which form a potent spacecraft fuel when liquefied. This process requires electricity, which in space is readily available via solar panels. Currently all

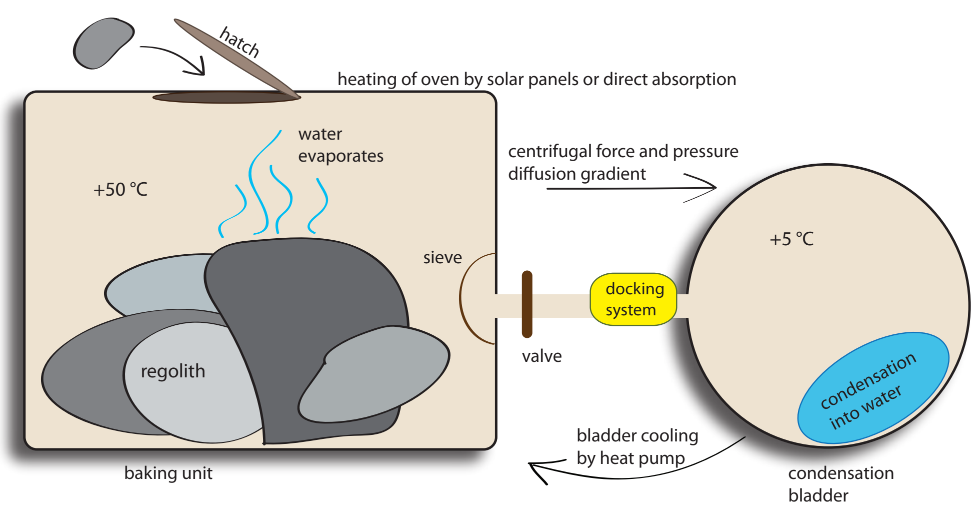

FIGURE 2 Illustration of a two-chamber unit that can be used in situ to extract water from asteroid regolith. Asteroid material is heated in the first chamber (left) so that water in the material vaporizes. Pressure gradient drives the water vapor into the second chamber (right), where it cools and condenses.

the fuel used by a spacecraft has to be lifted from the surface of the Earth and carried throughout the mission, requiring enormous fuel mass fractions. As an example, NASA's Juno mission to Jupiter, launched in 2011, had a liftoff mass of 3,625 kg, of which propellant accounted for more than 2,000 kg. We have come up with an approach to address this challenge, as described in the next section.

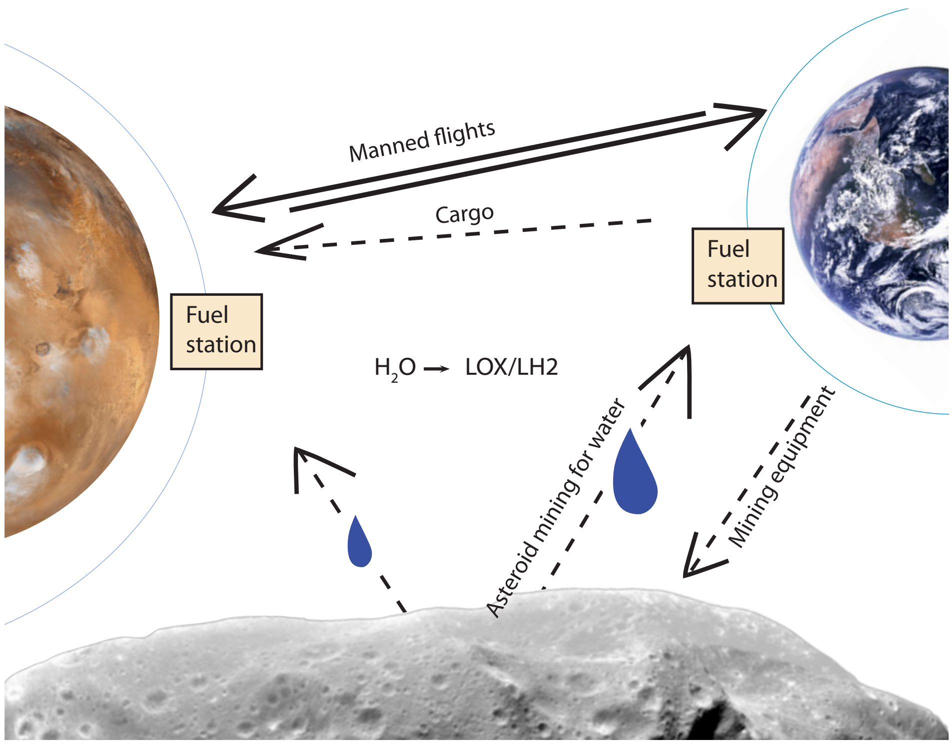

FIGURE 3 Schematic presentation of E-sail–facilitated Manned Mars Initiative (EMMI). At the heart of EMMI are asteroid mining operations: water from an asteroid (bottom) is transported to the planetary orbit and refined into liquid oxygen/liquid hydrogen LOX/LH2 fuel, which can be used for transportation to and from Mars. Pictures of the planets and asteroid surface are by NASA and not presented at scale.

EMMI: Manned Mars Flights Facilitated by the E-sail

In 2015 we proposed the E-sail–facilitated Manned Mars Initiative (EMMI; Janhunen et al. 2015). The idea behind EMMI is to mine water from asteroids and bring it to space-based "gas stations" in the orbits of Earth and Mars where it can be turned into rocket fuel. Such stations—with two on the way to/from Mars (figure 3)—can significantly facilitate manned Mars exploration in the near future.

Orbital fuel tank refills will allow for smaller tanks and thus considerably lighter spacecraft. Moreover, the spacecraft that lifts passengers and cargo from the surface of the Earth into orbit can be different from that which taxis between Earth and Mars. This will reduce the design requirements of both vehicles, as the one carrying passengers from Earth will not need to have capabilities for long-term life support, and the traverse shuttle will not need to survive atmospheric entry and launch vibrations and thermal loads. In addition, the availability of virtually free fuel on the Martian orbit will increase mission safety and enable speedy returns when necessary.

The asteroid-extracted water can also be used in life support as a source of potable water and even oxygen for breathing. Thick water layers around manned spacecraft and surface habitation modules can function as a radiation protection shield during the long traverses between Earth and Mars.

These spacecraft can be operated at a fraction of the current estimated Mars colonization costs: once in place, the EMMI is estimated to run on a budget comparable to the maintenance costs of the International Space Station (ISS). Moreover, launchers used for setting up EMMI can be of the same scale as those used for building the ISS.

Plasma Brake

A spin-off from the E-sail technology, a plasma brake, can be used to bring small satellites down from their orbits at the end of their viable life (Janhunen 2010b, 2014; Orsini et al. 2018). It can be attached to existing satellites and space debris with, for example, harpoons. Advantages of the plasma brake are low weight, potentially low cost, and high safety, as it can be operated without any volatiles, explosives, or inflammables.

A plasma brake payload is currently flying on a low Earth orbit (LEO) CubeSat mission, the Finnish Aalto-1, and waiting to be tested using a short (100 m)

E-sail tether (Kestilä et al. 2013). It is important to note that the relative speed of the spacecraft and ionosphere (~7 km/s) is not comparable to the solar wind speed (~400 km/s). However, as the tether voltage is varied in sync with the rotation of the satellite, the E-sail effect will be observable in changes in the CubeSat's rotational speed.

With Aalto-1, researchers are looking forward to verifying, and measuring, the E-sail force in real space environment.

Summary and Discussion

The design, production, and testing of electric solar wind sail prototypes are making good progress. E-sail technology could be available for solar system research within 10 years and, if successful, may revolutionize the way space travel and exploration missions are conceived and executed. The E-sail will enable affordable continuous manned Mars presence, considerably decrease travel times in the solar system, make it possible to tackle space debris, and help facilitate asteroid mining operations. The E-sail thus holds great promise for accessing both scientific and economical treasures of the solar system.

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Advances in engineered timber enable the construction of taller buildings at less cost and with reduced environmental impacts.

Supertall Timber:
Functional Natural Materials for High-Rise Structures

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Michael H. Ramage

Wood and wood products have been used as building materials since before recorded history, but the full potential of timber and other plants as building materials has not yet been realized.

Engineered timber materials, among them cross-laminated timber (CLT) and laminated veneer lumber (LVL), have enabled architects and engineers to design and build larger and larger timber buildings. The tallest is Brock Commons, a 55-meter, 18-story student dormitory completed in 2016 at the University of British Columbia. Before that, the tallest was Treet ("tree" in Norwegian), a 53-meter, 14-story condominium completed in 2015 in Bergen, Norway (figure 1). Brock Commons has two concrete cores, while Treet is a fully timber structure, so each may be the tallest of its type (Foster et al. 2016).

The scale of these contemporary buildings is significant, as the first metal-framed skyscraper, William Le Baron Jenney's Home Insurance Building in Chicago, was 55 meters tall when completed in 1891, and 1931 saw the completion of the Empire State Building in New York City, at 381 meters. Innovation in natural materials, design, and construction may allow a similar increase in the height of timber skyscrapers.

The use of natural materials instead of steel and concrete in taller and larger buildings can reduce carbon emissions. Furthermore, CLT construction requires only about 30 m^3 for an apartment for two people. Using wood from

FIGURE 1 Treet, a 14-story apartment building in Bergen, Norway, rises 52.8 meters and is made of cross-laminated and glued laminated timber.

only 30 percent of Europe's managed forests with current practices, the entire population of Europe could be housed in perpetuity, even assuming the entire housing stock was renewed every 50 years (Ramage et al. 2017a).

Background

Timber has exceptional properties for building, many of which have been overlooked in the construction of ever-taller buildings in the past century. Advances in biological knowledge, engineering of plant-based materials, and interest in renewable construction are converging to create new possibilities for materials and allow for larger, taller, and more natural engineered wood buildings (Green 2012; Ramage et al. 2017a).[1]

There is also competition in the building industry to construct the tallest timber tower. Height increases are currently incremental, but through a combination of theoretical design and physical testing, the viability of timber buildings can be demonstrated at much greater heights than previously possible (Ramage et al. 2017b).

By pushing the limits of theoretical designs into the realm of the supertall[2]—and sometimes beyond that which is feasible using current materials and construction technologies—our research sets out the requirements for the next generation of engineered plant-based materials. Research and the design and construction of contemporary large-scale timber buildings together further the architectural and structural engineering knowledge necessary to make tall timber buildings a reality.

Materials science has advanced the industrial production of steel and reinforced concrete since the mid-19th century. The materials science of natural materials is less well understood, but the use of biofuels has helped drive fundamental research on the makeup of plant cells and their constituent parts.

Improved information about how to break down plants into useful components can also enhance understanding of their underlying properties. As an example, the model plant *Arabidopsis thaliana*, whose genome is well defined and editable, is essentially the mouse of plant science. Through biochemistry, it can be grown with lignin-depleted cells for studies of the role of lignin in giving plant cells their characteristic properties. In *Arabidopsis*, lignin appears to help control the way cells move past each other as they are pulled apart in tensile tests.

With better knowledge of how the elements of cell walls contribute to the properties of plants and forest products, it may be possible to breed or genetically engineer plants with specific functional properties that are more favorable to construction.

Current Developments and Applications

Novel properties in trees may give rise to a new class of natural materials, but engineered timber products on the market are already giving designers around the world opportunities to innovate with large-scale construction. CLT can be used much like slabs of concrete in walls and floors, and glue-laminated timber and LVL can substitute for steel or concrete columns and beams. All can be used with existing modes of construction.

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[1] Also see the 2013 technical report of the SOM Timber Tower Research Project, available at www.som.com/ideas/research/timber_tower_research_project.

[2] Supertall buildings are 300–600 meters. For reference, the original 110-floor World Trade Towers in New York were just over 540 meters, and the Sears Tower in Chicago is 442 meters.

But there are limitations. For example, platform construction with CLT is limited by the perpendicular-to-grain crushing of panels at floor junctions, a phenomenon that is difficult to overcome above 10 stories or so. And although the axial strength of some hardwood LVL in compression and tension is sufficient to engineer very large buildings, the ability to transfer tensile loads that can be carried by the full section from one element of timber to another remains to be determined.

Our supertall timber project, in which we have designed wooden skyscrapers (figure 2), shows the viability of commercial and residential buildings at a new scale in timber, using components and materials that are commercially available today. Our design and research demonstrate the architectural, engineering, and economic possibilities that stem from thinking about traditional materials in new ways.

Other Plants

A variety of plants may add to the materials available. Bamboo has excellent properties in tension and compression, and is among the world's fastest growing plants—it can be harvested every few years. In addition, a number of processing methods exist to turn the raw product into an engineered material (Sharma et al. 2015), and more are being developed. Engineered

FIGURE 2 Maquette of River Beech Tower proposed for Chicago. The 80-story residential skyscraper is a design collaboration of Perkins+Will, Thornton Thomasetti, and Cambridge University Centre for Natural Material Innovation. Photo credit: Perkins+Will, Thornton Thomasetti, Cambridge University.

bamboo looks like wood and is crafted with woodworking equipment. It behaves differently as a structural material (Reynolds et al. 2016), so new engineering codes are necessary.

Other crops, such as flax and hemp, are being used to make structural composites for automotive and industrial design and at the same time engineered to deliver improved properties. All of these crops are available at a scale necessary for construction.

Advantages

Construction with timber has many advantages, not least for the environment.

- Timber is the only major building material that can be grown, and the sustainable harvest of lumber is vast—crop-planted forests around the world are expanding.
- Timber is five times lighter than concrete, so to construct an equivalent volume of building, only one timber truckload is needed, as compared to five concrete mixers.
- No formwork needs to be brought to site (and removed) and no reinforcing steel is necessary. The steel in timber connections is negligible. We roughly redesigned the Treet building in reinforced concrete for comparison and discovered that it would have five times as much steel in it as the timber building.
- The savings multiplier on construction truck traffic can be as high as eight.[3] These savings have implications for today's crowded metropolises: smaller foundations, or indeed no new ones, as the existing foundation for a demolished 10-story concrete building can hold a timber building three to four times as tall, with quieter construction and smaller cranes.
- Contemporary timber buildings are largely prefabricated for component assembly, meaning they are quick to erect accurately on site and tend to be naturally draft-proof and efficient, saving time and energy and improving overall quality.

Conclusion

As manufacturers, architects, engineers, and contractors learn to expand what they can do with large-scale engineered timber, a new architecture of 21st century timber will arise, drawing on a rich tradition of centuries of wooden construction while reaching higher to embrace the full potential of innovation and construction with natural materials.

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[3] Personal communication, February 2, 2017, with Ralph Austin of Seagate Structures, which has built a number of large-scale timber buildings in Vancouver.

Op-ed

Climate Risk Management: A Way Forward

Lee Kump is dean of the College of Earth and Mineral Sciences at Pennsylvania State University.

Uncertainty dogs all of our decisions and poses a challenge to success in our endeavors. Risk from these uncertainties can be managed, though, and, with sound investments, successful strategies can be adopted and goals achieved.

A growing area of concern is climate change. A focus on attribution has polarized society, with scientists viewed by some as perpetrators of a hoax, and politicians and fossil fuel executives viewed as climate change deniers. The polarization of the discussion concerning anthropogenic climate change has stymied progress. What is necessary to move beyond these debates toward consensus on the occurrence and impacts of climate change and on actions to be taken?

I served as head of the Geosciences Department at Pennsylvania State University for six years before becoming dean of the College of Earth and Mineral Sciences. The department boasts top programs in both climate change and the geology of fossil fuels. Its alumni advisory board includes individuals with successful careers in the oil and gas industry, government, environmental consulting, and academia.

Often I would invite individual faculty members to talk about their science to the board during its semiannual meeting. I noticed that talks presented as primers on climate change, explaining the greenhouse effect and advocating for action on climate change, were variably received, with some board members put off by what they felt was a patronizing presentation.

In 2013 I asked Klaus Keller, a climate scientist who leads Penn State's Center for Climate Risk Management, to address the group. He took a different tack, describing his research on sea level rise. He reported on a study, conducted with colleagues, to develop strategies enabling the Port of Los Angeles to account for highly uncertain outcomes of climate change and sea level rise in its infrastructure investments for the future. Keller and his colleagues used both robust decision-making analysis, to establish under what future conditions a decision to harden facilities against sea level rise would pass a cost-benefit test, and climate science to determine whether such conditions are sufficiently likely to justify the investment.

As Keller described his work to the advisory board, I saw the same people who were red in the face during the presentation on greenhouse effects nodding in agreement and approval. At the end of his talk, one of the industry alums exclaimed, "Now I get it!" After Keller left, the group asked me if he taught climate risk management courses to our students (he does) and recommended that all our students should learn to "think like Klaus!"

That experience convinced me that the way forward is to redirect the discussion from whether climate is changing and what or who is responsible for those changes, to the possible risks associated with climate change and how they should be managed. I think even self-identified climate deniers would agree that there is some (perhaps remote) possibility that future climates affected by rising carbon dioxide levels could be hostile to the conduct of their business, not to mention the survival of coastal communities and the productivity of agriculture worldwide, to name just a few of the threats.

Like most people, the deniers take out insurance against risks that are highly unlikely but hugely damaging if they occur. Why not likewise manage the risk of climate change?

Recent discoveries of oil and gas in unconventional reservoirs accessed through fracking enhance US energy independence and thus the nation's security. The unmitigated burning of fossil fuels, however, also poses nontrivial environmental risks. Moreover, current practices are not sustainable, as fossil fuels will simply run out.

The question is therefore not whether but when and how to transition to renewable energy sources. What are strategies to use fossil fuels responsibly and find sweet spots in the tradeoffs between the prospects and risks of that continued use?

Designing a sound roadmap for this transition requires input from citizens, industry, government, and non-governmental organizations. Universities such as Penn State can serve an important role in the process, investing intellectual capital and providing a trusted, neutral forum to help design and implement such a roadmap. The first step will be to establish the mix of renewable energy sources anticipated for the region of interest (e.g., the regional electric grid). Consensus building will emerge through the development of a sustainable path that maximizes economic prosperity while minimizing environmental impact and that focuses on risk management rather than climate change causes and attribution.

In any event, it is essential to develop a plan. Not to do so puts society at unacceptable risk

An Interview with . . .

Lori McCreary, Film and Television Producer

Photo by John Nowak.

RON LATANISION (RML): We are happy to talk with a producer with a background in science and engineering, for our series to enhance awareness of engineers' impact way beyond the typical expectations of them. Entertainment and the production of films are important aspects of our culture with very high visibility.

Can you tell us a bit about Revelations Entertainment? I see in a write-up that you and Morgan Freeman founded it in 1996 with a mission to produce entertainment that "reveals truth." I am curious about that. What was your original vision and how has that played out?

LORI McCREARY: I think it's about what Morgan and I gravitate to in terms of storytelling. There are a lot of stories about individuals like Morgan or me that have not been told over the years. We were excited about the opportunity to tell our own stories and to find stories of others that have been either overlooked or forgotten and ensure that those stories are told.

I think, as a society, the more we can reach out and understand each other culturally and just as human beings, the more we can come together. Our approach to revealing truth is about allowing voices from all parts of the world to be heard.

RML: *Invictus* was one of your movies, wasn't it? I think that was a very good movie. How did it meet the mission? Was it a statement about Mandela or about South Africa in a broad sense? I can see a lot of elements that might be pertinent.

MS. McCREARY: I think it's about the truth of reconciliation and healing. The conversation between Morgan and me started a long time ago. We made our first movie together, *Bopha!*, in 1992. He directed it and I produced it, and it was released in 1993 here in the States. It's about a black father in the South African police who was enforcing Apartheid, and his son who was part of the resistance movement. It's a story about the tearing apart of this family in South Africa in 1984 during the height of Apartheid and what happens when you have a father who is trying to provide for his family as part of the establishment and a son who is saying, "Dad, there is something wrong with what's going on here."

Nelson Mandela came to one of the premieres in San Francisco and I was fortunate to meet him. This was in 1993 before he became president. He said to me, "This is an important story." I never forgot when I was shaking his hand that (1) this is Nelson Mandela telling me that I told an important story, wow! and (2) oh my gosh, he reminds me in spirit of Morgan, and I had just met Morgan a couple of years before.

So I committed to myself that I was going to tell Mandela's story. It took 17 years to do it, but sometimes that is what it takes in our business. What struck Morgan and me was the idea of forgiveness, reconciliation, coming together—and that admitting to each other how we wronged each other is the bridge to coming back together peacefully.

RML: Do you and Morgan have a special interest in politics and public needs? What is currently on your radar screen, if you can tell us?

MS. McCREARY: We have a CBS television show on Sunday nights called *Madam Secretary*. We try not to be political but it is a show about the diplomatic world that intersects with politics. The truth we try to reveal in the show is that it's never black and white. When people watch the news it seems like, 'Why won't these people just make these decisions? It's easy!' There are

Invictus movie poster.

always complications. Often people's lives are at stake, and sometimes their livelihood, and it is not an uncomplicated system.

The public servants who have spent years giving their lives—and a lot of their family time—driving diplomacy and our country to be where we are today are often overlooked. We wanted to peel back the curtain and show the heroes of our diplomatic service.

RML: That's an interesting expression. A congressman from Massachusetts, Mike Capuano, has adopted the practice each week of circulating in his office something called "Behind the Curtain." He tries to look at the kinds of things you just described—what's happening behind the scenes in Washington that no one hears about that has an enormous impact on public life and public service and public need.

MS. McCREARY: I'll have to check that out.

RML: Does your background in computing find its way into your activities as a producer?

MS. McCREARY: Every day, yes.

CAMERON FLETCHER (CHF): Tell us how.

MS. McCREARY: I grew up from 8 years old doing theater, and by the time I was 15 I was running our local theater in Antioch, CA, which had just been given a grant by the state to build a state-of-the-art theater with a computerized lighting and sound board. I was like a kid in a candy shop! I got sent to Ithaca College to learn it.

I designed the most extraordinary sunrise for a show called *The Boy Friend*. It was a 5-minute sunrise because I had the computer. Before then, you had to move the dimmers with your hand and I would never have designed a 5-minute dimmer move because I wouldn't sit there for 5 minutes to move it. With the computer, there were all these beautiful intricate moves and it was going to make this gorgeous show. I was very excited. On opening night, I walked into the tech room and turned on the computer and nothing happened. I didn't know what to do. I couldn't get it to work and no one could help me get it to work, so I had to run the entire show manually—and it was a very complicated show.

By the time I talked with my guidance counselors and my parents about what I was going to do in college, I had been doing theater for 8 or 9 years and I thought, 'Well, if I'm going to tell stories I really need to learn this technology thing,' so I got a computer science degree. I went to UCLA because they told me I could write my own major. I explained that the technology industry and the entertainment industry (I said "theater" at the time) were converging and I wanted to write my own major. They said, "Of course, come down! You can write your own major."

So I wrote a paper about how I wanted to do this dual major—and they basically said, "Well, you can't cross the school of engineering and the school of fine arts. You can do a dual major as long as the two fields are in the same school." And I said, "But that's not the point." Then the guidance counselor said to me, "Maybe you should just go into theater." So I decided 'Definitely I'm taking computer science!' because I was a little annoyed that they wouldn't encourage me to go into the tech side of things.

I was one of only four women in that major in the class of 1984. The computer science program was very new—we had breadboard circuits, we had to build our own computers. It was very rigorous training and I loved it. I had no idea I was going to love it so much.

RML: That's a fantastic story. It's all about determination, right?

Lori McCreary and assistant Phoebe Paros on the set of *Invictus*. Photo by Gesine Thompson.

MS. McCREARY: Yes. And I still did things like write software for the new motors that were running the lighting systems in the theater, so I was back and forth between the two areas.

I got a little sidetracked for a couple years when I teamed up with a couple of entrepreneurs who started a software company called CompuLaw, which did legal software. I'm a very good programmer and I wrote a B-tree library, because there were no libraries that you could call on in terms of programming at the time. We wrote this big system for time and billing and docketing for lawyers. I had about 20 employees when I was 20-something.

CHF: As a producer, I imagine you don't get to do much in the way of software or programming any more?

MS. McCREARY: That's right. I did with my first movie, in 1992 in Zimbabwe. Then I left CompuLaw (I kept my stock, thank goodness) and decided I was going to try to do theater. I found this play that became the movie *Bopha!* It took seven years to get it to the point where Paramount Pictures would finance it. I was told by everyone I talked to in the industry, "You've never produced, so they're going to send a real producer to Zimbabwe to make this movie, they're never going to send you." I was petrified.

Later I realized I had been helping this guy who was writing the Movie Magic Budgeting and Scheduling Software, a DOS-based system; I would tell him, "Here are some bugs and here are some fixes." I was deeply entrenched in working around all the issues in the first generations of the software, and I was doing budgeting and scheduling on a compact dual-disk computer.

When the head of production at Paramount Pictures called me in, he sat with me for about an hour and asked me a lot of questions about the budget and the schedule. He would say things like "What if we had 58 days instead of 60?" or "I don't think you need 15 grips. How about 12?" I didn't even know what a grip was, but I could do a control-F search for "grip" and change the 15 to a 12, and then I would give him a number—like, "We'll save X thousands of dollars"—and he wrote down what I was saying. Then I left—and before I knew it we were sent off without another producer.

I found out that Paramount hadn't yet been doing its budget or schedules on a computer, so they thought I was this megagenius because I could tell them in seconds what took them much longer to figure out. So I feel like my engineering brain really gave me that leg up on my first movie!

And, by the way, I knew how to produce theater, but I learned in school the kind of critical thinking that's needed. To put together a software program you have to have skill in critical thinking and you need to know if you need to bring in other people. I say this a lot: Programming and producing are almost the same! Building software and writing code are very similar to coming up with a story you want to tell and bringing your team together and getting it onto the big screen or the little screen.

RML: This puts into perspective some of the committees you serve on. For example, I see that you're the founder of the Producers Guild of America Motion

Picture Technology Council. That suggests there are other folks who have similar interests or backgrounds. Or is this an indication of your hope to inspire that kind of inclination?

MS. McCREARY: There are over 8,000 producers in the Producers Guild. I'm currently one of the two presidents, and I don't think there's another producer in the guild with a computer science background. But everyone, especially in the last 5 years, has realized how much technology affects our ability both to tell stories to broader audiences and to streamline the process.

Our process is still not to the level of enterprise software in terms of running a film, which is what I would love. Thinking from my computer science/engineering brain, I know there are solutions that would make us more efficient and able to make movies and television for less money if we adopted them. But for us producers it requires so much of our time to simply get projects made that to also try to look at all those things at the same time becomes a bit unwieldy, and that's why the Motion Picture Technology Council (MPTC) came about.

How do we use technology to make our art better and to be more efficient in making the art?

The first thing the MPTC did was, in 2009, an assessment series with the new digital cameras at the time. It was called the Camera Assessment Series (CAS) and we worked with the American Society of Cinematographers (ASC) and various unions to pull it off. We had seven digital cameras and a film camera, and it was the first time such a comparative assessment had been done on an industrywide basis. We shot some very technically challenging scenes—day, night, water, fire—taking all the cameras through the exact same paces, and then made a presentation for the industry so people could see.

I was a big proponent of digital as long as we had the workflow to be able to process it, because that's as important as capturing the image. So three years later, in 2012, we worked with the ASC on another assessment, called the Image Control Assessment Series (ICAS), to basically assess the workflows of the then-current digital cameras. It was only three years later, but only three of the seven digital cameras were still around, so we picked a new crop of digital cameras and assessed the workflows, which we also presented industrywide.

RML: I think most people when they think about technology and movies think of animation, but what you're talking about is more technical, directed toward making the best use of visual technologies.

MS. McCREARY: Right, directed toward the art: How do we make our art better, how can we be more efficient in making the art, how do we make our images?

CHF: Is the MPTC different from the Society of Motion Picture and Television Engineers, of which you're also a member?

MS. McCREARY: SMPTE is more a standards board—they put together standards for different formats and make recommendations to the industry. They are heavy, heavy engineers.

The MPTC is made up of producers who can work with engineers to say, "These are the holes in our current system" or "This camera is okay but could you make it work with these lenses so that we can get a better look" or "It would be better for the operator to have this…." It brings together the end users, so to speak, and the people designing the systems.

RML: I notice your involvement with ClickStar.[1] Was ClickStar part of the evolution of your interest in things digital?

MS. McCREARY: Yes. ClickStar was my plea to our industry when the music industry was having a hard time in 2004. I was working with Intel at the time, helping them figure out how to get Intel-based systems into the digital effects world, which was basically dominated by Sun Microsystems with $40,000 computers.

I told Intel I was really nervous about what was happening with digital distribution of films. When I spoke to people at the studios, everyone was petrified—they didn't want to be the first person to let a feature film go on the Internet. 'What if we're the one that kills our business?'

The first thing I really wanted to do with Intel was educate our business, so we called a bunch of what we would call tastemakers in the industry—think of the top eight people whose names you would know if you're

[1] ClickStar was a broadband movie distribution company launched in 2006 by Freeman and McCreary. It was the first company to offer a legitimate motion picture download while the film was still playing in theaters.

not in the business. In 2005 we brought them into a room and said, "We want to talk to you about the future of our business from the distribution standpoint." We explained that people were going to look at movies on their phones (everyone rolled their eyes) and watch movies in one room and walk into another room—and people are going to start trying to steal the movies, so we should try to protect them.

One of the very smart actors in the room raised their hand and said, "I don't really get this. Can you show me?" So we literally built a digital home in the Revelations office, which was in Santa Monica at the time. We built a living room, a kids' room, and a neighbor's house and we mocked up what we knew the new technology would be. We showed them that people would be downloading movies in their living room, the kids would be playing the same movie in their bedroom on their laptop or phone—and a neighbor, if this movie is not protected, could interrupt the stream and steal the movie. That was when everyone said, "Ohhhhh."

We didn't at first want to start a company, but from that meeting we thought, 'Well, if anyone should start a digital distribution company for film, it should be a film company,' so we teamed up with a few other big players in our business and with Intel, and started ClickStar. Some people told us we were crazy—no one would download a movie to watch at home!

We were a little too early—it was 2005 when we launched and people were not streaming and downloading content as much as they are now—but we were the first. Before Netflix, we were there. It was great. I still have fond memories, and I feel like we helped the industry move forward a little faster than it might have otherwise.

RML: What was the approach to protecting the rights of the filmmakers? How did you prevent people from stealing movies?

MS. McCREARY: We adopted what was going on in the industry at the time, which was straight digital rights management (DRM) technology, and built it in. Until then no one had adopted DRM and implemented it, at least in terms of major motion pictures. We basically built the system that would follow it. At the time other companies, like CinemaNow and Movielink, were doing it, but ours was the first that was actor/producer driven, so we were giving better breaks to the filmmakers and talent that really are the face of the films, and having them be a part of it.

RML: That was pretty revolutionary for its time. Many of your predictions illustrated in that mock house seem to have materialized, no question about that.

MS. McCREARY: Yes, and now I don't go a month or two without one of the original team telling me, "You knew this was happening!"

CHF: Where do you see yourself and Revelations, or any of your other professional undertakings, in about 5 years?

MS. McCREARY: Good question. I have two brains: what I want to do on the storytelling side and what I want to do on the technology side. In 5 years I would love to have been involved in helping design or create or just birth an enterprise-level system for the actual making of film and television content, something like an end-to-end enterprise-level digital platform for producers to manage a project, or 20 projects. That would be great.

I have two brains: what I want to do in storytelling and what I want to do in technology.

I would also love to figure out a way to deal with the piracy issue in a way that honors people's privacy but also allows the film industry to keep going, because we are losing billions of dollars a year to piracy and we need help.

RML: How about in terms of the activity involved in producing a film, how do you see that changing? If you had a crystal ball into the future of filmmaking, how do you see the mechanics changing, if at all?

MS. McCREARY: The tools are getting smaller, and the cameras are of higher quality. Also, now anyone who has access to an iPhone can make a movie. This allows people who might not have known they were filmmakers to start practicing at a much earlier age with storytelling and seeing what that's like. So I'm really excited about the future because I think there are going to be more diverse storytellers out there. It used to be a very narrow funnel to get to be a filmmaker—you had to have very expensive equipment and hire giant crews—so people didn't aspire to it, or they thought 'I'm never going to be able do it,' or they spent years trying to do it and couldn't break through to the seven people who could say yes to them.

Now anyone can make a great story and put it up online and they might be the next great filmmaker. That to me is the most exciting thing. It comes with technology.

RML: Yes, but do you think technology adds cost or does it actually reduce the cost of the production of film?

MS. McCREARY: When we went to digital we found that it originally upped the cost a bit, but ultimately it cuts the cost. I went to Intel in the early 2000s and walked them through how we produce movies, and in any other industry our kind of blue collar way of doing it would have been subsumed by technology, and it hasn't been yet. It's the good thing about our industry because it is very people driven—there are 100 people working on a set.

I wouldn't want to have technology intercede so that we don't need people, but there are a lot of things—for example, just in terms of gathering information and sending it—that could be streamlined and we could save so much money. *And* we could prevent a lot of the piracy that happens during shooting if we had some enterprise-level solutions for filmmaking.

RML: I am curious to know whether you speak to college audiences about your activities or your industry? I imagine a lot of young people would find your story really compelling. Do you have time for that kind of activity?

MS. McCREARY: I definitely have time if anyone would ask. I just read a statistic the other day that less than 20 percent of college computer science majors are women. Less than 20 percent! I was horrified.

RML: In some of the sciences the number of women has grown dramatically—for example, in chemistry or biology it's around 50 percent. But it could well be that in some fields like computer science it's a much lower number.

MS. McCREARY: Yes, I thought it would be better than when I was in school.

RML: Do you have time to travel to IEEE meetings?

MS. McCREARY: Not since I've been president of the Producers Guild for the past 3 years. I've been woefully missing most of the trade meetings.

Morgan Freeman and Lori McCreary. Photo by John Nowak.

RML: I imagine you have a pretty full plate.

CHF: Turning back to your production company and its work, when you're looking at "revealing truth," what are some of your guiding lights? What are some of the criteria that you take into consideration when you're looking for topics?

MS. McCREARY: We often get stories that have been told before, but if it's a well-known story we look for a new take or a new perspective. For example, you could have made an argument that Nelson Mandela's story had been told many times and quite well. We looked for another "in" to his story that might reveal or highlight something a little different, which happened to be about the South African rugby team.

And we are always looking for stories that we've never heard of. There are so many, especially American stories. I wish I had made *Hidden Figures*. There are so many amazing stories out there that you can't believe no one has told them 100 times already.

CHF: Given the themes you've mentioned it sounds like an overarching theme for you and Revelations is social justice.

MS. McCREARY: I've never thought of it that way, but that is completely where my heart and soul are.

RML: Your description of your early experience with theater makes me wonder whether you feel any inclination to return to Broadway or live theater.

MS. McCREARY: There is nothing I enjoy more than sitting in a theater and the lights come down and the curtain comes up. I really love the medium I'm in right now, but I would consider theater if it was the right project.

We just did a show called *The Story of Us* for National Geographic that deals with the tribalism and "them and us" mentality that seems to be coming out in the world. The fact that we can do that kind of thing and get it on the air in 8 months makes me really love the medium of television and film in a way that is different from theater. A lot more people will see it.

RML: That's true. Lori, as we near the end of this conversation, I want to ask whether there is a message that you, from the perspective of someone who has distinguished herself as a producer of movies, would like to convey to our readers? They include not only the NAE members but members of Congress, schools of engineering, and other individuals interested in science and technology.

MS. McCREARY: As I said, I love storytelling and technology, so I am of two minds. We need technology to help our industry. Before I got into the entertainment industry I thought, 'Wow, when you see what we do with special effects and other things it seems like we are all state-of-the-art.' But we can use help from really smart engineers and technologists. It would be a great team effort if we could come up with some goals to work on together, not only in distribution and anti-piracy efforts but also in production and streamlining productions.

How can we each do something to make engineering more accessible to women and people of different backgrounds?

Another thing is, How can we each do something to make engineering more accessible to women and people of different backgrounds?

RML: That is a subject of great interest in the NAE: not only giving young people a clear understanding of what it means to be an engineer but also making science and technology understandable to the public.

MS. McCREARY: Yes. And there are so many amazing scientists and cosmologists and engineers all over the planet, we wondered, 'Why is no one showcasing the great work they're doing?' They're doing humanitarian work, work that is saving lives, work that makes our days easier through technology—and no one is showcasing them. That's the goal of our show *Through the Wormhole*.

RML: I think people take for granted the fact that when you look at medicine today it makes medicine 20 or 30 years ago look Neanderthal. It's really amazing, but people take it for granted. They just don't perceive the changes that have occurred and the effects that science and engineering have had on these fields—and our way of life.

MS. McCREARY: Absolutely.

CHF: We so appreciate your taking this time to talk with us, Lori. It's been a lot of fun and really interesting.

MS. McCREARY: It has been really fun. Not many people are as interested as you, or I don't think I can speak as bluntly and clearly with people who don't understand the engineering world. It's lovely to be able to have this conversation with you.

RML: It means a lot to the members and to us as well. I think the science and engineering community find it very interesting to discover that there are members of our community who are involved in such disparate parts of our culture, because the typical engineer would never think of some of these activities. We really appreciate your taking the time today.

MS. McCREARY: Thank you so much. And Cameron, Morgan and I are going to be in DC on November 1st for the American Film Institute 100th Anniversary of Movies, 50th Anniversary of AFI, and the 20th anniversary of Revelations—I would love to see if you have time to stop in.

CHF: I can't tell you how disappointed I am, 'though you may not agree with that once you hear why I can't accept your invitation: I'll be in Europe—Budapest, Bruges, Stuttgart….

MS. McCREARY: Very nice! That's a good excuse. We'll get you next time.

CHF: Please do.

RML: Thank you, Lori. We appreciate your taking the time.

CHF: Thanks, Lori.

MS. McCREARY: Thanks so much.

NAE News and Notes

Class of 2018 Elected

In February the NAE elected 83 new members and 16 foreign members, bringing the total US membership to 2,293 and the number of foreign members to 262.

Academy membership honors those who have made outstanding contributions to "engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature," and to "the pioneering of new and developing fields of technology, making major advances in traditional fields of engineering, or developing/implementing innovative approaches to engineering education."

A list of the newly elected members and foreign members follows, with their primary affiliations at the time of election and a brief statement of their principal engineering accomplishments.

New Members

Martín Abadi, principal scientist, Google Inc., Palo Alto, CA. For contributions to the formal theory of computer security.

Norman A. Abrahamson, chief engineering seismologist, Pacific Gas & Electric Co., Piedmont, CA. For contributions to seismic hazard assessment and for leadership in engineering seismology and earthquake engineering.

Robert W. Adams, senior fellow, Analog Devices Inc., Acton, MA. For contributions to digital storage and reproduction of high-fidelity audio.

Ongun Alsaç, consultant, Alsaç Inc., Chandler, AZ. For development of methods and software for electric power industry online grid analysis and optimization.

Pedro J.J. Alvarez, director, Nanosystems Engineering Research Center on Nanotechnology-Enabled Water Treatment, and George R. Brown Professor and chair, Department of Civil and Environmental Engineering, Rice University, Houston. For contributions to the practice and pedagogy of bioremediation and environmental nanotechnology.

Lallit Anand, Warren and Towneley Rohsenow Professor of Mechanical Engineering, Massachusetts Institute of Technology. For contributions to the development of plasticity for engineering technology: theory, experiment, and computation.

Lynden A. Archer, James A. Friend Family Distinguished Professor of Engineering, Smith School of Chemical and Biomolecular Engineering, Cornell University, Ithaca, NY. For advances in nanoparticle-polymer hybrid materials and in electrochemical energy storage technologies.

Aristos Aristidou, director, Biotechnology R&D, Cargill Inc., North Plymouth, MN. For contributions to bioprocess and metabolic engineering for the commercial production of sustainable chemicals and plastics.

Mary T. Barra, chair and chief executive officer, General Motors Co., Detroit. For leadership in automotive manufacturing, product engineering, and product development.

Angela M. Belcher, James Mason Crafts Professor of Biological Engineering and Materials Science and Engineering, Massachusetts Institute of Technology. For development of novel genetic evolution methods for the generation of new materials and devices.

Jeff Bezos, president, chief executive officer, and chair, Amazon.com Inc., and founder and chief executive officer, Blue Origin LLC, Kent, WA. For leadership and innovation in space exploration, autonomous systems, and building a commercial pathway for human space flight.

Dana C. Bookbinder, retired corporate fellow, global research, Corning Inc., Corning, NY. For product and process innovations in vehicle emissions control components and in optical data storage and transmission.

Aine M. Brazil, vice chair, Thornton Tomasetti Inc., Hoboken, NJ. For leadership in the design of innovative buildings and for contributions to engineering literacy.

Constance Jui-Hua Chang-Hasnain, John R. Whinnery Distinguished Chair Professor in Electrical Engineering and Computer Science, University of California, Berkeley. For contributions to wavelength tunable diode lasers and multiwavelength laser arrays.

Hongming Chen, chief scientific officer, Kala Pharmaceuticals Inc., Waltham, MA. For contributions to the research, development, and translation of drug delivery technologies.

Jacqueline H. Chen, distinguished member of the technical staff, Combustion Research Facility, Sandia National Laboratories, Livermore, CA. For contributions to the computational simulation of turbulent reacting flows with complex chemistry.

Margaret Sze-Tai Y. Chu, president, M.S. Chu and Associates LLC, New York City. For contributions and leadership in the US program for permanent disposal of radioactive waste in deep underground repositories.

Carolina Cruz-Neira, director, George W. Donaghey Emerging Analytics Center, and interim chair, Department of Computer Science, University of Arkansas, Little Rock. For contributions to immersive visualization.

Gabriel C. Ejebe, senior project manager, energy trading and markets, Open Access Technology International Inc., Minneapolis. For contributions to electric power system static and dynamic security assessments.

Jennifer Hartt Elisseeff, professor, Wilmer Eye Institute, and professor of biomedical engineering, Johns Hopkins University, Baltimore. For development and commercial translation of injectable biomaterials for regenerative therapies.

Bruce E. Engelmann, chief technology officer, Dassault Systèmes Simulia Corp., Johnston, RI. For development of software for the simulation of complex problems in engineering mechanics.

Dimitar P. Filev, executive technical leader, research and advanced engineering, Ford Motor Co., Dearborn, MI. For contributions to automotive research and practice in the fields of intelligent information and control systems.

Efi Foufoula-Georgiou, Distinguished Professor, Department of Civil and Environmental Engineering, University of California, Irvine. For contributions to hydrology and hydroclimatology with applications to engineered systems across scales.

Edward H. Frank, chief executive officer, Brilliant Lime Inc., San Francisco. For contributions to the development and commercialization of wireless networking products.

Eric E. Fullerton, director, Center for Memory Recording Research, and professor, electrical and computer engineering, Jacobs School of Engineering, University of California, San Diego, La Jolla. For the invention and development of multilayer high-density magnetic recording media.

William H. Gerstenmaier, associate administrator for human exploration and operations, National Aeronautics and Space Administration, Washington. For technical contributions and leadership in national and international human spaceflight programs.

Raymond J. Gorte, Russell Pearce and Elizabeth Crimian Heuer Professor, Department of Chemical and Biomolecular Engineering and Department of Materials Science and Engineering, University of Pennsylvania, Philadelphia. For fundamental contributions and their applications to heterogeneous catalysts and solid state electrochemical devices.

Amit Goyal, director, Research and Education in Energy, Environment, and Water Institute, and Empire Innovation Professor, Departments of Chemical and Biological Engineering, Electrical Engineering, Physics and Materials, Design, and Innovation, University at Buffalo (SUNY-Buffalo), Williamsville, NY. For materials science advances and contributions enabling commercialization of high-temperature superconducting materials.

Stephen C. Graves, Abraham J. Siegel Professor of Management Science, and professor of engineering systems and mechanical engineering, Sloan School of Management, Massachusetts Institute of Technology. For contributions to the modeling and analysis of manufacturing systems and supply chains.

William G. Gray, research professor, University of North Carolina, Chapel Hill, and adjunct professor, Department of Civil and Environmental Engineering, University of Vermont, Burlington. For advances in understanding of the physics of flow and transport in porous media.

Diane B. Greene, chief executive officer, Google Cloud, Google Inc., Mountain View, CA. For contributions in transforming virtualization from a concept to an industry.

David Haussler, Distinguished Professor, biomolecular engineering, University of California, Santa Cruz. For developments in computational learning theory and bioinformatics, including first assembly of the human genome, its analysis, and data sharing.

Chun Huh, research professor, Hildebrand Department of Petroleum and Geosystems Engineering, University of Texas, Austin. For enhancing understanding of ultralow interfacial tensions of oil/surfactant/water systems.

Sanjay Jha, chief executive officer, Globalfoundries Inc., Santa Clara, CA. For leadership in the design and development of semiconductor technology enabling universal digital access.

Ann R. Karagozian, Distinguished Professor, Department of Mechanical and Aerospace Engineering, University of California, Los Angeles. For contributions to combustion and propulsion, education of future aerospace engineers, and service to the country.

Oussama Khatib, director, Stanford Robotics Lab, and professor, Department of Computer Science, Stanford University. For contributions to the understanding, analysis, control, and design of robotic systems operating in complex, unstructured, and dynamic environments.

Brian A. Korgel, Edward S. Hyman Endowed Chair in Engineering and T. Brockett Hudson Professor of Chemical Engineering, University of Texas, Austin. For synthesis and applications of nanocrystals, nanowires, and their assemblies.

John S. Langford III, chair and chief executive officer, Aurora Flight Sciences Corp., Manassas, VA. For application of autonomy and robotics to the design, development, production, and operation of advanced aircraft.

Ming-Jun Li, corporate fellow, global research, Corning Inc., Corning, NY. For product and process inventions and commercial innovations in optical fiber design and transmission systems.

Robert A. Lieberman, president, Lumoptix LLC, Redondo Beach, CA. For innovation, development, and deployment of optical biosensors, physical sensors, and chemical sensors, and for support of international education in optical technologies.

Timothy Charles Lieuwen, executive director, Strategic Energy Institute, and professor and David S. Lewis Jr. Chair, School of Aerospace Engineering, Georgia Institute of Technology, Atlanta. For contributions to research and development in low-emissions gas turbine combustion systems and US energy policy.

David B. Lomet, principal researcher, Microsoft Corp., Redmond, WA. For contributions to high-performance database systems.

Jay R. Lund, director, Center for Watershed Sciences, and Ray B. Krone Professor, Department of Civil and Environmental Engineering, University of California, Davis. For analysis of water and environmental policy issues leading to integrated water resources planning and management.

Ajay P. Malshe, founder, executive vice president, and chief technology officer, NanoMech Inc., and Distinguished Professor, Twenty-First Century Endowed Chair in Materials, Manufacturing and Integrated Systems, University of Arkansas, Fayetteville. For innovations in nanomanufacturing with impact in multiple industry sectors.

Michael J. Mankosa, executive vice president for global technology, Eriez Manufacturing Co., Erie, PA. For engineering contributions to the conception, development, design, and application of advanced separation technologies for mineral processing.

Gary S. May, chancellor, University of California, Davis. For contributions to semiconductor manufacturing research and for innovations in educational programs for underrepresented groups in engineering.

Larry A. Mayer, director, Center for Coastal and Ocean Mapping, and professor, School of Marine Science and Ocean Engineering, University of New Hampshire, Durham. For development of techniques and technologies for coastal, Arctic, and ocean floor mapping.

Charles Meneveau, Louis M. Sardella Professor of Mechanical Engineering, Johns Hopkins University, Baltimore. For contributions to turbulence small-scale dynamics, large-eddy simulations, and wind farm fluid dynamics, and for leadership in the fluid dynamics community.

Jayadev Misra, Schlumberger Centennial Chair Emeritus in Computer Science and University Distinguished Teaching Professor Emeritus, University of Texas, Austin. For contributions to the theory and practice of software verification of concurrent systems.

Dennis A. Muilenburg, chair, president, and chief executive officer, Boeing Co., Chicago. For leadership in defense, space, security, and commercial aircraft.

Oliver C. Mullins, Schlumberger Fellow, Reservoir Characterization Group, Schlumberger, Houston. For developing downhole fluid analysis of oil and gas reservoirs, and elucidating the structure of asphaltenes in crude oils.

Raj Nair, executive vice president and president, North America, Ford Motor Co., Dearborn, MI. For leadership in the design and development of automotive vehicles and the transition to autonomous and electrified vehicles.

Paul F. Nealey, Brady W. Dougan Professor in Molecular Engineering, Institute for Molecular Engineering, University of Chicago. For the development of directed self-assembly of block copolymers as an industrially significant process for nanolithography.

Nils J. Nilsson, Kumagai Professor Emeritus of Engineering, Department of Computer Science, Stanford University, Medford, OR. For foundational contributions to robotics, heuristic search, planning, and machine learning.

Judith S. Olson, Donald Bren Professor Emeritus of Information and Computer Sciences, University of California, Irvine. For leadership, technical innovations, and development of systems that support collaborative work at a distance.

Stanley J. Osher, professor of mathematics, computer science, electrical engineering, chemical and biomolecular engineering, University of California, Los Angeles. For contributions to imaging, computer vision, and graphics, including level-set methods and efficient compressed sensing.

Eleftherios Terry Papoutsakis, Eugene DuPont Chair of Chemical Engineering, Department of Chemical Engineering and Delaware Biotechnology Institute, University of Delaware, Newark. For contributions to metabolic engineering, especially the industrial biotechnology of Clostridia, and to biomanufacturing of therapeutic proteins.

Chandrakant D. Patel, chief engineer and senior fellow, HP Inc., Palo Alto. For contributions in thermal and energy management of information technology systems.

José N. Reyes Jr., cofounder and chief technology officer, NuScale Power LLC, Corvallis, OR. For innovations in small modular nuclear reactor design, nuclear safety, entrepreneurship, and education.

Dean H. Roemmich, professor of oceanography, Scripps Institution of Oceanography, University of California, San Diego, La Jolla. For breakthroughs in ocean observations that have advanced the understanding of Earth's climate system.

David W. Roop, director, electric transmission operations and reliability, Dominion Virginia Power, Richmond, VA. For leadership in electric vehicles, grounding methods, and safety and training in transmission and distribution grid operations.

Barbara Estelle Rusinko, president, Bechtel Nuclear, Security & Environmental Inc., Reston, VA. For leadership of engineering and construction of complex megascale projects.

W. Mark Saltzman, Goizueta Foundation Professor of Biomedical Engineering and Chemical Engineering, Yale University, New Haven. For contributions in drug delivery, biomaterials, and tissue engineering that have led to improved patient treatments.

Ali H. Sayed, Distinguished Professor of Electrical Engineering, University of California, Los Angeles. For contributions to the theory and applications of adaptive signal processing.

David N. Seidman, Walter P. Murphy Professor, Department of Materials Science and Engineering, Northwestern University, Evanston, IL. For contributions to understanding of materials at the atomic scale, leading to advanced materials and processes.

Yang Shao-Horn, W.M. Keck Professor of Energy, Department of Mechanical Engineering and Department of Materials Science and Engineering, Massachusetts Institute of Technology. For contributions to design principles for catalytic activity for oxygen electrocatalysis for electrochemical energy storage for clean energy.

Mukul M. Sharma, W.A. "Tex" Moncrief Jr. Centennial Chair in Petroleum, Geosystems, and Chemical Engineering and professor, Cockrell School of Engineering, University of Texas, Austin. For contributions to the science and technology of production from unconventional hydrocarbon reservoirs.

Jianjun (Jan) Shi, Carolyn J. Stewart Chair and professor, Stewart School of Industrial and Systems Engineering, Georgia Institute of Technology, Atlanta. For development of data fusion-based quality methods and their implementation in multistage manufacturing systems.

Chanan Singh, Regents Professor and Irma Runyon Chair Professor, Department of Electrical and Computer Engineering, Texas A&M University, College Station. For advancement of theory, practice, and education in electric power system reliability.

Susan Mary Smyth, chief scientist for global manufacturing, and director, manufacturing systems research, General Motors Co., Rochester Hills, MI. For leadership in the development and implementation of manufacturing technologies for lightweight and electric vehicles.

Clifford L. Spiro, chief executive officer and founder, CSK Medical, Savannah, GA. For technical leadership in diverse fields ranging from combustion to microelectronics and medical technologies.

Lisa Su, president and chief executive officer, Advanced Micro Devices Inc., Austin, TX. For contributions to silicon-on-insulator technology and industry leadership.

Charles E. Sukup, president, Sukup Manufacturing Co., Sheffield, IA. For contributions to the design and manufacturing of agricultural equipment for grain handling and storage.

Daniel Tassin, president, International Bridge Technologies Inc., San Diego. For leadership in concrete segmental bridge design and construction.

Jerry D. Tersoff, principal research staff member, IBM T.J. Watson Research Center, IBM Corp., Yorktown Heights, NY. For theoretical contributions to the engineering science of materials growth and modeling, nanoscale electronic devices, and semiconductor interfaces.

Susan H. Tousi, senior vice president, product development, Illumina Inc., San Diego. For engineering leadership increasing throughput and decreasing costs of genome sequencing, enabling the path to the $100 human genome.

Peter Trefonas III, corporate fellow, electronic materials R&D, Dow Chemical Co., Marlborough, MA. For invention of photoresist materials and microlithography methods underpinning multiple generations of microelectronics.

David N.C. Tse, professor, Department of Electrical Engineering, Stanford University. For contributions to wireless network information theory.

Bipin V. Vora, founder and principal consultant, Vora International Process Corp., Naperville, IL. For catalytic process innovations leading to commercialized petrochemical technologies.

Lihong Wang, Bren Professor of Medical Engineering and Electrical Engineering, California Institute of Technology, Pasadena. For inventions in photoacoustic microscopy enabling functional, metabolic, and molecular imaging in vivo.

Robert S. Ward, president and chief executive officer, ExThera Medical Corp., Martinez, CA. For engineering and commercialization of biomedical devices and prosthetic implants.

M. Stanley Whittingham, Distinguished Professor, chemistry and materials science and engineering, Binghamton University, NY. For pioneering the application of intercalation chemistry for energy storage materials.

Kevin A. Wise, senior technical fellow, advanced flight controls, Phantom Works, Boeing Defense, Space and Security, Boeing Co., St. Charles, MO. For application of optimal, robust, and adaptive control to aircraft and advanced weapon systems.

New Foreign Members

John Ågren, professor, materials science and engineering, Royal Institute of Technology KTH, Stockholm. For development of integrated thermodynamics and kinetics analysis tools enabling computational materials engineering.

Juan A. Asenjo, professor and director, Center for Biochemical Engineering and Biotechnology, University of Chile, Santiago. For contributions to protein separations for the biotechnology industry and to biotechnology research, development, and entrepreneurship in Chile.

Jesús Carrera, research professor, Institute of Environmental Assessment and Water Research, Spanish Council for Scientific Research, Barcelona. For leadership in the development and application of subsurface flow and transport models in hydrology, mining, and geotechnical engineering.

Tariq S. Durrani, research professor, Department of Electronic and Electrical Engineering, Centre for Excellence in Signal and Image Processing, University of Strathclyde, Glasgow. For innovations in key areas of signal processing and leadership in engineering.

Evangelos S. Eleftheriou, IBM Fellow and senior manager, Cloud and Computing Infrastructure, Zürich Research Laboratory, IBM Corp., Zürich. For contributions to digital storage and nanopositioning technologies, as implemented in hard disk-, tape-, and phase-change memory storage systems.

Peter Fajfar, professor, structural and earthquake engineering, Faculty of Civil and Geodetic Engineering, University of Ljubljana, Slovenia. For leadership in the development of nonlinear structural analysis methods for earthquake engineering.

Jiming Hao, professor and dean, Institute of Environmental Science and Engineering, Tsinghua University, and director, Tsinghua-Toyota Research Center, Beijing. For leadership in the development and implementation of air pollution control theory, strategy, and technologies.

Ashok Jhunjhunwala, professor, Department of Electrical Engineering, Indian Institute of Technology, Madras, Chennai. For innovation and development of affordable technology solutions in communications and energy.

Petros Koumoutsakos, professor and chair, computational science, ETH Zürich. For contributions to computational methods and simulations for fluid mechanics, nanotechnology, and biology.

Lou-Chuang Lee, Distinguished Visiting Chair, Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan. For contributions to space physics and technical leadership in the FORMOSAT/COSMIC satellite program.

Ke Lu, professor and director, Shenyang National Laboratory for Materials Science, and director, Institute of Metal Research, Chinese Academy of Sciences, Shenyang. For discovery of nanotwinned materials and contributions to the advancement of nanostructured materials.

John A.L. Napier, Extraordinary Professor, Department of Mining Engineering, University of Pretoria, Hatfield, South Africa. For contributions to computational simulation of rock fracture around underground excavations.

Mark J. O'Malley, professor of electrical engineering, University College Dublin. For contributions to the integration of wind generation resources into the electric grid.

Sushil K. Soonee, advisor, retired chief executive officer, and founder, Power System Operation Corp. Ltd., New Delhi. For development of operational methods that enabled the interconnection of India's electric power grid.

Trevor David Waite, Scientia Professor, School of Civil and Environmental Engineering, and deputy dean of strategic initiatives, Faculty of Engineering, University of New South Wales, Sydney, Australia. For leadership in water treatment and environmental management.

Wei Yang, president, National Natural Science Foundation of China, Beijing. For contributions to multiscale modeling of mechanical failure and reliability, and leadership in engineering education and research.

NAE Newsmakers

Rakesh Agrawal, Winthrop E. Stone Distinguished Professor, Purdue University, has received the **Alpha Chi Sigma Award for Chemical Engineering Research** from the American Institute of Chemical Engineers. Dr. Agrawal was cited for "synthesizing wide-impact energy processes, developing solution-based routes to fabricate low-cost solar cells, and pioneering a systematic method for the synthesis of multicomponent distillation trains." The award was presented during the AIChE annual meeting in Minneapolis. Dr. Agrawal also delivered the **Peter V. Danckwerts Lecture** at the 10th World Congress of Chemical Engineering in October in Barcelona. The title of his lecture was "Challenges and Opportunities for Chemical Engineering in an Emerging Solar Economy."

Daniel Berg, Distinguished Research Professor of Engineering, University of Miami, has been honored by the International Academy of Information Technology and Quantitative Management (IAITQM) with the creation of the **Daniel Berg Award in Technology and Service Systems** in recognition of his distinguished achievements in those fields. The medal recognizes an individual who has made significant contributions to technology innovation, service systems, and strategic decision making. The inaugural award was presented to **Richard C. Larson**, Mitsui Professor of Engineering Systems and Civil and Environmental Engineering, Massachusetts Institute of Technology, at the Fifth International Conference on Information Technology and Quantitative Management (ITQM 2017) on December 9 at the University of New Delhi, India.

Barbara D. Boyan, dean, School of Engineering, and professor and Goodwin Chair in Tissue Engineering, Virginia Commonwealth University, has received Rice University's **Distinguished Bioengineering Alumna Award** for 2017. The award recognizes Rice alumni whose scholarship, mentorship, and innovations have made significant contributions to their professions and communities. Dr. Boyan is a world-renowned researcher and entrepreneur in the development of impact technologies for bone and cartilage repair.

Stephen H. Davis, McCormick Institute Professor and Walter P. Murphy Professor of Applied Mathematics, Northwestern University, has been **elected to the Academia Europaea**, Europe's academy of humanities, letters, and sciences.

Juan J. de Pablo, Liew Family Professor in Molecular Engineering, University of Chicago, has been selected for the **2018 Polymer Physics Prize** from the American Physical Society, "for his innovative models and algorithms for the simulation of macromolecular systems."

Elazer R. Edelman, Thomas D. and Virginia W. Cabot Professor of Health Sciences and Technology, MIT/Harvard Medical School, has received the **TCT** (Transcatheter Cardiovascular Therapeutics) **2017 Career Achievement Award**. The award, presented October 30, recognizes that he has transformed patient care by bringing together experts from various disciplines to create highly effective and clinically relevant solutions to medical problems. His research has contributed to generations of life-changing devices such as bare-metal and drug-eluting stents.

Farouk El-Baz, director, Center for Remote Sensing, and research professor, Boston University, is the recipient of the **2018 Inamori Ethics Prize**. Case Western Reserve University (CWRU) awards the prize annually to recognize significant and lasting contributions to ethical leadership on the global stage. Dr. El-Baz was part of the team of NASA scientists responsible for choosing the first lunar landing site and also created and still directs a NASA-recognized "Center of Excellence," the Center for Remote Sensing at Boston University. Dr. El-Baz will receive the award during a ceremony and academic symposium September 13–14 at CWRU, during which he will deliver a public lecture about the focus of his research and the challenges ahead.

Bruce R. Ellingwood, professor, Department of Civil and Environmental Engineering, Colorado State University, has received the **Albert Nelson Marquis Lifetime Achievement Award** for his many years' experience in his professional network and for his noted achievements, leadership qualities, and the credentials and successes he has accrued in his field.

Iraj Ershaghi, Omar B. Milligan Professor and director, Petroleum Engineering Program, University of Southern California, received the Society of Petroleum Engineers **Legion of Honor**, which recognizes individuals with 50 years of continuous SPE membership.

Barbara J. Grosz, Higgins Professor of Natural Sciences, SEAS, Harvard University, was chosen to receive the **2017 ACL Lifetime Achievement Award**. The Association of Computational Linguistics recognizes her for seminal contributions to the fields of natural language processing and multiagent systems. Dr. Grosz established the research field of computational modeling of discourse and developed some of the earliest computer dialogue systems. Her work on models of collaboration helped establish that field and has provided the framework for several collaborative multiagent and human-computer interface systems.

Laura M. Haas, dean, University of Massachusetts Amherst, has been awarded a **2017 WITI@UC Athena Award for Executive Leadership** from the Women in Technology Initiative at the University of California. The awards recognize the accomplishments of technology leaders and organizations fostering interest in computer science for the next generation of women and girls. Dr. Haas was recognized during a public symposium exploring innovation and entrepreneurship for women in technology on November 30 at the UC Santa Cruz Silicon Valley Center in Santa Clara.

Jennie S. Hwang, CEO and principal, H-Technologies Group Inc., received the **2017 Distinguished Alumni Award** from Kent State University. The award honors exceptional alumni who, through leadership, character, and hard work, have made outstanding contributions to their profession, communities, and the university.

Chad A. Mirkin, director, International Institute for Nanotechnology and George B. Rathmann Professor of Chemistry, Northwestern University, is a recipient of the **2018 Nano Research Award**. He is being honored for his achievements in nanoscience and nanotechnology, including his invention of dip-pen nanolithography, a suite of cantilever-free scanning probe lithography tools and spherical nucleic acids (SNAs) used in materials and colloidal crystal engineering, extracellular and intracellular molecular diagnostics, gene regulation, and immune modulation therapies. The award will be presented at the June 29–July 2, 2018, Sino-US Nano Forum in Chengdu. Dr. Mirkin has also been selected to receive the **Remsen Memorial Lecture Award** for his outstanding discoveries in chemistry. The award is presented annually by the American Chemical Society, Maryland Section, in conjunction with the Johns Hopkins Department of Chemistry. Dr. Mirkin will give the 73rd Remsen Memorial Lecture on November 15 in Baltimore.

Henry Samueli, cofounder, chair, and CTO, Broadcom Corporation, and **James E. West**, professor of electrical and computer engineering, Johns Hopkins University, have been named to the **2018 STEM Leadership Hall of Fame** by *US News & World Report*. Those selected for this honor have achieved measurable results in fields of science, technology, engineering, and math; challenged established processes and conventional wisdom; inspired a shared vision; and motivated aspiring STEM professionals. The recipients will be honored at an awards luncheon during the "*US News* STEM Solutions Presents Workforce of Tomorrow" conference, April 4–6 in Washington.

Nambirajan Seshadri, independent consultant and former chief technology officer, Broadcom Corporation, has been awarded the **2018 IEEE Alexander Graham Bell Medal** "for contributions to the theory and practice of wireless communications."

Ching W. Tang, Bank of East Asia Professor, Hong Kong University of Science and Technology, has been inducted into the **National Inventors Hall of Fame** for helping to pioneer the organic light-emitting diode (OLED).

Elias A. Zerhouni, president, Global R&D, Sanofi, was awarded **Executive of the Year** at the 13th Annual Scrip Awards in London on November 30. He was recognized for exemplary leadership in his field and commended for his role in the transformation of Sanofi's Research and Development operation into one of the highest performing in the industry.

The American Association for the Advancement of Science has elected its **Class of 2017** members. Included in the new class of 396 are the following NAE members: **Steven J. Battel**, president, Battel Engineering Inc.; **John H. Linehan**, clinical professor of biomedical engineering, Northwestern University; **James J. Riley**, PACCAR Professor of Engineering, University of Washington; **Ares J. Rosakis**, Theodore von Karman Professor of Aeronautics and professor of mechanical engineering, California Institute of Technology; and **Jerry M. Woodall**, Distinguished Professor, University of California, Davis.

The **Chinese Academy of Engineering** recently **elected foreign members**. Among the 18 newly elected are 10 NAE members: **Stephen P. Boyd**, Samsung Professor, School of Engineering, Stanford University; **Ann P. Dowling**, president, Royal Academy of Engineering; **Menachem Elimelech**, Roberto Goizueta Professor of Environmental and Chemical Engineering, Yale University; **William H. Gates Sr.**, cochair, Bill & Melinda Gates Foundation; **Michael R. Hoffmann**, James Irvine Professor of Environmental Science, California Institute of Technology; **S. Jack Hu**, vice president for research and J. Reid and Polly Anderson Professor of Manufacturing, University of Michigan; **Ahsan Kareem**, Robert M. Moran Professor of Engineering, University of Notre Dame; **Kai Li**, Paul M. Wythes '55 P'86 and Marcia R. Wythes P'86 Professor, Princeton University; **Kuo-Nan Liou**, Distinguished Professor of Atmospheric Sciences and director, Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles; **Nicholas A. Peppas**, Cockrell Family Regents Chair in Engineering #6 and professor of biomedical engineering, University of Texas at Austin; and **L. Rafael Reif**, president, Massachusetts Institute of Technology.

The **National Academy of Inventors** will induct its **2017 Class of Fellows** on April 5 during its Seventh Annual NAI Conference to be held in Washington, DC. Election to NAI Fellow status is the highest professional accolade bestowed to academic inventors who have demonstrated a prolific spirit of innovation in creating or facilitating outstanding inventions that have had a tangible impact on quality of life, economic development, and welfare of society. Among the 155 inductees are the following NAE members: **Hiroshi Amano**, professor, Nagoya University; **Diran Apelian**, Alcoa-Howmet Professor of Mechanical Engineering and founding director, Metal Processing Institute, Worcester Polytechnic Institute; **Craig H. Benson**, dean, School of Engineering, University of Virginia; **Donald L. Bitzer**, Distinguished University Research Professor, North Carolina State University; **Yet-Ming Chiang**, Kyocera Professor, Massachusetts Institute of Technology; **Ming Hsieh**, trustee, University of Southern California; **Rakesh K. Jain**, Andrew Werk Cook Professor of Radiation Oncology (Tumor Biology) and director, Edwin L. Steele Laboratories, Harvard Medical School; **Kazunori Kataoka**, Director General of Innovation, Center of NanoMedicine, and professor, University of Tokyo; **Donald B. Keck**, professor, University of South Florida; **Philip T. Krein**, Grainger Endowed Emeritus Chair in Electric Machinery and Electromechanics, University of Illinois at Urbana-Champaign; **Fred C. Lee**, University Distinguished Professor and director, Center for Power Electronics Systems, Virginia Polytechnic Institute and State University; **Sang Yup Lee**, dean, KAIST Institutes, and Distinguished Professor, Korea Advanced Institute of Science & Technology; **Tsu-Jae K. Liu**, TSMC Distinguished Professor in Microelectronics and chair of EECS, University of California, Berkeley; **Kishor C. Mehta**, P.W. Horn Professor of Civil Engineering, Texas Tech University; **C. D. Mote, Jr.**, president, National Academy of Engineering; **Jennifer Rexford**, Gordon Y.S. Wu Professor in Engineering, Princeton University; **Jonathan M. Rothberg**, chair, 4Catalyzer; **Henry Samueli**, cofounder, chair, and CTO, Broadcom Corporation;

Terrence J. Sejnowski, investigator, Howard Hughes Medical Institute, and Francis Crick Professor, Salk Institute for Biological Studies; **Mohammad Shahidehpour**, Bodine Chair Professor, Illinois Institute of Technology; **Krishna P. Singh**, president and chief executive officer, Holtec International; **Andrew J. Viterbi**, Presidential Chair Professor, University of Southern California; **Alan N. Willson Jr.**, Charles P. Reames Professor Emeritus, University of California, Los Angeles; and **Eli Yablonovitch**, professor of electrical engineering and computer sciences, University of California, Berkeley.

2017 EU-US Frontiers of Engineering Hosted by the University of California, Davis

On November 16–18 the EU-US Frontiers of Engineering symposium was held at the University of California, Davis, through the sponsorship of the College of Engineering. The NAE partnered with the European Council of Applied Sciences, Technologies, and Engineering (Euro-CASE). **Michael Tsapatsis**, professor and Amundson Chair of the Department of Chemical Engineering and Materials Science at the University of Minnesota, and Harri Kulmala, CEO of DIMECC Ltd., cochaired the symposium.

The meeting brought together approximately 60 engineers, ages 30–45, from US and European universities, companies, and government labs for a 2½-day meeting, where leading-edge developments in four topics—technologies for space exploration, next-generation solar cells, neuroengineering, and computational imaging—were discussed. Participants attended from the United States and 10 EU countries: Czech Republic, Denmark, Finland, France, Germany, Hungary, Romania, Slovenia, Switzerland, and the United Kingdom.

The first session described advances in technologies for space travel. The session started with a presentation on the electric solar wind sail, a revolutionary propulsion method that promises fast and economic travels through the solar system. The next talk discussed the challenges of placing new vision technologies in planetary landers to enable access to locations that are scientifically compelling but hazardous for landing. The session concluded with a talk on commercial spaceflight entities and the democratization of space, using the services offered by Virgin Orbit as a case study.

The price of electricity from solar panels has dropped dramatically over the past decade, and new materials and devices could significantly decrease the cost even further. Hybrid perovskite materials in particular offer the possibility of dramatically low-cost, high-efficiency, printable solar cells that may be used as a single junction or added to existing technologies like silicon or copper indium gallium selenide (CIGS) to form high-efficiency tandem solar cells. Presentations in this session described the challenges and promise of second- and third-generation photovoltaics, perovskite/silicon tandem solar cells and modules, perovskite quantum

Attendees at EU-US Frontiers of Engineering

EU-US FOE participants enjoyed a tour of the UC Davis Coffee Lab.

dots, and high-efficiency CIGS thin-film solar cells and tandem devices with perovskites.

Engineers and neuroscientists are working together to make breakthroughs in understanding of the brain in order to create innovative medical devices and therapies. The first speaker in the neuroengineering session described technologies for imaging and measuring signals from the brain and how the resulting data can be used to explore new theories in cognitive neuroscience as well as build models of brain function. The next presentation focused on the interface between state-of-the-art organic microelectronics and the human brain. This was followed by a talk about how neural devices are changing the lives of people with movement disorders such as Parkinson's disease and the clinical and ethical implications of using improved technologies for treatment of conditions such as epilepsy and depression. In the final presentation, attendees learned how neurotechnologies are developed and brought to market and the challenges of distributing new neurodevices and neurotherapies worldwide.

End-to-end design of image capture and processing has pushed imaging science to unprecedented resolutions and scales through novel use of computation, enabling gigapixel imagers, superresolution microscopy, 3D imaging, and high dynamic range imaging. The session on computational imaging focused on the core computational problems and hardware designs that can significantly expand imaging capabilities. The first speaker talked about recent advances in computer vision algorithms that use machine learning for 3D scene reconstruction. The next presenter discussed optical imaging in biological and complex networks. The concluding talk described how to use computational tricks to speed up MRI scans by several orders of magnitude without sacrificing resolution, enabling real-time MRI imaging of dynamic events.

The dinner speaker on the first evening was Chancellor **Gary S. May**, who noted that UC Davis is the most academically comprehensive university on the West Coast and the most diverse large national research university in the United States, with 26 percent of new undergraduates who enrolled in 2017 from historically underrepresented groups.

Besides the formal presentations, a poster session preceded by flash poster talks was held on the first afternoon. This served as both an icebreaker and an opportunity for all participants to share information about their research and technical work. On the second afternoon the group enjoyed tours of UC Davis's Wine and Food Science Center, Coffee Lab, and Design Center. In addition, a number of the engineering faculty joined the sessions and the dinners, and the resulting interactions enriched the attendees' experience.

Financial support for the symposium was provided by the University of California, Davis, The Grainger Foundation, and the National Science Foundation. The NAE would especially like to thank UC Davis Dean of Engineering Jennifer Sinclair Curtis and NAE member **Subhash Mahajan** for their support of this activity.

The next EU-US FOE will be held in 2019, and the Royal Swedish Academy of Engineering Sciences will assume the organizational role for the EU side. Michael Tsapatsis will continue as US cochair.

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

New Community Manager for *EngineerGirl* and Online Ethics Center

The Program Office is pleased to welcome **Mary Mathias** as the new community manager for *EngineerGirl* and the Online Ethics Center (OEC). She will work with Simil Raghavan and Beth Cady.

Mary joins the NAE from the web and communications teams of the American Astronomical Society (AAS), and previously worked as communications manager for the Association of Science-Technology Centers (ASTC). At AAS she maintained a number of society-associated websites, created content, and edited and published user-submitted posts and events. At ASTC she led the development of the ASTC Community, a website for discussion and resource sharing among museum professionals around the world. She also managed ASTC's social media presence and nearly doubled the association's following on both Facebook and Twitter.

Mary holds a BS in aerospace engineering from Washington University in St. Louis and will finish her master's in museum studies at Johns Hopkins University this spring. For her master's degree she is exploring the communication strategies of science museums and their work with the public.

Mary Mathias

Message from NAE Vice President Corale L. Brierley

Corale Brierley

I am thrilled to report that more than 652 members and friends of the NAE invested more than $5.3 million in new cash and pledges in 2017. Thank you!

Because of your tremendous support, the NAE was able to promote engineering to young girls who want to change the world; teachers across the country gained access to online resources in order to better educate their students in engineering; and nearly 1,000 industry experts and undergraduate students from around the world convened in Washington for the Third Global Grand Challenges Summit.

These and other programs are possible *because of you*.

As a nonprofit organization, the NAE relies heavily on support from its members and friends. In 2017 private philanthropic support made up nearly one third of the NAE's annual budget. I am grateful for your confidence in NAE leadership. Your generosity enables the NAE to serve the engineering community, young people, policymakers, and the public.

In addition to recognizing our Annual Giving Society donors, I would like to welcome new members of the Einstein Society (5), Golden Bridge Society (19), and Heritage Society (1). It is also worth noting that we once again can boast 100% giving participation from the NAE Council leadership—this marks three years in a row! I hope you will make note of the new giving society members and thank them and all the generous NAE donors named in the following pages.

Challenge Update

In October 2016 NAE chair **Gordon England** announced a matching challenge grant to motivate members to pledge their support of the NAE. Thanks to his leadership, six more challenges were initiated. I am thrilled to report that the five challenges for 2017 met and surpassed their goals—*congratulations to Sections 1, 2, 4, 5, and 7 for a successful year!*

There are four $100,000 matching challenge grants for 2018: **R. Noel Longuemare** has challenged Section 1, the **Arindam Bose** family has challenged Section 2, **Chad Holliday** has challenged Section 8, and the **Blankenship** family has challenged Section 12. Please visit the NAE website at www.nae.edu/giving for information about these matching challenges and to see the results from 2017.

Onward

The NAE furthers its mission *to advance the well-being of the nation* by promoting a vibrant engineering profession and by marshalling the expertise and insights of eminent engineers to provide independent advice to the federal government on matters involving engineering and technology. Your ongoing philanthropic investment ensures a solid foundation from which to sustain important projects and spearhead inspiring new programs.

The energy and vision of our members and friends make it possible for the NAE to drive forward. Thank you for your continued support.

Corale L Brierley

Corale L. Brierley

PS Keep an eye out for the *2017 Annual Report*, which will be available online this summer. It will provide a more comprehensive list of the year's gifts and donors, and present a detailed financial report for the Academy.

For more information about ways to give, please contact:

Radka Nebesky, Director of Development
202.334.3417 or RNebesky@nae.edu

Lauren Bartolozzi, Associate Director of Development
202.334.3258 or LBartolozzi@nae.edu

2017 Honor Roll of Donors

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

Lifetime Giving Societies

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

Einstein Society

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

$10 million or more

Arnold and Mabel **Beckman***
Bernard M. Gordon
Fred Kavli*
Daniel E. Koshland, Jr.*
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Raymond* and Beverly Sackler
James H. and Marilyn Simons

$5 million to $9.9 million

Donald L. Bren
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$1 million to $4.9 million

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$500,000 to $999,999

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Andrew and Erna* **Viterbi**
Alan M. Voorhees*
Anonymous (1)

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Janet and **Richard M.*** **Morrow**
Ralph S. O'Connor
Kenneth H. Olsen*

*Deceased

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Stephen* and Anne Ryan
Henry and Susan **Samueli**
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Golden Bridge Society

In recognition of NAE members and friends who have made lifetime contributions totaling $20,000 to $99,999. Boldfaced names are NAE members.

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During the 2016 annual meeting, Chairman Gordon England announced the creation of a $100,000 Chairman's Challenge for Section 1 that he personally funded and asked others to join him in creating matching gift challenges for each section by the 2017 annual meeting. Donors who participated in the Chairman's Challenge are noted with the # symbol.

Fran Ligler, a member of the NAE Council, and her husband George pledged $100,000 in 2015 to encourage new and increased giving by Section 2 members for five years, or until the $100,000 goal is reached. Members who participated in the Ligler Challenge are noted with the † symbol.

In response to the Chairman's Challenge, Paul Boulos gave $25,000 to fund a challenge for Section 4. Donors who participated in the Section 4 Challenge are noted with the ◊ symbol.

In response to the Chairman's Challenge, Tom Leighton, Gordon Bell, and Bob Sproull gave $100,000 to fund a challenge for Section 5. Donors who participated in the Section 5 Challenge are noted with the Ω symbol.

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Calendar of Meetings and Events

March 1–31	Election of NAE Officers and Councillors
March 21	NAE Regional Meeting: Anticipating the Future: Historical Narratives, Imagination, and Innovation Chemical Heritage Foundation, Philadelphia
March 28	NAE Regional Meeting University of California, San Diego
April 4	NAE Regional Meeting: Geoscience on Earth and Beyond Schlumberger, Houston
April 5–6	Workshop on Reinventing Power Programs through Sustainability-focused Curriculum
April 23–24	NAE-AAES Convocation and AAES General Assembly Meeting
May 3	NAE Regional Meeting: Transforming Health Care through Engineering University of Wisconsin–Madison
May 10–11	NAE Council Meeting
May 22	2018 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education Presentation Stanford University
May 24	Perspectives on Global Climate Change Case Western Reserve University, Cleveland
June 18–20	Japan-America Frontiers of Engineering Tsukuba
July 16	NAE-CAE Symposium: Human and Artificial Intelligence 2.0 CAE Headquarters, Beijing

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

In Memoriam

WALTER L. BROWN, 93, adjunct professor of material science and engineering, Lehigh University, died October 29, 2017. Dr. Brown was elected to the NAE in 1986 for discovery of semiconductor surface channels crucial in field effect transistors, and for contributions to ion beam uses in semiconductor diagnostics and processing.

NAI Y. CHEN, 91, Distinguished Research Professor, University of Texas at Arlington, died March 30, 2017. Dr. Chen was elected to the NAE in 1990 for discovery of commercially important shape-selective catalytic processes for producing premium fuels and lubricants.

ZVI HASHIN, 88, professor emeritus, Mechanics of Solids, Tel Aviv University, died October 29, 2017. Dr. Hashin was elected a foreign member of the NAE in 1998 for contributions to the theory and technology of advanced composite materials.

MAX A. KOHLER, 102, retired associate director, National Weather Service, died October 12, 2017. Dr. Kohler was elected to the NAE in 1981 for leadership in advancing the science of hydrology through research and international collaboration.

ALAN LAWLEY, 84, professor emeritus, Drexel University, died October 17, 2017. Dr. Lawley was elected to the NAE in 1998 for the science and practice of powder metallurgy processing.

JOSEPH C. LOGUE, 93, retired fellow and director, Packaging Technology, IBM Thomas J. Watson Research Center, died February 11, 2014. Mr. Logue was elected in 1983 for contributions and leadership in the design, development, and manufacture of computer circuits and data processing equipment.

JAMES E. TURNER JR., 83, retired president and chief operating officer, General Dynamics Corporation, died December 27, 2017. Mr. Turner was elected to the NAE in 1998 for leading the implementation of innovative engineering and design processes and establishing a new standard for naval ship design and acquisition.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street NW–Keck 360, Washington, DC 20055. For more information or to place an order, contact NAP online at <*www.nap.edu*> or by phone at (888) 624-6242. *(Note: Prices quoted are subject to change without notice. There is a 10 percent discount for online orders when you sign up for a MyNAP account. Add $6.50 for shipping and handling for the first book and $1.50 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NY, NC, VA, WI, or Canada.)*

Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2017 Symposium. This volume presents papers on the topics covered at the NAE's 2017 US Frontiers of Engineering Symposium. Every year the symposium brings together 100 outstanding young leaders in engineering to share their cutting-edge research and innovations in selected areas. The 2017 symposium was held September 25–27 at the United Technologies Research Center in East Hartford. The intent of this book is to convey the excitement of this unique meeting and to highlight innovative developments in engineering research and technical work.

NAE member **Robert D. Braun**, dean, College of Engineering and Applied Science, University of Colorado Boulder, chaired the symposium organizing committee. Paper, $45.00.

Engineering Societies and Undergraduate Engineering Education: Proceedings of a Workshop. Engineering professional societies in the United States engage in a range of activities involving undergraduate education, but these activities generally are not coordinated and have not been assessed either in a way that information about their procedures and outcomes can be shared or to determine whether they are optimally configured to mesh with corresponding initiatives by industry and academia. Engineering societies work largely independently on undergraduate education, raising the question of how much more effective their efforts could be if they worked more collaboratively—with each other as well as with academia and industry. To explore the potential for enhancing societies' role at the undergraduate level, the NAE held a workshop on the engagement of engineering societies in undergraduate engineering education. This publication summarizes the workshop presentations and discussions.

NAE members on the workshop steering committee were **Leah H. Jamieson** (chair), Ransburg Distinguished Professor, Electrical and Computer Engineering, and John A. Edwardson Dean Emerita of Engineering, Purdue University; **Don P. Giddens**, professor, Emory University, and dean emeritus, College of Engineering, Wallace H Coulter Department of Biomedical Engineering, Georgia Institute of Technology; **Asad M. Madni**, independent consultant, and retired president, COO, and CTO, BEI Technologies Inc.; and **John C. Wall**, retired vice president and CTO, Cummins Inc. Paper, $45.00.

Fostering Integrity in Research. The integrity of knowledge that emerges from research is based on individual and collective adherence to core values of objectivity, honesty, openness, fairness, accountability, and stewardship. Organizations in which research is conducted must encourage those involved to exemplify these values in every step of the research process. Understanding the dynamics that support—or distort—practices that uphold the integrity of research by all participants can ensure that the research enterprise advances knowledge. The 1992 National Academies report *Responsible Science: Ensuring the Integrity of the Research Process*, which evaluated issues related to scientific responsibility and the conduct of research, was for 25 years a crucial basis for thinking about research integrity. Now—as experience has accumulated with various forms of research misconduct, detrimental research practices, and other forms of misconduct; as empirical research has revealed more about the nature of scientific misconduct; and as technological and social changes have altered the environment in which science is conducted—it is clear that the 1992 framework needs to be updated. *Fostering Integrity in Research* identifies best practices in research and recommends practical options for discouraging and addressing research misconduct and detrimental research practices.

NAE members on the study committee were **Robert M. Nerem** (chair), Institute Professor and

Parker H. Petit Professor Emeritus, Institute for Bioengineering and Bioscience, Georgia Institute of Technology; and **Rebecca M. Bergman**, president, Gustavus Adolphus College. Paper, $54.00.

Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light. The laser revolutionized many areas of science and society, transforming scientific investigation and enabling trillions of dollars of commerce. Now a second laser revolution is under way with pulsed petawatt-class lasers (1 petawatt = 1 million billion watts) that deliver nearly 100 times the world's total power in a pulse that lasts less than one-trillionth of a second. Such light sources can accelerate and collide intense beams of elementary particles, drive nuclear reactions, heat matter to conditions found in stars, or even create matter out of the empty vacuum. These powerful lasers came largely from US engineering but, while the principal research funding agencies in Europe and Asia began in the last decade to invest heavily in new facilities that will employ these high-intensity lasers for fundamental and applied science, no similar programs exist in the United States. This report assesses the opportunities and recommends a path forward for possible US investments in this area of science.

NAE members on the study committee were **Elsa M. Garmire**, Sydney E. Junkins 1887 Professor of Engineering Emerita, Dartmouth College; **Jacqueline G. Gish**, retired director of advanced technology, Northrop Grumman Aerospace Systems; **Marshall G. Jones**, Coolidge Fellow, GE Global Research; **Peter F. Moulton**, senior staff, MIT Lincoln Laboratory; **C. Kumar N. Patel**, president and CEO, Pranalytica Inc.; and **Eli Yablonovitch**, professor of electrical engineering and computer sciences, University of California, Berkeley. Paper, $150.00.

An Assessment of the Smart Manufacturing Activities at the National Institute of Standards and Technology Engineering Laboratory: Fiscal Year 2017. The mission of the Engineering Laboratory (EL) of the National Institute of Standards and Technology (NIST) is to "promote US innovation and industrial competitiveness by advancing measurement science, standards, and technology for engineered systems in ways that enhance economic security and improve quality of life." To support this mission the EL has developed strategic goals and programs in smart manufacturing, construction, and cyberphysical systems; in sustainable and energy-efficient manufacturing materials and infrastructure; and in disaster-resilient buildings, infrastructure, and communities. The technical work of the EL is performed in five divisions—Intelligent Systems, Materials and Structural Systems, Energy and Environment, Systems Integration, and Fire Research—and in two offices, on Applied Economics and the Smart Grid. At the request of NIST's acting director, the National Academies of Sciences, Engineering, and Medicine assesses the scientific and technical work performed by the EL. This publication reviews technical reports and program descriptions prepared by NIST staff and summarizes the findings of the authoring panel.

NAE members on the study panel were **Hadi Abu-Akeel**, cofounder and chief robotics officer, Robotics & Intellectual Property; **Joseph J. Beaman Jr.**, professor of mechanical engineering, University of Texas at Austin; **Dianne Chong**, retired vice president, Materials, Manufacturing Structure & Support, Boeing Research and Technology; **David E. Crow**, professor of mechanical engineering, University of Connecticut, and retired senior vice president of engineering, Pratt and Whitney; **S. Jack Hu**, vice president for research and J. Reid and Polly Anderson Professor of Manufacturing, University of Michigan; **Eugene S. Meieran**, Intel Senior Fellow (ret.), Intel Corporation; **William F. Powers**, vice president (ret.), research, Ford Motor Company; **H. Donald Ratliff**, Regents' Professor and executive director, Supply Chain & Logistics Institute, Georgia Institute of Technology; **Emanuel M. Sachs**, chair, Scientific Advisory Board, 1366 Technologies Inc., and professor post tenure, Massachusetts Institute of Technology; **Laurence C. Seifert**, executive vice president (ret.), AT&T Wireless Group, AT&T Corporation; chair, Airbiquity; chair, Entomo; and director, iFoodDecisionSciences LLC; **F. Stan Settles**, professor emeritus, Viterbi School of Engineering, University of Southern California; and **David D. Yao**, Piyasombatkul Family Professor, Industrial Engineering and Operations Research, Columbia University. Free PDF.

An Assessment of the National Institute of Standards and Technology Material Measurement Laboratory: Fiscal Year 2017. This report assesses the scientific and technical work performed by the NIST Material Measurement Laboratory. It reviews technical reports and program descriptions prepared by NIST staff and summarizes the findings of the authoring panel.

NAE members on the study panel were **Elsa Reichmanis** (chair), professor, Department of Chemical & Biomolecular Engineering, Georgia Institute of Technology; **Nicholas L. Abbott**, John T. and Magdalen L. Sobota Professor, Department of Chemical and Biological Engineering, University of Wisconsin–Madison; **Richard C. Alkire**, Charles and Dorothy Prizer Chair Emeritus, Department of Chemical and Biomolecular Engineering, University of Illinois at Urbana-Champaign; **Kevin R. Anderson**, Mercury Senior Fellow, Brunswick Corporation–Mercury Marine Division; **Philip A. Bernstein**, Distinguished Scientist, Microsoft Corporation; **Dennis E. Discher**, Robert D. Bent Professor, University of Pennsylvania; **Jennie S. Hwang**, CEO, H-Technologies Group; **Warren C. Oliver**, president, Nanomechanics Inc.; **Isaac C. Sanchez**, William J. Murray Jr. Endowed Chair in Engineering, Department of Chemical Engineering, University of Texas; **Subhash C. Singhal**, Battelle Fellow Emeritus, Pacific Northwest National Laboratory; **Anil V. Virkar**, professor and chair, Department of Materials Science and Engineering, University of Utah; and **James C. Wyant**, professor emeritus, College of Optical Sciences, University of Arizona. Free PDF.

Innovations in Federal Statistics: Combining Data Sources While Protecting Privacy. Federal government statistics provide critical information to the country and serve a key role in a democracy. For decades, sample surveys with instruments carefully designed for particular data needs have been one of the primary methods for collecting data for federal statistics. However, the costs of conducting such surveys have been rising while response rates have been declining, and many surveys are not able to fulfill growing demands for more timely information and for more detailed information at state and local levels. This report proposes a paradigm shift in federal statistical programs that would use combinations of diverse data sources from government and private sector sources in place of a single census, survey, or administrative record. This first publication of a two-part series discusses the challenges faced by the federal statistical system and the foundational elements needed for a new paradigm.

NAE member **Cynthia Dwork**, Distinguished Scientist, Computer and Information Sciences, Microsoft Research, was a member of the study panel. Paper, $58.00.

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