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Editor's Note

Features

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NAE News and Notes

Editor's Note

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The Promise of Engineering

Each year the US Frontiers of Engineering (US FOE) Symposium brings together outstanding engineers, ages 30 to 45, to share ideas, network, and learn about cutting-edge research across a spectrum of topics relevant to advancing society. The competitively selected attendees come from a wide range of backgrounds and have a variety of interests and expertise. The symposium offers participants a unique opportunity to meet emerging leaders across a range of disciplines, learn about the latest research trends and potential breakthroughs in engineering areas other than their own, and facilitate collaborative work and the transfer of new approaches and techniques across fields. Through both formal sessions and informal discussions, these annual meetings have proven an effective mechanism for the establishment of cross-disciplinary and cross-sector contacts among the participants.

On September 9–11, approximately 100 emerging engineering leaders from academia, industry, and government gathered at the Arnold and Mabel Beckman Center in Irvine, California. The meeting was organized in four sessions with the following themes: Cybersecurity and Privacy, Engineering the Search for Earth-like Exoplanets, Optical and Mechanical Metamaterials, and Forecasting Natural Disasters. Eight papers, representing the highly engaging topics covered by this year's presentations, were selected for publication in this issue of the *Bridge*.[1]

[1] All 15 symposium presentations can be viewed at www.naefrontiers.org/symposia/USFOE.aspx.

The first session focused on Cybersecurity and Privacy in a society that is increasingly dependent on networked computer systems and software. Cochaired by David Brumley of Carnegie Mellon University and Daniela Oliveira of the University of Florida, the session explored the development of sound methods and practices to protect computer systems from attack and users from privacy threats created by ubiquitous computer systems. It is a daunting task to secure systems against not just lone individuals but also nation-states using computer systems to carry out political and military agendas. The speakers led insightful discussions of engineering security including layers of abstraction, the engineering of secure medical devices, and engineered systems that protect user privacy. In this issue, papers by Franziska Roesner (University of Washington) and Kevin Fu (University of Michigan) address human factors aspects of cybersecurity and the engineering of secure medical devices.

The session on Engineering the Search for Earth-Like Exoplanets, cochaired by Mitchell Walker of Georgia Tech and Sara Seager of MIT, looked at the technologies and capabilities needed to find and identify Earth-like exoplanets among the hundreds of billions of stars in the Milky Way galaxy and hundreds of billions of galaxies in our universe. In particular, speakers highlighted starlight suppression technologies and the deployment and construction of large optical telescopes. After a description of the enabling technologies and observing capabilities of the NASA James Webb Space Telescope, planned for launch in 2018, the audience heard about technologies that suppress starlight so that the planet light that enters the telescope is accentuated. The session concluded with a presentation on the construction of large structures in space, either through large deployables or space-based assembly, and the control requirements and capabilities required for such systems. In these pages, Dmitry Savransky (Cornell University) and Jeffrey Banik (Air Force Research Laboratory) review the technologies needed for starlight suppression and on-orbit construction.

In the session on Optical and Mechanical Metamaterials, cochaired by Jennifer Dionne of Stanford University and Luke Sweatlock of Northrop Grumman, speakers described the rapidly increasing ability to engineer properties of high-performance materials for applications ranging from high-efficiency energy production and storage to advanced medical imaging and therapeutics. They illustrated the design of composites whose properties derive as much from their structure as from their composition, and described mechanical metamaterials, advanced nano- and microscale manufacturing of large-area metamaterials, optical metamaterials and metasurfaces, and microelectromechanical devices. Papers by Christopher Spadaccini (Lawrence Livermore National Laboratory) and Julia Greer (Caltech) convey the mechanical advances enabled by engineering systems at the micro- and nanoscale.

The final session focused on engineering capability to forecast natural disasters, with a look into the future of useful forecasts, effective messaging, and avoidance of catastrophic societal failures. Presentations addressed the future of probabilistic, quantitative natural hazard risk assessment in support of risk management, the role of human behavioral bias and poor decision making, and risk assessment and management opportunities provided by new technologies. Cochaired by Amir AghaKouchak (UC Irvine) and James Done (National Center for Atmospheric Research), the session reviewed hurricane modelling, damage and risk assessment, and the rapid public dissemination of accurate knowledge about the state of our dynamic planet. In this issue, Ning Lin (Princeton) and Jeffrey Czajkowski (University of Pennsylvania) report engineering advances in hurricane modelling and risk assessment.

In addition to the presentations, FOE symposia provide time for lively Q&A sessions, panel discussions, and other activities that promote personal interactions and networking. At this year's meeting the dinner speaker, a traditional highlight of the program, was Dr. Corale Brierley, vice president of the National Academy of Engineering and an expert in mining, metallurgy, and microbiology. She presented an engaging perspective on the role of microorganisms in the mining industry in a talk entitled "The Black Swan."

As chair of the 2015 US FOE symposium, I would like to express my sincere gratitude to the NAE staff whose boundless energy and enthusiasm made this program a success. Specifically, I appreciate the tireless contributions of Janet Hunziker, NAE senior program officer, who went to great lengths to make this event, and this community, feel so special. I also thank Al Romig, executive officer of the National Academy of Engineering, and Mitchell Walker for stepping in, at the last minute, to help lead the symposium forward when a family medical issue complicated my participation. And I thank the sponsors of this year's symposium: The Grainger Foundation, DARPA, NSF, AFOSR, DOD ASDR&E STEM Development Office, Microsoft Inc., and Cummins Inc.

It is an honor to serve as chair of the organizing committee for the US FOE Symposia. As a young engineer and US FOE participant in 2000, this program means a great deal to me. I recall leaving the 2000 symposium invigorated about the future of our profession. Chairing this symposium 15 years later, I can attest to the enthusiasm and promise of the emerging engineering leaders who participated in this year's symposium. Our profession remains in good hands.

Looking forward, I encourage you to nominate eligible colleagues for the September 2016 US FOE Symposium, to be held in Houston.

User-driven access control improves users' security and privacy by changing the system to better match their expectations, rather than the other way around.

Computer Security and Privacy

Where Human Factors Meet Engineering

Franziska Roesner

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As the world becomes more computerized and interconnected, computer security and privacy will continue to increase in importance. In this paper I review several computer security and privacy challenges faced by end users of the technologies we build, and considerations for designing and building technologies that better match user expectations with respect to security and privacy. I conclude with a brief discussion of open challenges in computer security and privacy where engineering meets human behavior.

Introduction

Over the past several decades new technologies have brought benefits to almost all aspects of daily life for people all over the world, transforming how they work, communicate, and interact with each other.

Unfortunately, however, new technologies also bring new and serious security and privacy risks. For example, smartphone malware is on the rise, often tricking unsuspecting users by appearing as compromised versions of familiar, legitimate applications (Ballano 2011); by recent reports, more than 350,000 variants of Android malware have been identified (e.g., Sophos 2014). These malicious applications incur direct and indirect costs by stealing financial and other information or by secretly sending costly premium SMS messages. Privacy is also a growing concern on the web, as advertisers and others secretly track user browsing behaviors, giving rise to ongoing efforts at "do not track" technology and legislation.[1]

Such concerns cast a shadow on modern and emerging computing platforms that otherwise provide great benefits. The need to address these and other computer-related security and privacy risks will only increase in importance as the world becomes more computerized and interconnected. This paper focuses specifically on computer security and privacy at the intersection of human factors and the engineering of new computer systems.

Designing with a "Security Mindset"

It is vital to approach the engineering design process with a "security mindset" that attempts to anticipate and mitigate unexpected and potentially dangerous ways technologies might be (mis)used. Research on computer security and privacy aims to systematize such efforts by (1) studying and developing cryptographic techniques, (2) analyzing or attempting to attack deployed technologies, (3) measuring deployed technical ecosystems (e.g., the web), (4) studying human factors, and (5) designing and building new technologies. Some of these (e.g., cryptography or usable security) are academic subdisciplines unto themselves, but all work together and inform each other to improve the security and privacy properties of existing and emerging technologies.

> *Computer security and privacy challenges arise when users' expectations don't match the actual properties and behaviors of the technologies they use.*

Many computer security and privacy challenges arise when the expectations of end users don't match the actual security and privacy properties and behaviors of the technologies they use—for example, when installed applications secretly send premium SMS messages or leak a user's location to advertisers, or when invisible trackers observe a user's behavior on the web.

There are two general approaches to try to mitigate these discrepancies. One involves trying to help users change their mental models about the technologies they use to be more accurate (e.g., to help users think twice before installing suspicious-looking applications), by educating them about the risks and/or by carefully designing the user interfaces (UIs) of app stores. Recent work by Bravo-Lillo and colleagues (2013) on designing security-decision UIs to make them harder for users to ignore is a nice example of this approach.

The alternative is to *(re)design technologies themselves* so that they better match the security and privacy properties that users intuitively expect, by "maintaining agreement between a system's security state and the user's mental model" (Yee 2004, p. 48).

Both approaches are valuable and complementary. This paper explores the second: designing security and privacy properties in computer systems in a way that goes beyond taking human factors into account to actively remove from users the burden of explicitly managing their security and/or privacy at all. To illustrate the power of this approach, I review research on user-driven access control and then highlight other recent examples.

Rethinking Smartphone Permissions with User-Driven Access Control

Consider smartphones (such as iOS, Android, or Windows Phone), other modern operating systems (such as recent versions of Windows and Mac OS X), and browsers. All of these platforms both allow users to install arbitrary applications and limit the capabilities of those applications in an attempt to protect users from potentially malicious or "buggy" applications. Thus, by default, applications cannot access sensitive resources or devices like the file system, microphone, camera, or GPS. However, to carry out their intended functionality, many applications need access to these resources.

Thus an open question in modern computing platforms in recent years has been: How should untrusted applications be granted permissions to access sensitive resources?

Challenges

Most current platforms explicitly ask users to make the decision about access. For example, iOS prompts users

[1] Congress introduced, but did not enact, the Do-Not-Track Online Act of 2013, S.418. Available at https://www.congress.gov/bill/113th-congress/senate-bill/418.

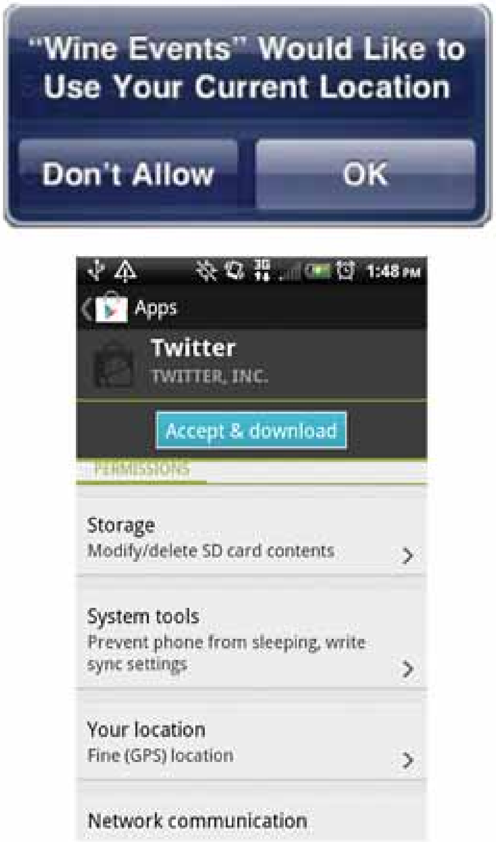

FIGURE 1 Existing permission-granting mechanisms that require the user to make explicit decisions: runtime prompts (as in iOS, above) and install-time manifests (as in Android, below).

to decide whether an application may access a sensitive feature such as location, and Android asks users to agree to an install-time manifest of permissions requested by an application[2] (figure 1).

Unfortunately, these permission-granting approaches place too much burden on users. Install-time manifests are often ignored or not understood by users (Felt et al. 2012a), and permission prompts are disruptive to the user's experience, teaching users to ignore and click through them (Motiee et al. 2010). Users thus unintentionally grant applications too many permissions and become vulnerable to applications that use the permissions in malicious or questionable ways (e.g., secretly sending SMS messages or leaking location information).

In addition to outright malware (Ballano 2011), studies have shown that even legitimate smartphone applications commonly leak or misuse private user data, such as by sending it to advertisers (e.g., Enck et al. 2010).

Toward a New Approach

It may be possible to reduce the frequency and extent of an application's illegitimate permissions by better communicating application risks to users (e.g., Kelley et al. 2013) or redesigning permission prompts (e.g., Bravo-Lillo et al. 2013). However, my colleagues and I found in a user survey that people have existing expectations about how applications use permissions; many believe, for example, that an application cannot (or at least will not) access a sensitive resource like the camera unless it is related to the user's activities within the application (Roesner et al. 2012b). In reality, however, after being granted the permission to access the camera (or another sensitive resource) once, Android and iOS applications can continue to access it in the background without the user's knowledge.

Access Based on User Intent

This finding speaks for an alternate approach: modifying the system to better match user expectations about permission granting. To that end, we developed *user-driven access control* (Roesner et al. 2012b) as a new model for granting permissions in modern operating systems.

Rather than asking the user to make explicit permission decisions, user-driven access control grants permissions automatically based on existing user actions within applications. The underlying insight is that *users already implicitly indicate the intent to grant a permission through the way they naturally interact with an application*. For example, a user who clicks on the "video call" button in a video chat application implicitly indicates the intent to allow the application to access the camera and microphone until the call is terminated.

If the operating system could interpret the user's permission-granting intent based on this action, it would not need to additionally prompt the user to make an explicit decision about permissions and it could limit the application's access to a time intended by the user. The challenge, however, is that the operating system cannot by default interpret the user's actions in the custom user interfaces (e.g., application-specific buttons) of all possible applications.

Access Control Gadgets

To allow the operating system to interpret permission-granting intent, we developed *access control gadgets*

[2] Android M will use runtime prompts similar to iOS instead of its traditional install-time manifest.

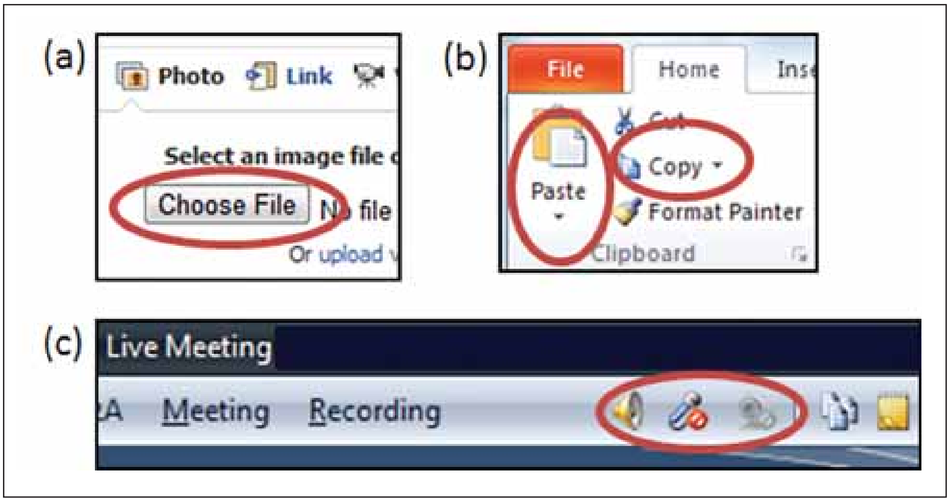

FIGURE 2 Access control gadgets (ACGs) are system-controlled user interface elements that allow the operating system to capture a user's implicit intent to grant a permission (e.g., to allow an application to access the camera).

(ACGs), special, system-controlled user interface elements that grant permissions to the embedding application. For example, in a video chat application, the "video call" button is replaced by a system-controlled ACG. Figure 2 shows additional examples of permission-related UI elements that can be easily replaced by ACGs to enable user-driven access control.

The general principle of user-driven access control has been introduced before (as discussed below), but ACGs make it practical and generalizable to multiple sensitive resources and permissions, including those that involve the device's location and clipboard, files, camera, and microphone. User-driven access control is powerful because it improves users' security and privacy by changing the system to better match their expectations, rather than the other way around. That is, users' experience interacting with their applications is unchanged while the underlying permissions granted to applications match the users' expectations.

Other Examples

User-driven access control follows philosophically from Yee (2004) and a number of other works. CapDesk (Miller 2006) and Polaris (Stiegler et al. 2006) were experimental desktop computer systems that applied a similar approach to file system access, giving applications minimal privileges but allowing users to grant applications permission to access individual files via a "powerbox" user interface (essentially a secure file picking dialog). Shirley and Evans (2008) proposed a system (prototyped for file resources) that attempts to infer a user's access control intent from the history of user behavior. And BLADE (Lu et al. 2010) attempts to infer the authenticity of browser-based file downloads using similar techniques. Related ideas have recently appeared in mainstream commercial systems, including Mac OS X and Windows 8,[3] whose file picking designs also share the underlying user-driven access control philosophy.

Note that automatically managing permissions based on a user's interactions with applications may not always be the most appropriate solution. Felt and colleagues (2012b) recommended combining a user-driven access control approach for some permissions (e.g., file access) with other approaches (e.g., prompts or post facto auditing) that work more naturally for other permissions or contexts. The approach of designing systems to better and more seamlessly meet users' security and privacy expectations is much more general than the challenges surrounding application permissions discussed above.

Following are a few of the systems that are intentionally designed to better and more automatically match users' security and privacy expectations. Such efforts are often well complemented by work that attempts to better communicate with or educate users by changing the designs of user interfaces.

Personal Communications

To secure communications between two parties, available tools like PGP have long faced usability challenges (Whitten and Tygar 1999). Efforts that remove the burden from users while providing stronger security and privacy include Vanish (Geambasu et al. 2009), which supports messages that automatically "disappear" after a period of time; ShadowCrypt (He et al. 2014), which

[3] Apple posted information in 2011 on the "App sandbox and the Mac app store" (available at https://developer.apple.com/videos/wwdc/2011/); and Windows information on "Accessing files with file pickers" is available at http://msdn.microsoft.com/en-us/library/windows/apps/hh465174.aspx.

replaces existing user input elements on websites with ones that transparently encrypt and later decrypt user input; and Gyrus (Jang et al. 2014), which ensures that only content that a user has intended to enter into a user input element is what is actually sent over the network ("what you see is what you send").

Commercially, communication platforms like email and chat are increasingly moving toward providing transparent end-to-end encryption (e.g., Somogyi 2014), though more work remains to be done (Unger et al. 2015). For example, the security of journalists' communications with sensitive sources has come into question in recent years and requires a technical effort that provides low-friction security and privacy properties to these communications (McGregor et al. 2015).

User Authentication

Another security challenge faced by many systems is that of user authentication, which is typically handled with passwords or similar approaches, all of which have known usability and/or security issues (Bonneau et al. 2012). One approach to secure a user's accounts is two-factor authentication, in which a user must provide a second identifying factor in addition to a password (e.g., a code provided by an app on the user's phone). Two-factor authentication provides improved security and is seeing commercial uptake, but it decreases usability; efforts like PhoneAuth (Czeskis et al. 2012) aim to balance these factors by using the user's phone as a second factor only opportunistically when it happens to be available.

Online Tracking

As a final example, user expectations about security and privacy don't match the reality of today's systems with respect to privacy on the web. People's browsing behaviors are invisibly tracked by third-party advertisers, website analytics engines, and social media sites.

In earlier work we discovered that social media trackers, such as Facebook's "Like" or Twitter's "tweet" button, represent a significant fraction of trackers on popular websites (Roesner et al. 2012a). To mitigate the associated privacy concerns, we applied a user-driven access control design philosophy to develop ShareMeNot, which allows tracking *only when* the user clicks the associated social media button. ShareMeNot's techniques have been integrated into the Electronic Frontier Foundation's Privacy Badger tool (https://www.eff.org/privacybadger), which automatically detects and selectively blocks trackers without requiring explicit user input.

Challenges for the Future

New technologies are improving and transforming people's lives, but they also bring with them new and serious security and privacy concerns. Balancing the desired functionality provided by increasingly sophisticated technologies with security, privacy, and usability remains an important challenge.

This paper has illustrated efforts across several contexts to achieve this balance by designing computer systems that remove the burden from the user. However, more work remains to be done in all of these and other domains, particularly in emerging areas that rely on ubiquitous sensors, such as the augmented reality technologies of Google Glass and Microsoft HoloLens.

By understanding and anticipating these challenges early enough, and by applying the right insights and design philosophies, it will be possible to improve the security, privacy, and usability of emerging technologies before they become widespread.

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To enhance the safety and effectiveness of emerging medical devices, manufacturers need to more deliberately address cybersecurity risks during the initial engineering and design.

On the Technical Debt of Medical Device Security

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Kevin Fu

Cybersecurity shortfalls in medical devices trace to decisions made during early engineering and design. The industry is now paying the cybersecurity "technical debt" for this shortsightedness.

Introduction

Computer networking, wireless communication, wireless power, the Internet, and a host of other engineering innovations, combined with electronic health records and the reengineering of clinical workflow, have enabled innovative therapeutics and diagnostics—but at the cost of information security and privacy, or *cybersecurity*.

Complexity breeds technological insecurity. In the last few decades, medical devices have evolved from simple analog components to complex digital systems with an amalgam of software, circuits, and advanced power sources that are much more difficult to validate and verify. Whereas a classic stethoscope depended on well-understood analog components, modern devices such as linear accelerators, pacemakers, drug infusion pumps, and patient monitors depend critically on computer technology.

When a medical device is compromised, its behavior becomes unpredictable: the device may deliver incorrect diagnostic information to clinicians, be unavailable to deliver patient care during repair, and, in extreme cases, cause patient harm. Lack of security may even introduce an

FIGURE 1 An old drug compounder running on a consumer operating system, Windows XP Embedded, was infected with malware, according to a US Food and Drug Administration Manufacturer and User Facility Device Experience (MAUDE) adverse event report in 2010. A former engineer from the company later explained that the malware was accidentally spread to other compounders during the repair. © Kevin Fu.

unconventional dimension of risk to safety and effectiveness: intentional harm.

Much cybersecurity risk is attributable to legacy medical devices dependent on Windows XP and other unmaintainable operating systems that no longer receive security patches (figure 1). But proprietary embedded systems are no less vulnerable.

Complexity introduced at the design stage is the root cause of many cybersecurity problems, not hackers. Complexity increases the *attack surface*, the points of unintended access to a computer system. By uncovering the implications of the flaws baked in from early engineering choices, hackers are merely the "collectors" and messengers of this cybersecurity technical debt.

Brief History of Medical Device Security

Research: Case Studies

There's a rich history of efforts to ensure trustworthy medical device software (Fu 2011). The classic and eye-opening Therac-25 study showed how a linear accelerator caused a number of injuries and deaths from massive radiation overdoses in the late 1980s and early 1990s (Leveson and Turner 1993). While project mismanagement, complacency, and overconfidence in unrealistic probabilities played a role, the most interesting root cause was the adoption of poorly designed software instead of well-understood analog components to safely control the radiation delivery.

More recently, research on ways to improve medical device security led to an interdisciplinary paper on the security of an implantable cardiac defibrillator (Halperin et al. 2008). The study took several years because of the interdisciplinary nature of the problem and clinical challenges such as attending live surgery to fully understand the threat model. In the paper my colleagues and I demonstrated that it was possible to wirelessly disable the device's life-saving shocks and induce ventricular fibrillation (a deadly heart rhythm).[1]

We articulated the engineering principle that a secure medical device should not be able to run an operation that causes it to induce the hazardous state (in this instance, ventricular fibrillation) it is designed to prevent. The paper also includes a number of defensive approaches primarily centered on the concept of zero-power security, requiring the provision of wireless power to ensure that the implant can protect the availability of its precious battery power. And, importantly, our research showed that, despite the security risks, patients predisposed to health risks who are prescribed a wireless medical device are far safer accepting the device than not.

The Role of Hackers

A few years later, the hacker community began to replicate academic experiments on medical devices. Barnaby Jack famously replicated our pacemaker/defibrillator experiment in a manner more appealing to the general public. Although formal peer-reviewed proceedings were rare, the hackers gave captivating talks and pointed demonstrations that attracted attention to the subject. The hacker community began to find new security flaws in medical devices such as insulin pumps and infusion pumps (e.g., demonstrations by Billy Rios, Barnaby Jack, Jay Radcliffe, Scott Erven, and others). The hacker community uncovered security vulnerabilities that have led to unprecedented FDA actions.

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[1] The device has not been sold for several years, and the manufacturer established a rigorous training program for security engineering.

National Facilities for Medical Device Security

To promote deeper intellectual inquiry into medical device security, I created the Open Medical Device Research Library (OMDRL) to collect and share hard-to-find implants with security researchers. Unfortunately, the demand did not justify the high cost of biohazard decontamination, and computer science staff were uncomfortable with managing biohazard facilities, so the library was short lived. However, researchers from MIT did engage with the OMDRL to invent a novel radio frequency (RF) jamming protocol that blocks legacy implanted cardiac devices from transmitting insecure "plaintext" messages and overlays an encrypted version (Gollakota et al. 2011).

Device manufacturers have difficulty testing beyond the component level because of (1) the diverse array of configurations and interoperating medical devices and (2) uncertain risk to patients during live testing. For this reason, the OMDRL is adapting from a library to a testbed at the University of Michigan.

The notional Bring Your Own Hospital (BYOH) testbed, as part of the Archimedes Center for Medical Device Security (secure-medicine.org), will enable security testing and experimentation on systems of medical devices with automated and highly configurable threat simulators to better prepare manufacturers and hospitals to cope with the changing threat landscape. Efforts will include control studies to compare the effectiveness of different hospital information security policies, and emergency preparedness "fire drills" to train manufacturers and clinicians on how to respond to cyberattacks and malware infections that affect the timely delivery of care. The first experiment involves mapping out the infection vectors created by reuse of USB drives to understand how fast infections can spread in clinical facilities and determine the most effective ways to control an outbreak.

Recent Federal and Other Measures

In July 2015, a few days after the National Highway Traffic Safety Administration issued the first recall of an automobile solely because of a cybersecurity risk (Kessler 2015), Hospira became the first medical device company to receive an FDA (2015) safety communication because of a cybersecurity risk. Although not legally a recall, the FDA notice had a similar effect: the agency strongly discouraged healthcare facilities from purchasing the company's infusion pump because of a cybersecurity vulnerability that could let hackers induce over- or underinfusion of drugs and thus potentially cause patient harm.

In addition, FDA (2014) premarket guidance on cybersecurity calls for a technical cybersecurity risk analysis in all applications for premarket clearance to sell medical devices in the United States. And the FDA is expected to release a postmarket guidance document on coordinated vulnerability disclosure, incident reporting, and continuous surveillance of emerging cybersecurity risks. The preparation of this document is more complicated because it involves a number of unusual bedfellows, ranging from the vulnerability research community to the Department of Homeland Security to the US Computer Emergency Response Team.

Complementing these federal measures, the Association for the Advancement of Medical Instrumentation (AAMI) sets the major standards for medical device safety. The AAMI medical device security working group consists of both healthcare providers and medical device engineers who have written a technical information report (TIR 57) (currently under ballot) that provides much-needed advice to engineers on how to think methodically about cybersecurity across the product development lifecycle of a medical device.

Analog Cybersecurity

Many of the vulnerabilities and solutions (figure 2) for medical device security involve analog cybersecurity. Cybersecurity risks that begin in the analog world can

FIGURE 2 My former students and I cofounded Virta Labs, Inc. to detect malware and anomalies on medical devices using a smart power outlet rather than installed software. Machine learning and side channels in reactive AC power enable detection in a manner that does not cause alarm fatigue (Clark et al. 2013).

infect the digital world by exploiting semipermeable digital abstractions. Analog cybersecurity is the focus of research on side channels and fault injection attacks that transcend traditional boundaries of computation. Security problems tend to occur in boundary conditions where different abstractions meet. In particular, the analog-digital abstraction poses subtle security weaknesses for cyberphysical systems such as medical devices and the Internet of Things.

Researchers have demonstrated how an adversary can violate widely held computing abstractions as fundamental as the value of a bit. For example, ionizing radiation and computing faults cause smartcards and processors to divulge cryptographic secrets (Boneh et al. 2001; Pellegrini et al. 2010). Intentional electromagnetic interference causes sensors to deliver incorrect digital values to closed-loop feedback systems such as pacemakers (Kune et al. 2013). Acoustic and mechanical vibrations cause drones to malfunction by hitting the resonant frequency of a microelectromechanical systems (MEMS) gyroscope (Son et al. 2015). The row hammer attack[2] enabled malicious flipping of bits in computer memory to adjacent physical rows of memory (Kim et al. 2014). The GSMem paper (Guri et al. 2015) shows how computer memory can emit RF signals in cellular frequencies.

Such analog cybersecurity weaknesses will likely remain a significant challenge for automated systems such as medical devices. Traditional research and education in cybersecurity focus on software flaws and solutions. I believe that threats to the digital abstraction represent the next frontier of security engineering. The Internet of Things and cyberphysical systems such as medical devices, automobiles, and aircraft have awakened interest in analog threats affecting digital vulnerabilities that have physical consequences.

Conclusion

Medical devices help patients lead more normal and healthy lives. The innovation of such devices results from a complex interplay of medicine, computer engineering, computer science, human factors, and other disciplines, and this complexity breeds design-induced cybersecurity risks.

The greatest near-term risk is old malware that accidentally breaks into clinical systems running old operating systems, causing damage to the integrity and availability of medical devices and in turn interrupting clinical workflow and patient care. While targeted malware will likely become a problem in the future, medical devices are currently challenged by basic cybersecurity hygiene, such as hospitals spreading malware with USB drives or vendors infecting their own products by accident.

To enhance the trustworthiness of emerging medical devices and patients' confidence in them, manufacturers need to address cybersecurity risks during the initial engineering and design, and maintain postmarket surveillance throughout the product lifecycle.

Acknowledgments

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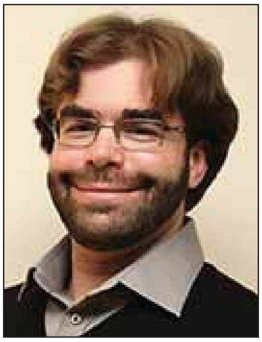
Advances in adaptive optics, coronagraphy, and telescopes will enhance exoplanet detection, but the best chance of directly imaging an Earth-like planet lies in space.

Starlight Suppression
Technologies for Direct Imaging of Exoplanets



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Dmitry Savransky

Of the nearly 2,000 planets confirmed to exist outside the solar system, only a handful were detected directly rather than inferred from their interaction with the stars they orbit. The vast majority were discovered by sifting years of observations of thousands of stars for periodic changes in the stars' colors or fluxes, which indicate an orbiting planet.

Imaging allows for planetary detection with just one observation and confirmation with a few observations taken only months apart. More importantly, it enables spectroscopic characterization of exoplanets, often at spectral resolutions significantly exceeding those possible with any other detection method. With spectroscopy it is possible to probe the atmospheric and, potentially, surface composition of exoplanets and to validate models of planet formation and evolution.

Imaging is therefore a crucial component of exoplanet detection and characterization. Exoplanet imagers in ground observatories are already producing exciting discoveries (Macintosh et al. 2015), and the next generation of space instrumentation has the potential to detect Earth-like planets and indications of the presence of life.

This short paper reviews the challenges of exoplanet imaging, techniques used to overcome them, and the status of technology development for exoplanet imagers in space.

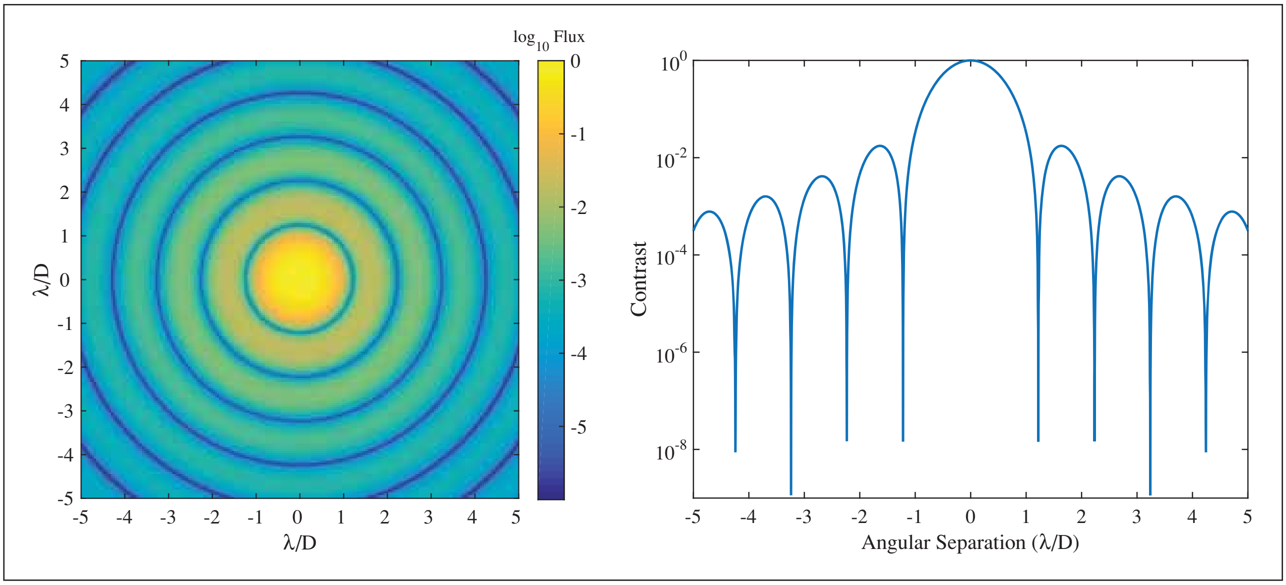

FIGURE 1 Numerical simulation of an Airy disk—the impulse response of a circular aperture. *Left:* Image of a point source, with color indicating intensity in log scale. *Right:* The (radially symmetric) contrast profile of the image. λ = wavelength; *D* = aperture diameter.

Imaging of Exoplanets

A telescope operates by collecting light from an astronomical source using a finite-sized aperture—either the entrance pupil of a refractive system or the primary mirror of a reflective one—and bringing the light to a focus on an imaging detector, such as a charge-coupled device (CCD). Diffraction effects limit the spatial resolving capabilities of telescopes, with angular resolution inversely proportional to the size of the aperture. For a circular pupil the minimum angular resolution (α_r) of the system will be greater than approximately $1.22\lambda/D$, where λ is the wavelength of light and D the diameter of the aperture. This is most easily understood by considering the point spread function (PSF) of the telescope—the impulse response generated by imaging a point source.

For a circular aperture, the PSF is an Airy disk, shown in figure 1—a bright central spot of radius α_r surrounded by a series of annuli that decrease exponentially in brightness with angular separation. Between these annuli are small, dark regions called *nulls*.

Planets are significantly fainter than their host stars, with contrasts of 10^6 for the very brightest, self-luminous, young Jovian planets, and 10^{10} for Earth-sized planets in reflected visible light. Even if it were possible to observe a planet when it was precisely located on one of the deeper nulls of a perfect, diffraction-limited telescope, it would still not be possible to image it, as no detector has the dynamic range required to capture both the signals from the planet and the PSF of the star in the same image.

Coronagraphy

Fortunately, this problem was partially solved in the early 20th century by solar astronomers studying the sun's corona, which is 1 million times fainter than the sun itself. Previously, the corona could be studied only during full solar eclipses. In the 1930s, however, Bernard Lyot demonstrated the first solar coronagraph—a system designed specifically to block bright, on-axis sources and thus enable the study of faint, off-axis ones (Lyot 1939).

Figure 2 shows a schematic view of a Lyot (pron. Lee-*o*′) coronagraph, along with images taken at the pupil of a coronagraphic system. The pupil is conjugate with the entrance pupil of the whole system, so that the first image, where no coronagraph elements are in place, is equivalent to the intensity distribution seen by the entrance aperture of the whole system. The central dark spot in the first image is due to the secondary mirror that partially obscures the primary aperture in this system. On-axis starlight, together with off-axis planet light, enters the telescope and is brought to a focus where the on-axis source is blocked by a small, hard-edged focal plane mask (FPM). The remaining light is propagated to the next pupil plane (middle image). Most of the starlight is blocked by the FPM, but some will diffract around the mask's edges, creating telescope design, and most coronagraphs remove some of the planet light along with the starlight. Many coronagraph designs are also highly sensitive to misalignment, vibration, and optical surface errors.

Coronagraphs being evaluated for use in space all rely on active wavefront control via deformable mirrors, which have only recently begun to be demonstrated for use in space (Cahoy et al. 2014).

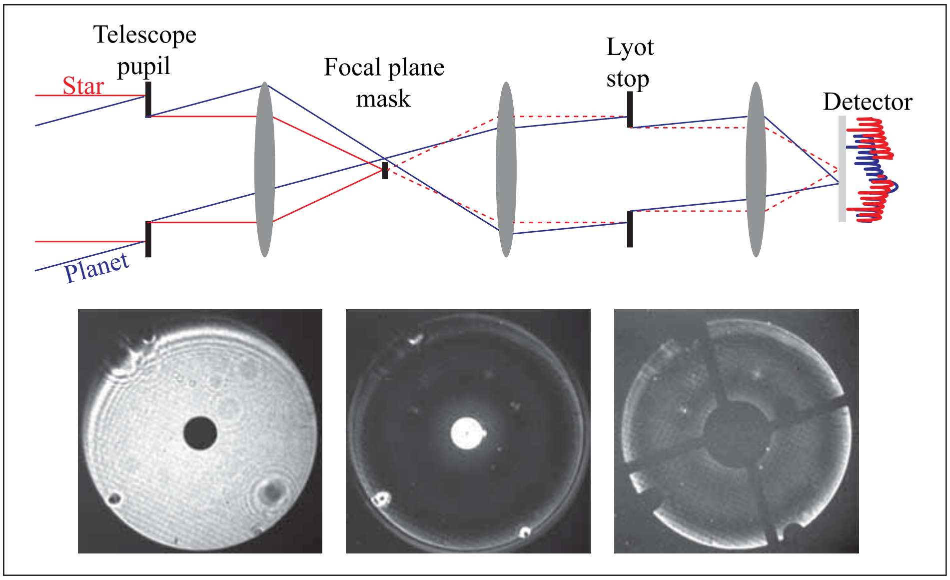

FIGURE 2 *Top:* Schematic of a Lyot coronagraph. Based on Sivaramakrishnan et al. (2001). *Bottom:* Images taken at the pupil plane of the Lyot stop showing (left) the unobscured entrance pupil, (middle) only the focal plane mask, and (right) both the focal plane mask and Lyot stop. Each image is individually stretched and the final image has less than 1% of the light in the first image.

a pattern of rings along with a bright central spot. The remaining light is blocked by introducing another hard-edged mask, called a *Lyot stop*, into the pupil, leaving very little residual light, as shown in the image on the right. The Lyot stop can also include additional features to handle diffraction about other mechanical elements, such as struts that hold up the secondary mirror.

To deal with residual diffracted light in the classical Lyot coronagraph, an additional pupil plane can be introduced before the FPM with a partially transmissive mask to apodize the beam and minimize diffraction effects downstream (Soummer 2005). An alternate approach is to introduce a specially shaped hard-edged pupil ahead of the FPM to change the PSF so it is no longer radially symmetric, leaving high-contrast regions in the downstream focal plane (Kasdin et al. 2005).

Other strategies involve replacing the hard-edged FPM of the original Lyot coronagraph with a phase-shift mask to produce destructive interference of the on-axis light (i.e., the starlight cancels itself out, while planet light is mostly unaffected; Roddier and Roddier 1997). One can also achieve the beam apodization by using pupil-mapping mirrors to change the geometrical redistribution of the light (Guyon et al. 2005).

All of these approaches have various pros and cons, but all share the same basic limitations. Coronagraphs are still limited by the diffraction limit of the telescope. A coronagraph's design is highly specific to a particular

Starshades

An alternate approach, first suggested by Lyman Spitzer (1962), involves blocking the starlight before it enters the telescope. This method requires a space telescope to fly in formation, over a baseline of tens of thousands of kilometers, with an occulting spacecraft, or *starshade*. The starshade must be tens of meters in diameter and specifically shaped, as diffraction effects would cause light to be scattered back into the shadow cast by a simple flat plate. Fortunately,

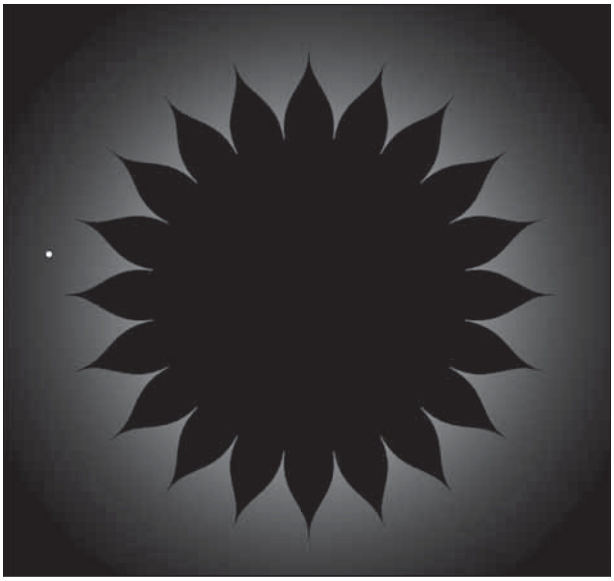

FIGURE 3 Schematic view of a starshade as seen by an occulted telescope. The starshade creates a shadow region of high contrast at the telescope aperture, allowing for exoplanets to be detected. Starshade design from Vanderbei et al. (2007).

by Babinet's principle, the occulter is complementary to a pinhole camera, allowing starshades to be designed in much the same way as shaped pupil masks for internal coronagraphs, via numerical optimization (Vanderbei et al. 2007). This allows for constraints to be placed on minimum feature sizes to ensure that the produced designs are manufacturable. The resulting optimized shapes are radially symmetric, with a circular central core surrounded by petal-like extensions (figure 3).

The main advantage of starshades is that they can achieve high contrasts with any conventional telescope design and without any active wavefront control. Furthermore, the minimum angular separation of a detectable planet for a starshade is determined solely by geometry—the size of the starshade and its distance from the telescope—and is the same at all wavelengths.

On the other hand, while a telescope with an internal coronagraph merely needs to pivot in order to observe a new target, a starshade must be repositioned over large distances, with weeks of slew time between observations, leading to fewer stars observed and making scheduling optimization more difficult (Savransky et al. 2010). Starshade contrasts are also highly sensitive to shape, positioning, and alignment errors, leading to µm order manufacturing tolerances, mm deployment tolerances, and meter-scale alignment tolerances throughout the course of an observation (Shaklan et al. 2010). The requirement for precise alignment for extended periods also makes formation flying more difficult in geocentric orbits, so that most starshade mission concepts plan for operations in orbit about the second Earth-Sun Lagrange point (Kolemen et al. 2012). Finally, unlike coronagraphs, it is impossible to fully test starshades on the ground, so proxy experiments must be developed to build confidence in this technique (Sirbu et al. 2014).

Current and Future Exoplanet Imagers

Multiple exoplanet imagers, such as the Gemini Planet Imager (Macintosh et al. 2014) and SPHERE (Sauvage et al. 2013), are currently operating at some of the largest ground-based observatories. These instruments couple advanced coronagraphs with extreme adaptive optics systems (Tyson 2010), which correct for the effects of the turbulent atmosphere, to produce the highest levels of contrast ever demonstrated from the ground. Still, these systems will be able to detect only the very youngest, self-luminous giant planets on relatively large orbits—akin to Jupiter in the first 100 million years of its existence.

Advances in adaptive optics and coronagraphy, and the construction of the next generation of extremely large telescopes, will allow for the detection of smaller, older planets, but the best chance of directly imaging and getting spectra of an Earth-like planet lies in space.

NASA is developing a coronagraphic instrument for the Wide Field Infrared Space Telescope (WFIRST; Spergel et al. 2015), the next major astrophysics mission to be launched after the James Webb Space Telescope.

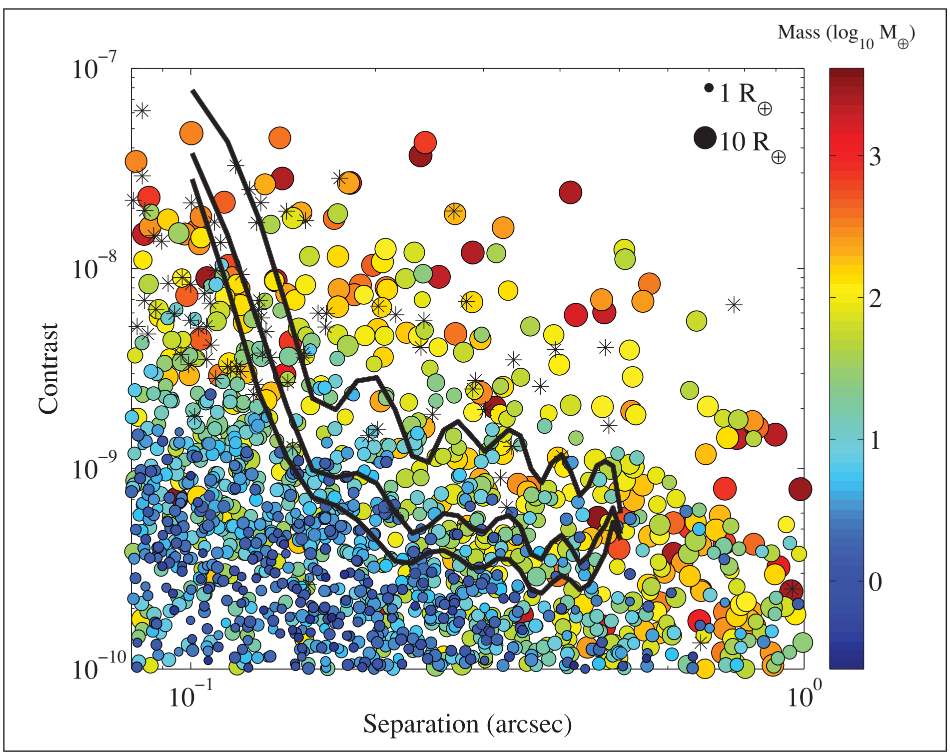

FIGURE 4 Colored points represent a simulated population of exoplanets based on prior surveys; asterisks represent contrast estimates for known, indirectly detected exoplanets at their most favorable viewing geometries; and the black lines are the predicted contrasts for one design of the Wide Field Infrared Space Telescope (WFIRST) coronagraph at various levels of telescope stability. M⊕ = mass of Earth; R⊕ = radius of Earth. Based on Savransky (2013).

The WFIRST coronagraph will be capable of detecting a wide variety of exoplanets, ranging from those like Neptune to "super-Earths," a class of potentially rocky planets up to twice the radius of the Earth that do not exist in our solar system.

Figure 4 shows a simulation of the population of planets around nearby stars, based on statistics from indirect surveys (Fressin et al. 2013; Howard et al. 2010), along with the expected contrast of one design for the WFIRST coronagraph with varying assumptions of telescope stability (Krist 2014).

The NASA Astrophysics Division has sponsored two science and technology definition teams to study $1 billion mission concepts based on a starshade (Exo-S) and coronagraph (Exo-C).[1] These and other concept studies are helping to identify the remaining engineering challenges in direct imaging and guide technology development programs.

These efforts may lead to the operation of a space-based direct imaging instrument in the next decade, producing exciting new science and helping validate the technologies needed to discover Earth-like planets and perhaps even alien life.

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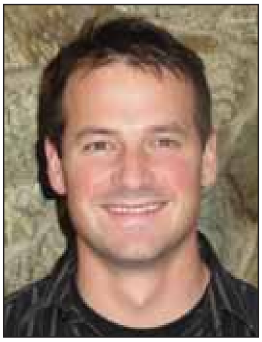
Emerging technologies are opening the door to a new era of space structures that will greatly enhance exploration and discovery.

Realizing Large Structures in Space

Jeremy A. Banik



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Since the dawn of space access in 1957 the size of spacecraft payloads and solar arrays has steadily grown. Yet the demand for larger antenna arrays and telescope mirrors and higher power on spacecraft continues to outpace availability.

Background

Large structures in space have one simple purpose: to support payloads that manipulate the electromagnetic spectrum. Telescopes operate at short wavelengths for astronomy and surveillance missions, from ultraviolet to near infrared. Star shades block visible sunlight for direct imaging of Earth-like planets. Sun shields reject the shortwave spectrum to keep instruments cool. Solar sails reflect photons in the short wave, generating constant propulsion for interplanetary exploration and station-keeping maneuvers.

For practical Earth-based applications, communication and radar antennas transmit and receive microwaves for communications, coarse imaging, and object tracking. The larger the antenna or radar in space, the smaller the antenna on a soldier's back and the greater number of objects tracked. Photovoltaic solar arrays convert photons to electrons for charging satellite batteries. Radio frequency missions require larger antennas to generate higher-resolution radar imaging for Earth science, and to keep up with the higher data throughput demands of modern hand-held devices.

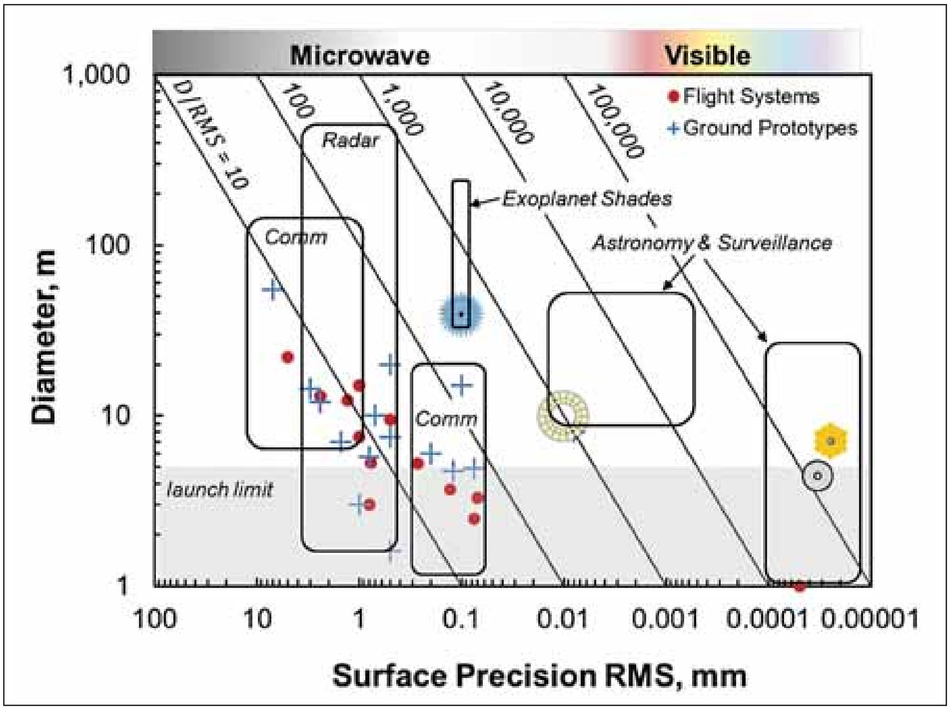

FIGURE 1 Size and surface figure precision are indirectly related in space structure design. Boxes indicate the current art of the possible. Comm = communications; JWST = James Webb Space Telescope; MOIRE = Membrane Optical Imager for Real-Time Exploitation; RMS = root mean square.

In each of these examples the larger the space structure, the more effective the mission data return. Exoplanet discovery is no exception. Larger optical mirrors and bigger starshade occulters are needed to detect both a larger number of stars, thus increasing Earth-like exoplanet discovery opportunities, and a broad range of the electromagnetic spectrum for exoplanet spectral characterization.

But the design, construction, and deployment of larger antennas and mirrors are fraught with highly specialized challenges. The largest commercial radio frequency antenna on-orbit is 22 meters in diameter, and the largest space telescope mirror is 6.5 meters. These structures must be designed to hold extreme dimensional precision and stability tolerances.

Optical and radio signal quality are directly related to the precision of the surface from which the signal emanates. The larger the structure, the more difficult it is to achieve a given figure precision. Radio frequency missions operate on long wavelengths so precision requirements are not as stringent as for optical missions, but because signal gain scales inversely with the square of wavelength, radio antennas require larger apertures than optical.

Once unfolded in space, these structures face extreme temperature swings that can cause large static and dynamic dimensional changes. Spacecraft in a geosynchronous orbit endure daily temperature swings from −200°C to +200°C over a typical 15-year lifetime. Materials must exhibit a low coefficient of thermal expansion, and assembly interfaces are extensively tested to control the characteristics of such expansion.

Current Capabilities and Constraints

Figure 1 illustrates the indirect relationship between structure size and dimensional precision. As this ratio grows, payload cost escalates. Some of the highest-performing space structures to date are represented on this chart, yet they are restricted to relatively low diameter-to-precision ratios when compared to future needs in the tens to hundreds of meters.

Aside from dimensional precision challenges, large space structures must also be folded compactly for a violent trip to orbit. Once designed, built, and stowed in a 5 meter launch vehicle fairing, these payloads endure 10 to 70 g peak accelerations during the 10-minute trip to low Earth orbit, reaching a velocity of 7 km/s. Once on-orbit, the structure must unfold precisely and reliably.

As an example, an exoplanet starshade must unfurl from 5 meters to 34 meters into a shape that is within 0.1 mm precision, approximately the width of a human hair, across a span similar to an eight-lane interstate overpass. Figure 2 and table 1 show the relative scale of the largest launch vehicles, the typical large structures that must stow in them, and the respective packaging ratios.

The mechanical approach thus far for realizing large communication antennas, telescopes, and radar antennas has generally been to fold a deep truss structure and self-deploy using multiple pin-clevis joints, motors, torsion springs, and dampers. This approach has led to

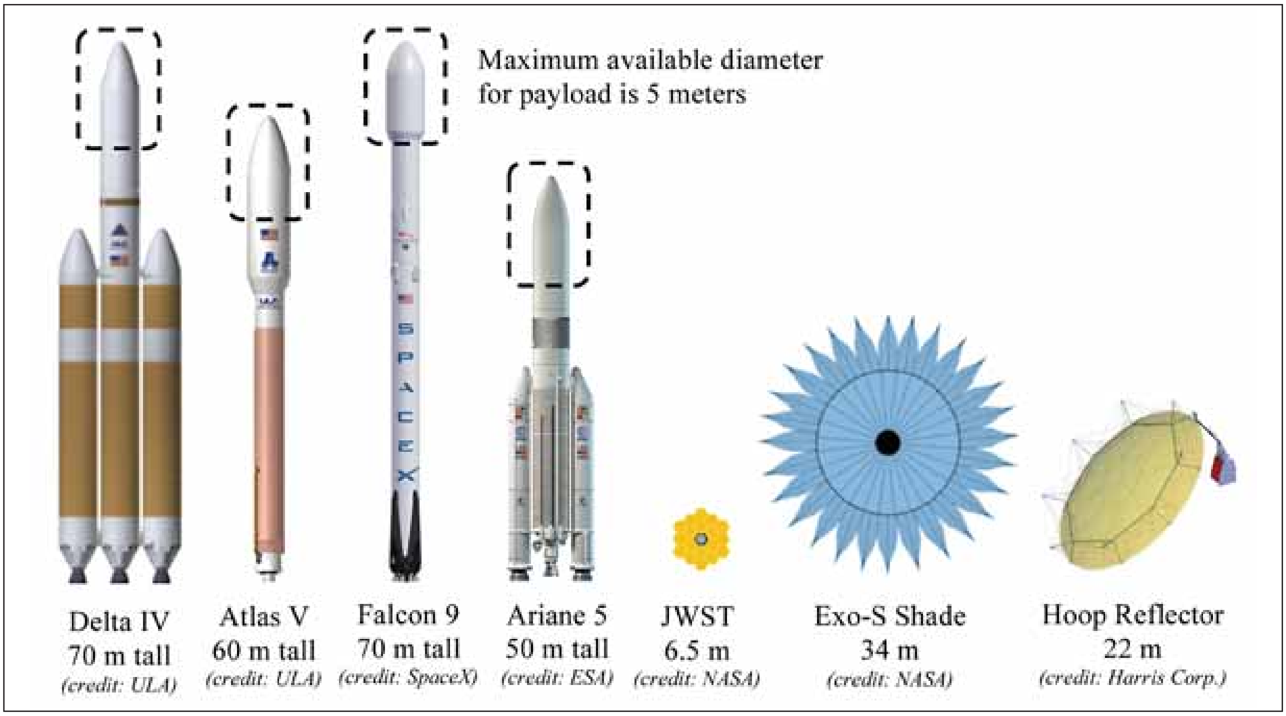

FIGURE 2 Scale of the largest launch vehicles (left) relative to representative large space structures (right). Images reprinted with permission.

incremental improvements in size, weight, and power over the past 50 years, but these heritage mechanisms and structural support schemes are reaching size and mass limits. Adding hinges to package larger payloads into these limited launch volumes is causing reliability concerns and cost escalation.

Emerging Approaches

Two structural design techniques show high payoff potential: (1) tension-aligned antennas and optics and (2) high-strain composite mechanisms. These methods have been used successfully for decades, but in very limited form because of the absence of high-strength, high-stiffness carbon fiber composites and robust analytical and test tools.[1]

Tension-Aligned Antennas and Optics

As more sophisticated computerized testing and analysis tools became available and the use of high-strength carbon fibers in aircraft became prevalent, feasible new space architectures began to surface, enabling the ground testing of the Innovative Space-based Radar Antenna truss in 2007 (Lane et al. 2011), the flexible unfurlable and refurlable lightweight (FURL) solar sail in 2010 (Banik and Ardelean 2010), and in 2013 the Membrane Optical Imager for Real-Time Exploitation (MOIRE) brassboard telescope (Domber et al. 2014). Most recently, the roll-out solar array (ROSA; Spence et al. 2015) was manifested for a spaceflight experiment to the International Space Station in 2016.

Other advanced concepts currently under development by government and industry all share high-strain composite features for folding functionality and/or tension as the means of structural stability: a low-cost multiarm radial composite radio-frequency reflector

TABLE 1 Packaged size of typical precision space mirror, shade, and antenna

	Deployed size	Stowed size	Packaging ratio
JWST Primary	6.5 m	4.0 m	1.6:1
Exo-S Starshade	34 m	5.0 m	9:1
SkyTerra-1 Mesh Reflector	22 m	2.4 m	9:1

JWST = James Webb Space Telescope; m = meter.

[1] Two historical space structures that used lower-stiffness glass and aramid fiber composites are the Continuous Longeron Mast of the 1960s and the Wrap-Rib reflector of the 1970s.

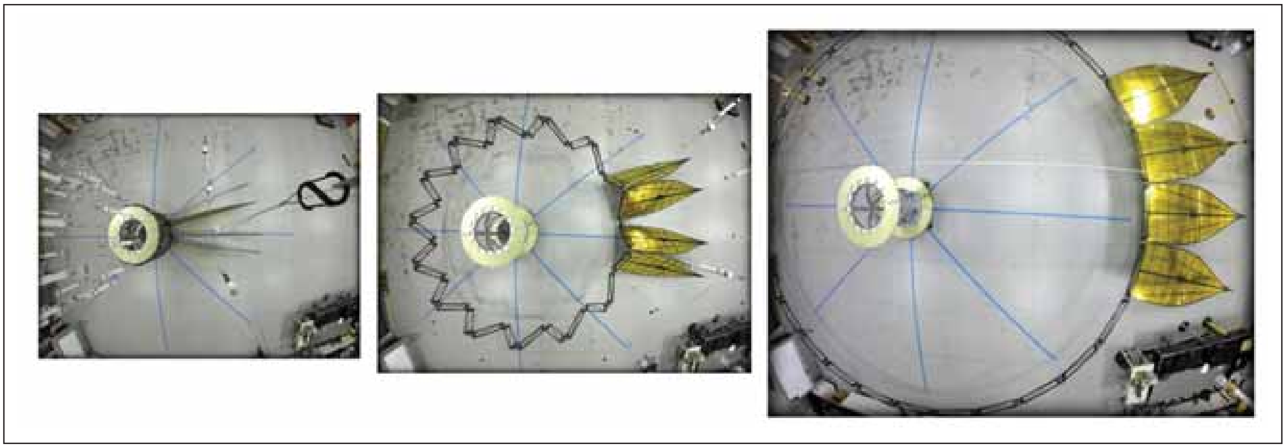

FIGURE 3 Ground deployment sequence of a starshade demonstration model shows a perimeter truss collapsed against a central drum (left). As the truss articulates radially (center) petals begin to rotate into position. Finally the perimeter truss is fully locked out (right), providing full support to the four petals. Source: NASA JPL (2015).

(Footdale and Banik 2016), an isogrid column (Jeon et al. 2016), a starshade occulter (figure 3; NASA 2015), an extremely high expansion deployable structure (Warren et al. 2007), a triangular rollable and collapsible mast (Banik and Murphey 2010), and a tensioned planar membrane antenna (Warren et al. 2015).

High-Strain Composite Mechanisms

High-strain composites are defined as thin carbon and glass fiber polymer matrix laminate materials used to construct shell structures that undergo large elastic deformations during folding and then release the stored strain energy to enforce deployment.

Architectures constructed from these materials have 7x greater deployment force, 20x greater dimensional stability, and 4x higher stiffness compared to traditional metallic flexure mechanisms (Murphey et al. 2013, 2015; Welsh et al. 2007). Moreover, when compared to traditional pin-clevis-type hinges, the payoff is a reduced mechanism part count, less susceptibility to binding, and more robust deployments. The hinges have greater lateral and torsion compliance during the transition from folded to deployed, a critical transition when there is a high risk of binding (e.g., when asymmetric solar heating and resulting expansion induce side loads on hinges). High-strain composite hinges can operate through this state and achieve a repeatable, dimensionally stable locked-out condition due to the near-zero coefficient of thermal expansion of carbon fibers.

Combined with the kinematic determinacy of a tensioned antenna or optic, these technologies are cracking open the door to a new era of space structures where 50-meter telescopes, 100-meter antennas, and megawatt-class solar arrays are all feasible.

Long-Term Possibilities and Considerations

Despite the potential of tension-aligned payloads and high-strain composite mechanisms, even these will eventually reach limitations in size scaling, mass efficiency, and dimensional stability. It will be necessary to push beyond these limits to meet long-term civil and military space needs.

As the promise of robotic assembly and in-space additive manufacturing technologies is only beginning to emerge, the best tack is not yet clear. Certainly the unique realities and constraints of space flight must remain front and center in any pursuit of exciting new technologies.

Few industries are more risk-averse than those involved in space flight. NASA and DOD program managers regularly spend hundreds of millions (sometimes billions) of dollars on a single spacecraft to try to ensure mission success. For example, the price tag on the 6.5 meter James Webb Space Telescope has reportedly reached $8.7 billion during the 16 years from inception to launch (Leone 2011). If this paradigm holds, a 20-meter space telescope will remain in development for 87 years and cost $47.5 billion (Arenberg et al. 2014).

It is a spiraling effort. As more money is spent, additional testing and analysis are required to try to increase the certainty of spacecraft success. Schedules are then drawn out, further adding to the costs.

Spaceflight is a one-shot business. Hundreds of critical systems must work together flawlessly the first

TABLE 2 Common metrics for evaluation of large space structure performance

Metric	Description	Equation
Packaging ratio	deployed length/stowed length	$\frac{L_d}{L_s}$
Linear packaging density	deployed size/stowed volume	$\frac{D}{V}$
Areal packaging density	deployed area/stowed volume	$\frac{A}{V}$
Beam performance index (Murphey 2006)	Strength moment, bending stiffness, linear mass density	$\mu = \frac{\left(M^2EI\right)^{1/5}}{w}$
Solar array scaling index (Banik and Carpenter 2015)	acceleration load, frequency, boom quantity, length, area, blanket areal mass density, total mass	$\kappa = (af)^{0.216}\, n^{0.231} L_{pb}\, A^{0.755}\, \frac{\gamma_b{}^{0.176}}{m}$
Mass efficiency	diameter/mass	$\frac{D}{m}$
Surface precision	diameter/root mean square (RMS) figure error	$\frac{D}{RMS}$
Dimensional stability	coefficient of thermal expansion	α
Telescope mission cost (Arenberg et al. 2014; Stahl et al. 2012)	diameter, wavelength, temperature of operation	$MC = \frac{C\,D^{1.7}\lambda^{-0.3}T^{-0.25}}{0.11 + 0.09ln(D)}$

time or the mission is lost. Deployable structures are notorious as one of the highest sources of failure. Mission managers therefore expend great effort, time, and resources on testing in space simulation chambers. But even then the effects of gravity and the lack of a truly representative space environment always raise questions about the validity of these tests despite decades of experience and evidence.

Of course, the pursuit of innovation should not be deterred by these challenges. Rather, they should motivate the continued evaluation of new architectures against all measures of success—not just structural performance but also cost factors such as ease of ground testing and validation, simplicity of analysis methods, and reduced quantity of mechanical interfaces and unique parts.

It is difficult to quantify each key cost factor in the early conceptual design phase, but this is precisely when critical design decisions are made that most affect cost. Cost evaluation metrics are therefore essential. Until they are available, rational comparison of competing structural architectures must rely on structural performance metrics along with subjective cost assessments. A common list of such metrics is provided in table 2; note the highly sophisticated telescope mission cost metric (bottom row).

Conclusion

The challenges to realize large space structures are great, but if they are successfully addressed the opportunities will be well worth the effort and cost. No doubt, one of the most exciting possibilities is discovery of Earth-like planets that might have sustained life—or perhaps still do. . . .

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Microstructural design, together with advanced additive micro- and nanomanufacturing techniques, can yield new material systems with previously unachievable property combinations.

Mechanical Metamaterials

Design, Fabrication, and Performance

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Christopher M. Spadaccini

Material properties are governed by the chemical composition and spatial arrangement of the constituent elements at multiple length scales. This characteristic fundamentally limits the properties with respect to each other and requires tradeoffs when selecting materials for specific applications. For example, strength and density are inherently linked so that, in general, the more dense the material, the stronger it is.

In my laboratory we are combining advanced microstructural design, using flexure and screw theory as well as topology optimization, with advanced additive micro- and nanomanufacturing techniques to create new material systems with previously unachievable property combinations. The performance of these *mechanical metamaterials* is controlled by geometry at multiple length scales rather than by chemical composition alone.

We have demonstrated designer properties of these mechanical metamaterials in polymers, metals, ceramics, and combinations thereof, yielding properties such as ultrastiff lightweight materials, negative stiffness, and negative thermal expansion. Our manufacturing techniques include projection microstereolithography (PμSL), direct ink writing (DIW), and electrophoretic deposition (EPD). With these methods, we can generate three-dimensional micro- and nanoscale architectures with multiple constituent materials in the same structure.

Introduction

Material properties can be controlled via intricate assemblies and structural organization at multiple length scales, as evidenced by naturally occurring cellular materials such as honeycombs (Ando and Onda 1999), trabecular bone (Ryan and Shaw 2013), plant parenchyma (Van Liedekerke et al. 2010), and sponges (Shen et al. 2013). It is the architecture of the material's structure at the micro- and nanoscale, as much as the chemical composition, that yields its mechanical properties. By designing highly ordered architectures in cellular solids, it is possible to engineer the mechanical response of these materials to create mechanical metamaterials (Deshpande et al. 2001; Gibson and Ashby 2001).

The ability to decouple properties via micro- and nanoarchitectural control can allow for unique material performance such as ultralightweight, high-stiffness, and high-strength materials (Bauer et al. 2014; Schaedler et al. 2011), negative Poisson's ratio (Lakes 1987), negative stiffness (Lakes et al. 2001), and negative thermal expansion coefficient (Sigmund and Torquato 1997). Paramount to achieving these often unnatural properties is an ability to design, fabricate, and characterize structures for the properties of interest. In fact, this method of choosing a unique property and engineering a material's performance through its architecture could be described as an *inverse design* problem. Normally, material properties are taken to be absolute and functional structures are then created from these materials. Mechanical metamaterials result from exactly the opposite approach.

A classic example of architectural control and the resulting unique material performance is the octet truss stretch-dominated lattice (Deshpande et al. 2001) shown in figure 1. This structure, which contains b struts and j frictionless joints, satisfies Maxwell's criterion, where $b - 3j + 6 > 0$, which defines a stretch-dominated structure. Because the struts in the unit cell are designed to be in either tension or compression under applied load, as opposed to bending, the lattice is mechanically efficient with a high stiffness-to-weight ratio (E/ρ). In fact, it is designed to have a linear scaling relationship between stiffness and density, $E/E_s \propto (\rho/\rho_s)$, where the subscript s denotes bulk properties.

Most naturally occurring materials with stochastic porosity have a quadratic or even cubic relationship: for every order of magnitude decrease in density there is a corresponding 2 to 3 order of magnitude decrease in

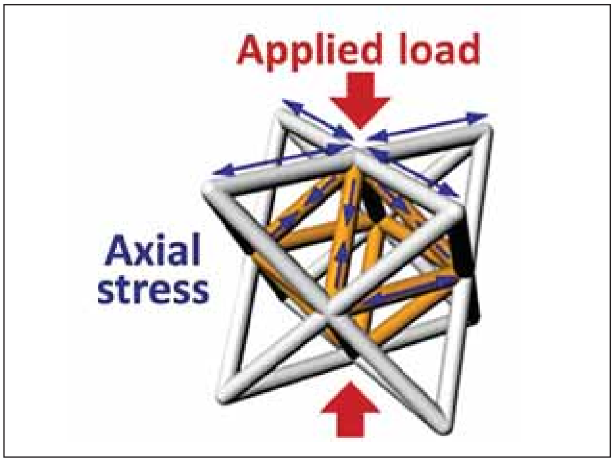

FIGURE 1 Octet truss stretch-dominated unit cell that can be tessellated in space to form a lattice. *Source:* Zheng et al. (2014).

stiffness. The architected design fundamentally changes the scaling relationship of the lattice material through geometry rather than composition. This concept can be further advanced by taking advantage of nanoscale size effects. Strength to density relationships can be effectively manipulated with control at size-scales below the critical flaw and crack dimensions (Jang et al. 2013).

Design

Numerous methods can be used to solve the inverse design problem for mechanical metamaterials. In our laboratory and with key collaborators, we have primarily been developing and using two techniques, one analytical and the other computational. The analytical method is known as *freedom, actuation, and constraint topologies* (FACT) and it relies on design of flexure and screw elements to create unit cells and lattices with prescribed properties (Hopkins and Culpepper 2010a,b). The computational method we have been using is *topology optimization* (TO), which involves optimizing a unit cell's layout subject to an objective function and boundary conditions.

The FACT Method

The FACT method relies on use of a previously developed, comprehensive library of geometric shapes that define fundamental flexure and screw motion. These shapes enable the designer of a unit cell to visualize all the regions wherein various microstructural elements may be placed to achieve desired bulk material properties.

As an example, consider a two-dimensional (2D) unit cell design with negative thermal expansion that

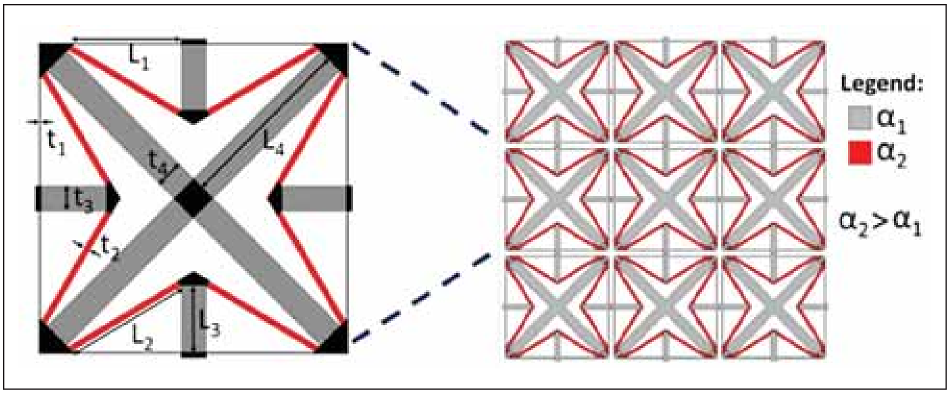

FIGURE 2 Unit cell and lattice with negative thermal expansion designed using freedom, actuation, and constraint topologies (FACT). α = coefficient of thermal expansion; L = length; t = thickness. Adapted from Hopkins et al. (2013).

was derived using FACT and is shown in figure 2 (Hopkins et al. 2013). In this unit cell, two materials (shown in red and grey) plus void space are required to achieve the negative property. As the unit cell heats up, the red material, which has a larger thermal expansion than the grey material, volumetrically expands more relative to its grey counterpart. Consequently, the red angled component pulls inward the center of the flexure element, which makes up the sidewall of the unit cell, while simultaneously pushing the corners of the unit cell outward. When arranged in a lattice connected at the midpoint of each sidewall, the corners grow into the void space while the sidewalls are pulled inward, resulting in an overall contraction of the lattice and hence negative thermal expansion.

The FACT technique can be used to design other mechanical metamaterials with properties such as negative Poisson's ratio and nonlinear responses.

Topology Optimization

Topology optimization is a computationally driven inverse design method. In our implementation, we utilize a finite element solver as the core physics engine and an optimization algorithm subject to an objective function and constraints to evolve the design.

A negative thermal expansion metamaterial again serves as an example. In a typical implementation, we begin with a unit cell with three phases randomly distributed throughout the space: a high thermal expansion constituent material, a relatively lower thermal expansion constituent material, and void space. An objective function such as a specific target thermal expansion for the unit cell is defined along with quantitative constraints such as stiffness and volume fraction bounds.

Initially, the finite element solver calculates the material properties for the random distribution of phases. These properties will likely be far from the target and may also violate the constraints. At this point, the optimization algorithm, which in this case is a gradient-based method, will redistribute the three phases by some small amount and the finite element solver again calculates properties. The new properties are then evaluated against the target and the previously calculated values and the optimization algorithm again redistributes material based on this information in an attempt to approach the target.

This iterative process is repeated until it converges to a design that minimizes the objective function and satisfies all constraints. An example of a topology-optimized negative thermal expansion unit cell design is shown in figure 3. In some cases convergence may not be achieved because the problem is overconstrained and/or has poor initial conditions.

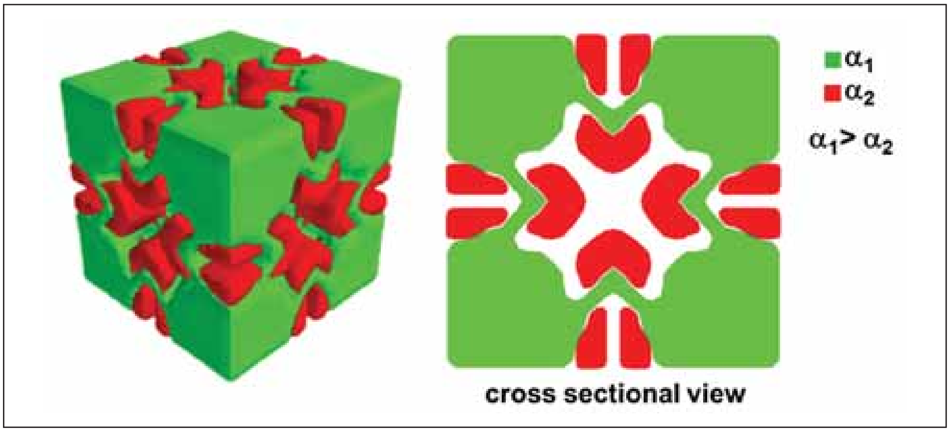

FIGURE 3 Negative thermal expansion metamaterial unit cell designed using topology optimization. The red and green represent two different materials with different thermal expansion coefficients (α).

There are significant limitations to TO methods, including a lack of knowledge about practical manufacturing constraints in the algorithm, a propensity to converge to a local minimum solution rather than a global one, and, for more sophisticated design problems, the need for expensive high-performance computing resources.

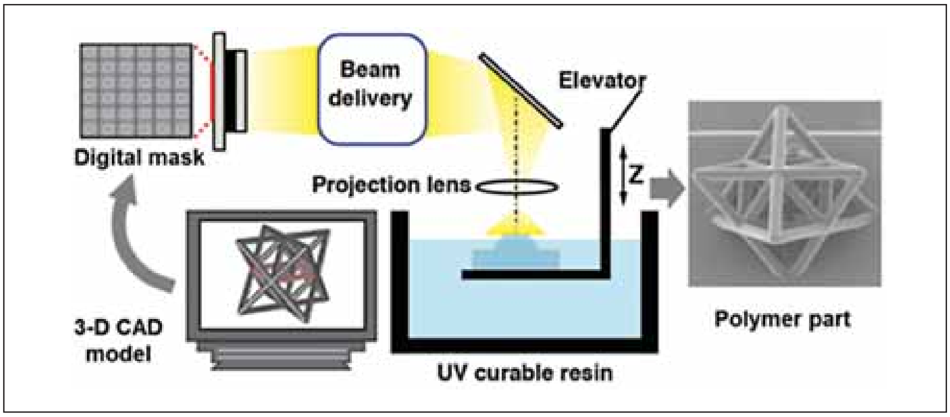

FIGURE 4 Schematic (left) of projection microstereolithography (PμSL) and photo (right) of a fabricated component. CAD = computer-aided design; UV = ultraviolet. *Source:* Zheng et al. (2014).

Fabrication

Physical realization of mechanical metamaterials requires a suite of fabrication processes with unique capabilities. Additive manufacturing (AM) methods are particularly well suited to the geometric complexity of these structures and lattices. But some features and geometries in these structures are not attainable with commercially available AM tools, and so we have developed our own custom processes and materials, described and illustrated in the following sections.

Projection Microstereolithography

Projection microstereolithography (PμSL) uses a spatial light modulator—a liquid crystal on silicon (LCoS) or digital micromirror device (DMD)—as a dynamically reconfigurable digital photomask to fabricate three-dimensional materials in a layer-by-layer fashion.

A 3D computer-aided design (CAD) model is first sliced into a series of closely spaced horizontal planes. These 2D image slices are sequentially transmitted to the reflective LCoS chip, which is illuminated with ultraviolet (UV) light from a light-emitting diode (LED) array. Each image is projected through a reduction lens onto the surface of a photosensitive resin. The exposed liquid cures, forming a layer in the shape of the 2D image, and the substrate on which it rests is lowered, reflowing a thin film of liquid over the cured layer. The image projection is then repeated with the next image slice until the desired number of layers has been fabricated to complete the 3D structure. A schematic of the basic system is shown in figure 4 along with a photo of an example structure (Zheng et al. 2014).

We have also recently developed a scanning version of this concept, enabling us to rapidly fabricate structures approaching 10 cm in size while maintaining features as small as 10 microns.

Direct Ink Writing

Another method that we have been utilizing to fabricate these metamaterials is direct ink writing (DIW). DIW is a layer-by-layer printing approach in which concentrated inks are deposited in planar and 3D layouts with lateral dimensions (minimum ~400 nm) that are at least an order of magnitude lower than those achieved by conventional extrusion-based printing methods. Paramount to this approach is the creation of concentrated inks that can be extruded through fine deposition nozzles as filaments and then undergo rapid solidification to maintain their shape, as shown in figure 5 (Lewis 2002; Smay et al. 2002). In many cases they can even span significant gaps across unsupported regions (Ahn et al. 2009).

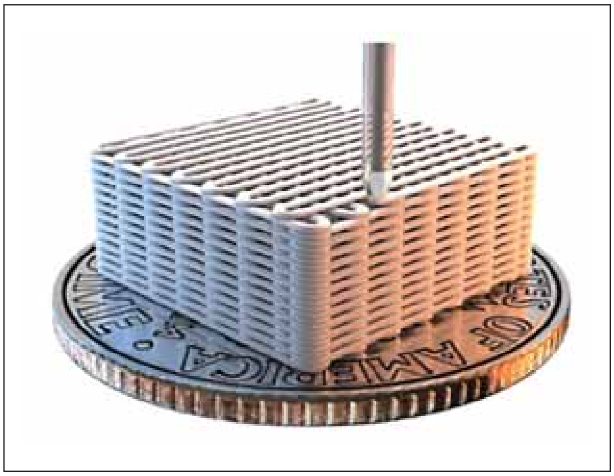

FIGURE 5 Direct ink writing is an extrusion-based process.

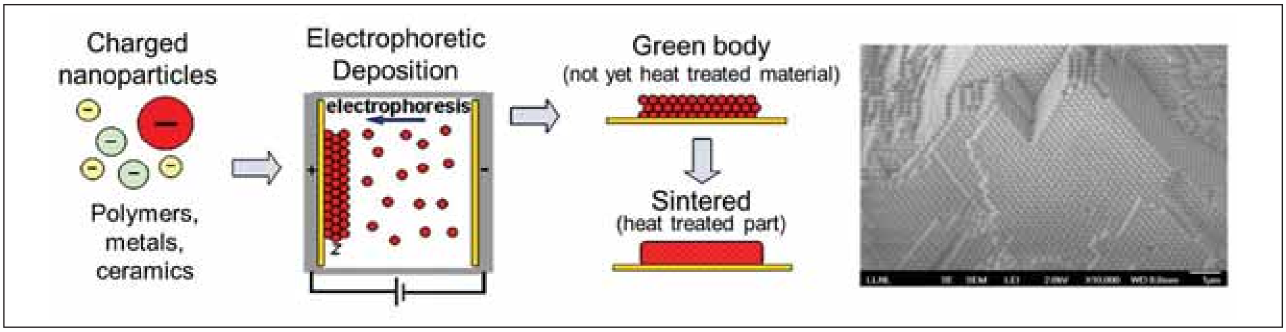

FIGURE 6 Schematic (left) of the electrophoretic deposition (EPD) process and (right) photo of a fabricated structure.

Techniques such as DIW offer an attractive alternative to conventional manufacturing technologies because of the low cost of the printing equipment, ease of manufacture, and flexibility of material systems and dimensions.

Electrophoretic Deposition

A third fabrication method that allows for the deposition of a range of materials is electrophoretic deposition (EPD), a bottom-up fabrication process that utilizes electric fields to deposit charged nanoparticles from a solution onto a substrate (Besra and Liu 2007; Pascall et al. 2014).

EPD can be used with a wide range of nanoparticles, including oxides, metals, polymers, and semiconductors. Once the particles are deposited the green body can be dried and/or sintered to adhere the particles together into a fixed structure. A schematic and fabricated nanostructure are shown in figure 6.

EPD has traditionally been used for coating applications, such as depositing ceramic materials onto metal tooling. We have expanded the technology to enable patterning of mesoscale multimaterial structures with micron-scale tailoring. Our modifications include automated sample injection during deposition to tailor the material composition, the use of dynamic electrodes

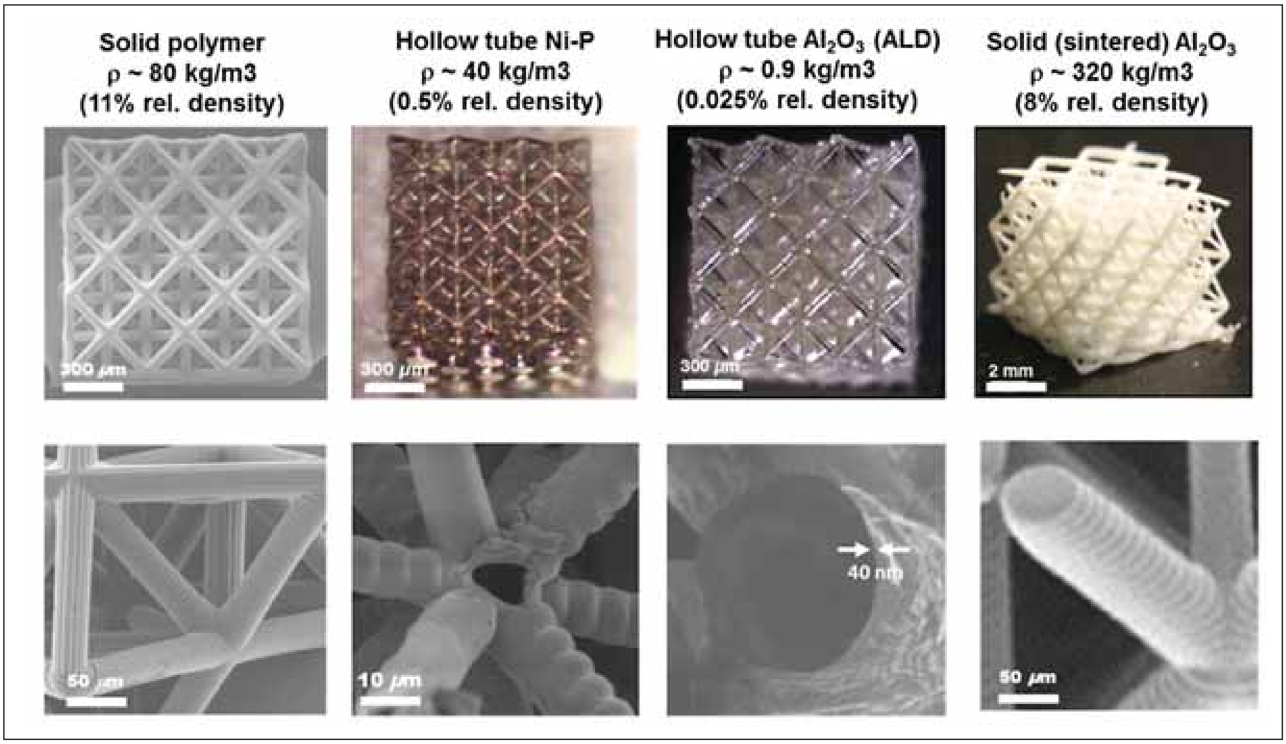

FIGURE 7 Octet truss–based mechanical metamaterials of varying materials and configurations. See text for description of techniques used to produce these structures. Al_2O_3 = aluminum oxide; ALD = atomic layer deposition; Ni-P = nickel phosphorus. *Source:* Zheng et al. (2014).

to controllably vary the electric field profile on the deposition plane and precisely pattern geometries, and in-depth process modelling to predict the deposition parameters required to achieve a specific packing structure.

Postprocessing Techniques

Postprocessing techniques can help expand the palette of usable materials and/or improve final component properties. Thermal treatments such as sintering and hot isostatic pressing are frequently used. The use of polymer structures as templates for other materials is another common method for achieving an expanded material set.

For example, a polymer structure fabricated with any one of the methods described above could be coated via electroless plating, atomic layer deposition (ALD), or chemical vapor deposition (CVD) processes. The polymer in these hybrid structures could then be thermally or chemically removed, converting the structure to pure metallic or ceramic hollow structures.

Finally, nanoparticles can be suspended in the base feedstocks such as liquid monomers, resulting in a hybrid structure with particles distributed throughout the polymer. Thermal processing can then be used to remove the polymer and densify the particles, leaving a relatively pure, nonpolymeric structure.

Performance

Mechanical metamaterials are becoming a reality thanks to advanced fabrication and design methods. Two examples of simple lattice-based materials with unique properties are ultralight, ultrastiff microlattices and elastomeric cellular architectures with negative stiffness.

Figure 7 shows four types of octet truss stretch-dominated lattices fabricated at the microscale using PµSL. The images in the first column show a basic polymeric lattice made from hexanediol diacrylate (HDDA) with solid microscale struts and 11 percent relative density. In the next column, the same polymer structure was electrolessly plated with nickel phosphorus (Ni-P) and the polymer core was then removed via thermal processing, resulting in a lattice with 0.5 percent relative density. A hollow tube ceramic lattice, shown in the third column, was formed via ALD and similar polymer removal. This structure represents the lightest fabricated material in this test series, with a relative density of 0.025 percent and wall thickness less than 50 nm. Finally, we fabricated a lattice with alumina nanoparticles suspended in the polymer and conducted sintering procedures to remove the polymer and densify the ceramic, yielding a solid ceramic lattice with 8 percent relative density (far right column; Zheng et al. 2014).

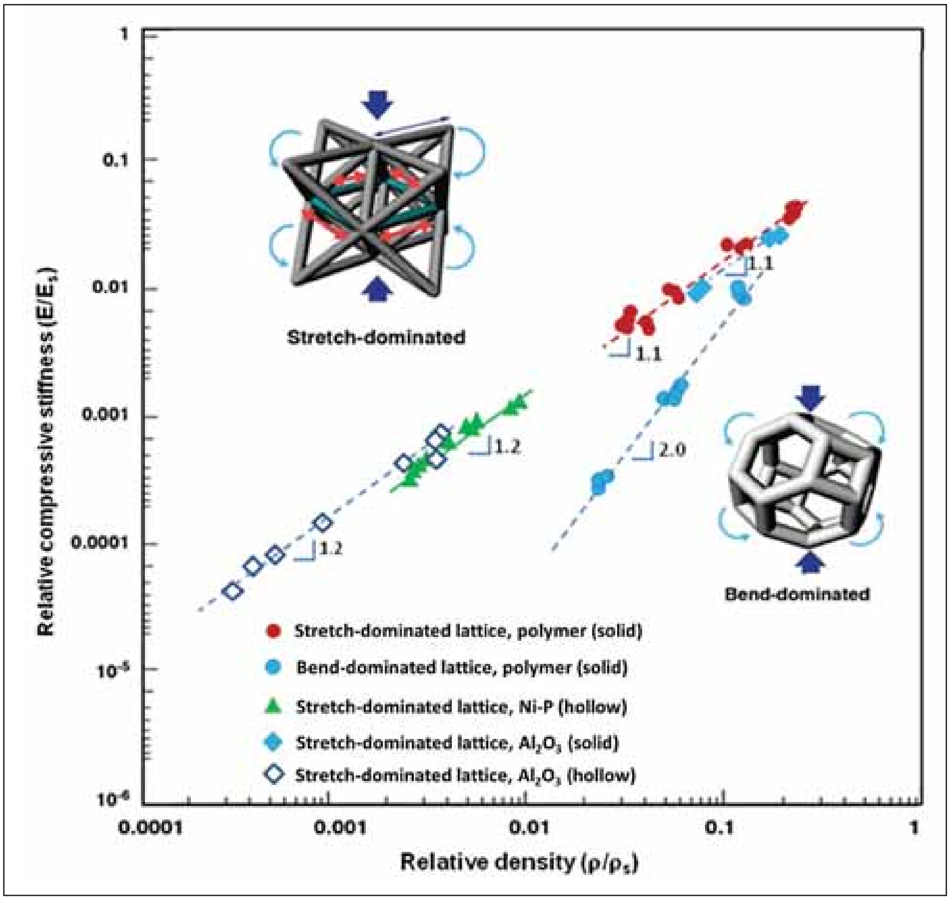

FIGURE 8 Nondimensional performance of ultralight octet truss stretch-dominated lattices. Al_2O_3 = aluminum oxide; HDDA = hexanediol diacrylate; Ni-P = nickel phosphorus. Adapted from Zheng et al. (2014).

The performance of these mechanical metamaterials is illustrated in figure 8, where nondimensional stiffness

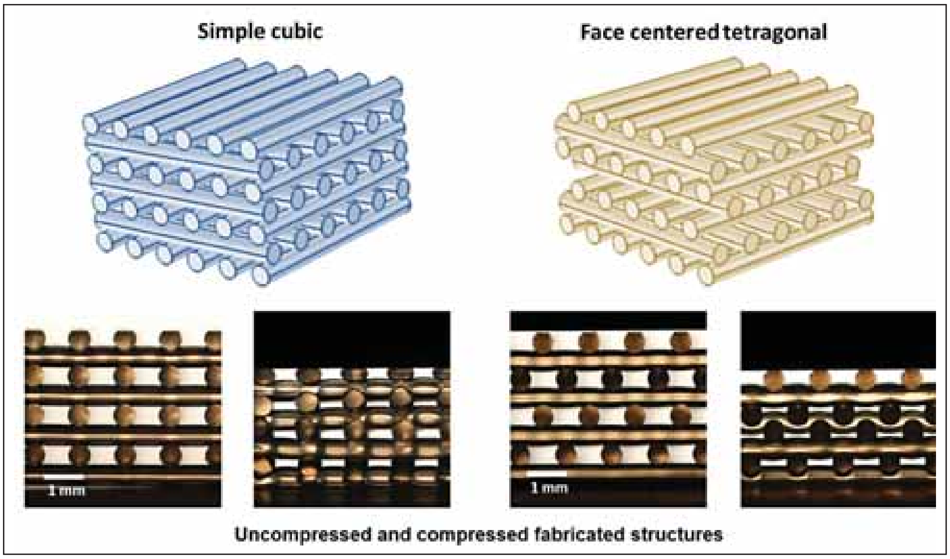

FIGURE 9 Schematics (top) and images (bottom) of silicone structures fabricated using direct ink writing (DIW). Adapted from Duoss et al. (2014).

is plotted versus relative density. The fact that the measured scaling relationship between these two parameters is approximately linear across all constituent material types, all relative density regimes, and regardless of hollow tube or solid strut configurations clearly demonstrates the impact of the stretch-dominated architecture. For comparison, a bend-dominated Kelvin foam architecture displayed the classic quadratic relationship when tested. Furthermore, in absolute terms, the hollow tube alumina lattices have densities approaching aerogels (known as some of the lightest materials in the world), but with 4 to 5 more orders of magnitude in stiffness due to the architected structure (Zheng et al. 2014).

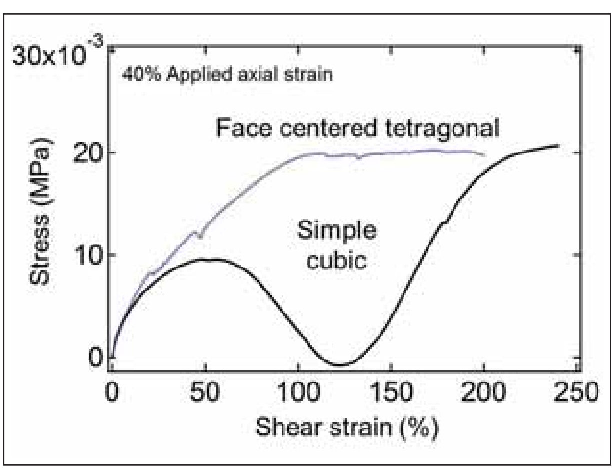

FIGURE 10 Shear response of elastomeric cellular architectures showing negative stiffness. MPa = megapascals. Based on Duoss et al. (2014).

Another interesting mechanical metamaterial is shown in figure 9. These “woodpile” structures were fabricated out of silicone with the DIW process. Varying the architecture between a simple cubic (SC) type structure and a face-centered tetragonal (FCT) configuration results in different bulk-scale mechanical properties. The cross sections in the bottom row of the figure clearly show that the two structures will have different compressive behavior: the SC layout will be stiffer than the FCT-structured material because of the aligned versus staggered arrangement of the nodes (Duoss et al. 2014).

However, what is not as obvious is the difference in shear response of the two materials. Figure 10 elucidates this difference, which manifests as “negative stiffness” and can be seen in the negative slope of the stress-strain response in the SC material. The negative stiffness is a unique “snap-through” property that can be engineered into the material. It is now possible not only to control the compressive response but also to independently design and control the shear response, perhaps even with negative stiffness (Duoss et al. 2014).

We have also begun to explore *multifunctional metamaterials*, combining normally disparate physics into lattice-type architectures. Figure 11 shows an early example, a printed graphene aerogel structure (Zhu et al. 2015). This simple woodpile lattice has enhanced mechanical properties and, because of the nature of graphene, significant electrical and/or chemical functionality as well. Supercapacitors with high compressibility and durability, for example, may become possible.

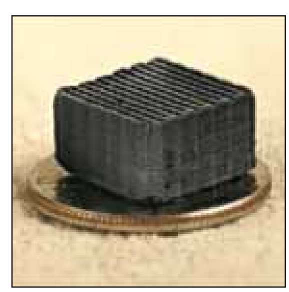

FIGURE 11 Image of printed graphene aerogel, positioned atop a quarter to show size. *Source:* Zhu et al. (2015).

Future Directions

By combining mechanical metamaterials with inverse design methods and custom micro- and nanoadditive manufacturing techniques, we have been able to develop unique properties not previously attainable in known materials. This is just the beginning of a powerful new methodology for approaching material design and realization.

There are many potential future directions for advancing the state of the art, including through continued exploration of size-scale effects and efforts that push the boundaries of multimaterial design and fabrication. This could lead to unique new materials with groundbreaking mechanical properties and electrical or photonic functionality all in one.

Acknowledgment

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Nanoarchitected metamaterials feature previously unattainable combinations of properties—light weight and enhanced mechanical performance—as well as unique thermal, optical, acoustic, and electronic attributes.

Materials by Design

Using Architecture and Nanomaterial Size Effects to Attain Unexplored Properties

Julia R. Greer

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Engineers are actively trying to mimic hard biomaterials such as mollusk shells and beaks because of their resilience and damage tolerance, which are believed to stem from hierarchical arrangements in their design. Technological advances in fabrication methods make it possible to create architected structural metamaterials using materials whose design and dimensionality are similar to those found in nature and whose hierarchical ordering ranges from angstroms and nanometers at the level of material microstructure to microns and millimeters at the level of macroscale architecture.

The use of architectural features in defining multidimensional material design space will enable the independent manipulation of coupled physical attributes and the development of materials with unprecedented capabilities. The result is that the behavior and properties of architected structural metamaterials can no longer be defined solely by the properties of the constituent solid or by the structure or architecture; instead they benefit from the linked behavior of the material and the structure at very small dimensions. The material creation paradigm will shift from *structure→processing→property* to *property→architecture→fabrication*.

The feasibility of this "materials by design" approach is gated by the ability to understand and predict the mechanical responses of metamaterials, whose properties are controlled by engineered structure in addition to atomic composition, and whose feature size and geometry are critical design parameters.

Current research is making significant headway testing, demonstrating, and understanding these properties.

Introduction

The concept of architecture in the design of materials is common in nature. For example, the properties of butterfly wings are a function of their multiscale, hierarchical construction. The nanoarchitecture of a butterfly wing interacts with light to create multicolored wings, and for shells such as nacre small ceramic platelets are key to their extreme resilience (Von Freymann et al. 2013). Many research groups have attempted to mimic and replicate the properties of these and other natural materials.

Hierarchically designed cellular materials have been used for many decades as the basis for mechanically robust engineered structures, such as the Eiffel Tower. The introduction of architectural elements enables the creation of structures that are both lightweight, because they use a fraction of monolithic material with the same dimensions, and strong, because the architecture provides a way to more efficiently distribute load-bearing capability.

Nanoarchitected structural metamaterials extend the concept of architecture to the micro- and nanometer length scale, often down to the atomistic level of material microstructure, enabling the use of material size effects to create metamaterials with amplified properties. Size effects that emerge in solids at the nanoscale—single crystalline metals become stronger, nanocrystalline metals become weaker, and metallic glasses and ceramics undergo brittle-to-ductile transition (Greer and De Hosson 2011)—can be exploited by using micron- to nanometer-scale building blocks to create larger structures.

Structural Metamaterials: Manipulation of Cellular Properties

The mechanical performance of architected solids on the macroscale is a function of their deformation mechanism, relative density, and constituent material properties (Deshpande and Fleck 2001; Fleck et al. 2010; Gibson and Ashby 1997; Meza et al. 2014; Ng et al. 2009; Schaedler et al. 2011; Valdevit et al. 2013; Wadley et al. 2003). Cellular solids offer a useful combination of light weight and mechanical integrity and have been studied at the macroscale experimentally, computationally, and theoretically. All of these studies assume that material properties of the constituent solid are constant and geometry is the single tunable parameter (Fleck and Qiu 2007; Fleck et al. 2010; Hutchinson and Fleck 2006; Symons and Fleck 2008).

Cellular solids can deform by either bending or stretching of the elements, both of which are dictated by lattice geometry and its nodal connectivity (Sun et al. 2013; Wang et al. 2003). A three-dimensional (3D) structure must have a connectivity of $Z = 6$ at the nodes to be rigid; a connectivity of $Z = 12$ to be stretching-dominated, which leads to the stiffest materials; and a connectivity of $6 \leq Z < 12$ to be bending-dominated, which results in more compliant materials (Wang et al. 2003).

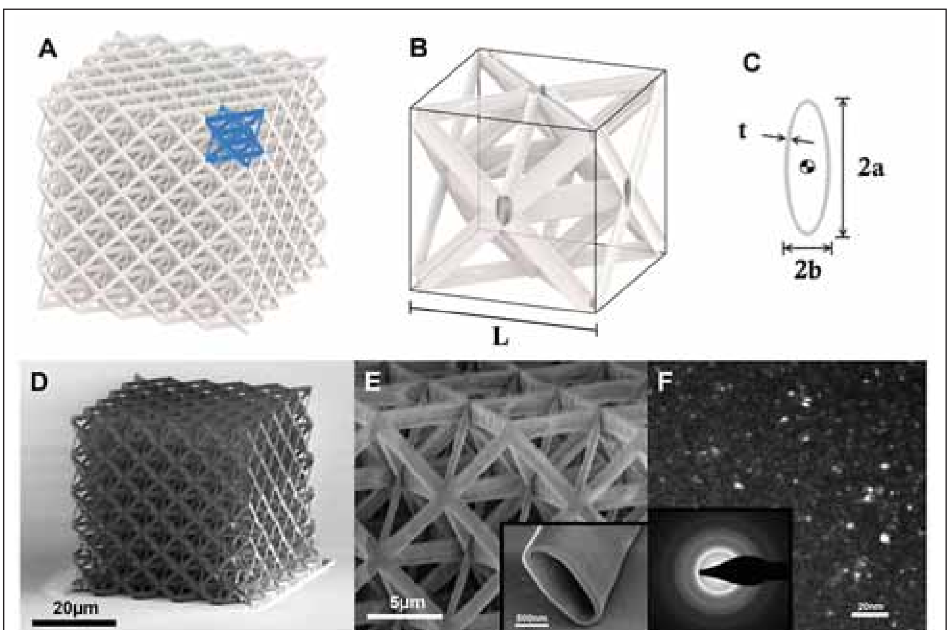

FIGURE 1 Octet truss design. (A) Single unit cell highlighted. (B) Cutaway of hollow octet truss unit cell. (C) Schematic of hollow elliptical nanolattice tube. (D) Scanning electron microscope image of alumina nanolattice. (E) Zoomed-in image of (D). (F) Dark field transmission electron microscope image with diffraction pattern: amorphous microstructure. Reprinted with permission from Meza et al. (2014).

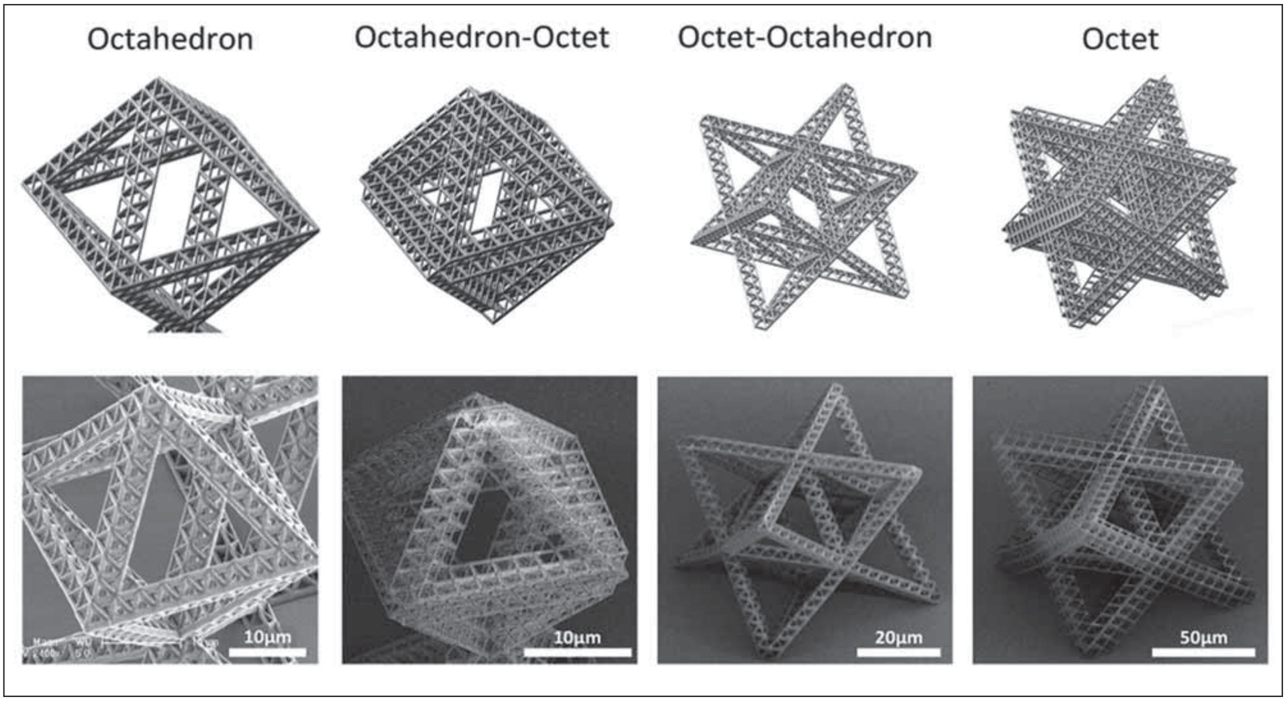

FIGURE 2 Computer-aided designs and scanning electron microscope images of fractal nanotrusses with various geometries specified above each set. Reprinted with permission from Meza et al. (2015).

The structural deformation mechanism, determined by the nodal connectivity, directly affects the stiffness and yield strength of the overall structure (Deshpande et al. 2001a,b). The yield strength and stiffness of 3D open-cell bending-dominated structures, such as honeycombs, scale as $\sigma_y = 0.3\bar{\rho}^{1.5}\sigma_{ys}$ and $E = \bar{\rho}^2 E_s$, where σ_{ys} and E_s are the yield strength and modulus of the constituent solid (Gibson and Ashby 1997). For 3D stretching-dominated structures, such as the octet truss, the yield strength and modulus scale as $\sigma_y = 0.3\bar{\rho}\sigma_{ys}$ and $E = 0.3\bar{\rho}E_s$, causing strength to decrease less rapidly (compared to bending-dominated structures) as relative density decreases.

Relative densities of cellular solids, along with stiffness and strength, can be modulated by using hollow tubes instead of solid rods in the same architecture or by creating hierarchical structures (figure 1). When hollow tubes are used in low-density cellular solids, structural effects can be activated by changing the various ratios of geometric parameters that define the lattice tubes. For example, reducing the slenderness ratio from 1 to 20 causes a 2 order of magnitude reduction in relative density, and hollowing out the tubes reduces density by an additional order of magnitude. Replacing solid beams with self-similar, fractal-like elements gives a further 1.5 to 2 order of magnitude reduction in density.

Demonstrated Improvements in Mechanical Behavior

Recent work in our research group demonstrated the attainment of simultaneous light weight, high strength/stiffness, and recoverability by combining the architecture and material size effect of nanomaterials. We tested the mechanical behavior of octet alumina nanolattices, a class of new, lightweight durable materials that have optimized nano-sized induced material properties, high surface area, and 3D architectures and are desperately needed for a variety of applications (e.g., small-scale energy storage devices, biomedical devices, space travel vehicles, wind turbines, personnel protection, and lightweight thermal insulation).

One way to think about such nanolattices is a 2D nanoribbon wrapped around a 3D architecture (figure 2). Ordered cellular solids such as the octet truss and kagome lattice have robust mechanical properties such as a combination of high strength and fracture toughness (Deshpande et al. 2001a,b). The geometry of these structures makes it possible to create materials with not only improved mechanical properties but also low densities and high surface area to volume ratios.

We found that they contain ~99 percent air recovered after compression of more than 50 percent (Jang et al. 2013; Meza and Greer 2014; Meza et al. 2014, 2015;

Montemayor et al. 2014). Hollow rigid nanolattices have recently attracted much interest as they attained GPa-level stiffnesses at ~10 percent of the density of the parent solid (Jang et al. 2013; Meza and Greer 2014; Meza et al. 2014, 2015; Montemayor et al. 2014). At some critical wall thickness nearly all nanotrusses—ceramic, metallic, and metallic glass—fully recovered after <50 percent compression without sacrifice in strength. Our most recent work demonstrated that these nanolattices also exhibit insensitivity to flaws, i.e., failure tolerance (Montemayor et al. 2015).

All of these developments position scientists favorably to address the challenge of developing lightweight and damage-tolerant materials that can have a suite of other valuable properties, such as thermal insulation (conductivity), as well as electronic and optical response.

Fabrication

Significant efforts are under way to develop architected materials with precisely designed (i.e., nonstochastic) geometries that can support the prototyping of exceptionally lightweight, strong, and tough metamaterials. Control of such nanolattice geometries has been made possible by advances in 3D micro- and nanofabrication techniques, ranging from polymer waveguides to microstereolithography to direct laser writing two-photon lithography (Zheng et al. 2014).

Direct Laser Writing Two-Photon Lithography (DLW TPL)

Advantages of the TPL method over other 3D fabrication techniques are precise nanometer and submicron feature resolution, smooth beam surfaces, and extreme versatility in geometry (Fischer and Wegener 2013; Sun and Kawata 2004; Xiong et al. 2012). Nanolattices fabricated by TPL enable a reduction in size by up to 3 orders of magnitude compared to microlattices fabricated by 3D printing or by self-propagating polymer waveguides, and they are amenable to subsequent coating and scaffold removal. Their appearance is monolithic and may resemble an iridescent aerogel whose strength is comparable to that of metals and ceramics.

The individual building blocks that constitute nanolattices have dimensions that are below the resolution of the human eye, with strut lengths of 3–20 μm, diameters of 100 nm–1 μm, and wall thicknesses of 5–600 nm (Jacobsen et al. 2007; Jang et al. 2013; Meza and Greer 2014; Meza et al. 2014, 2015; Montemayor et

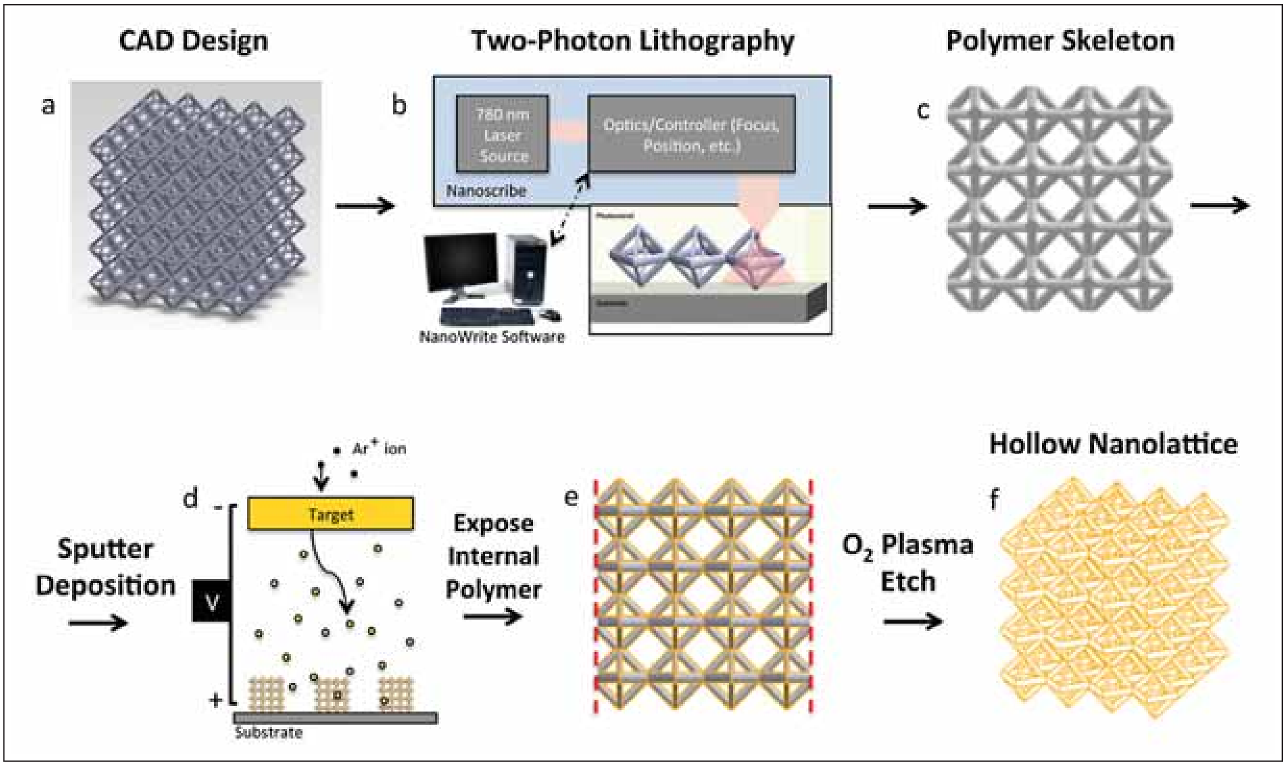

FIGURE 3 A schematic of the two-photon lithography technique followed by the deposition of material of interest and etching out of the internal polymer scaffold. Reprinted with permission from Montemayor et al. (2014).

al. 2014, 2015). Their useful properties arise from a combination of size-dependent nanomaterial properties and structural response of the discrete architecture; they cannot be predicted solely by scale-free continuum theories (Gibson and Ashby 1997; Torrents et al. 2012; Valdevit et al. 2013).

Figure 3 shows a schematic representation of the fabrication steps during the nanolattice creation procedure. Nanolattices were first fabricated from a negative photoresist (IP-Dip 780) using DLW TPL, which uses a 780 nm femtosecond pulsed laser focused into a small volume element, a voxel, in the polymer. The energy is sufficient to cross-link the monomer and to harden the material within the voxel before the two photons are absorbed. The elliptical voxel is rastered in three dimensions in a droplet of photoresist to effectively sculpt the prescribed structure, which can have virtually any geometry; some examples are shown in figures 1, 2, and 4.

Other Methods

To make nanolattices out of different materials, the polymer scaffolds are coated (as conformally as possible) with the specific material of interest (e.g., metals, semiconductors, oxides, metallic glasses, piezoelectric materials, other polymers). We have demonstrated the feasibility of sputtering different metals onto nanolattices up to ~300 nm (Montemayor et al. 2014; Montemayor and Greer 2015); and Meza and colleagues and several other research groups successfully utilized atomic layer deposition to apply ~5–60-nm-thick ceramic alumina (Al_2O_3) and titanium nitride (TiN) coatings onto polymer scaffolds (Jang et al. 2013). After deposition, the original internal polymer scaffold is exposed by slicing two of the six sides off the sample using a focused ion beam and then removed using an oxygen plasma, revealing a hollow-tube nanolattice that is made entirely of the coating material (Meza and Greer 2014; Meza et al. 2014, 2015; Montemayor and Greer 2015; Montemayor et al. 2014, 2015).

Demonstration of Enhanced Properties

Hollow Nanolattices

Our group has demonstrated that hollow Al_2O_3 nanolattices with octet truss geometry and relative densities of $\rho = 10^{-4} - 10^{-1}$ recovered up to 98 percent of their initial height after uniaxial compressions in excess of 50 percent (Jang et al. 2013; Meza and Greer 2014; Meza et al. 2014, 2015). Their ductile-like deformation and recoverability were attributed to the critical ratio between the wall thickness (t) and the semimajor axis (a) of the hollow elliptical strut cross section. When (t/a) is less than the critical value (~0.03 for alumina), the nanolattices deformed via shell buckling and recovered after deformation; at greater (t/a) values, they failed catastrophically with little to no recovery (Meza and Greer 2014; Meza et al. 2014).

The constituent Al_2O_3 is a brittle ceramic; reducing the wall thickness to the nanometer level and "wrapping" the film around a 3D architecture enables the metamaterial to bypass the properties of the constituent solid and to exhibit a diametrically opposite property, recoverability. The ~10 nm thickness reduces the number and size of flaws in the Al_2O_3—the largest is only 10 nm! The combination of Weibull statistics flaw

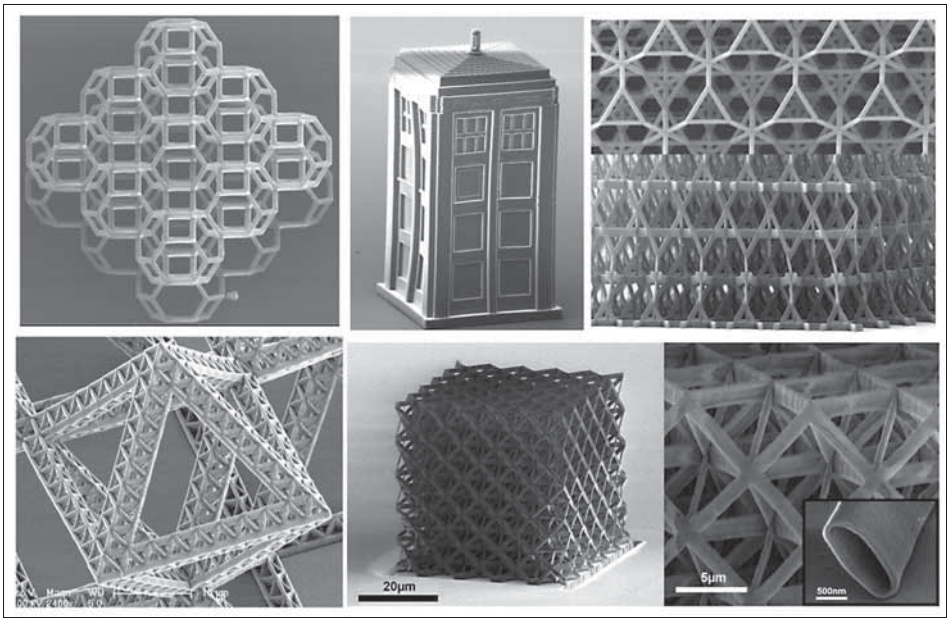

FIGURE 4 Examples of different architectures written by the two-photon lithography technique showing the versatility of this approach. Reprinted with permission from Meza et al. (2015) (bottom row left) and Meza et al. (2014) (bottom row center and right).

distribution-based fracture, a material size effect, and structural deformation mechanism as a function of (t/a) makes it possible for ceramic nanolattices to have such unique properties (Jang et al. 2013; Meza and Greer 2014; Meza et al. 2014, 2015).

Solid Nanolattices

The enhanced properties induced by the interplay of structural and material size effects have also been observed in TPL-created lattices with solid metal struts (Blanco et al. 2000). Copper (Cu) mesolattices were created using an inverse DLW TPL method: a negative of the scaffold was patterned in a positive-tone resist, and then Cu was electroplated into the exposed pores (Blanco et al. 2000). Removal of the polymer mold revealed a free-standing mesolattice with solid Cu beams whose thickness and grain size were ~2 μm. These mesolattices had relative densities between 40 percent and 80 percent and a unit cell of 6 μm and 8 μm, and at the highest density their compressive yield strength was ~330 MPa, which is a factor of ~2.5 higher than that of bulk copper, 133 MPa.

This amplification in strength is a result of the size effect in single crystalline metals ("smaller is stronger") (Blanco et al. 2000). These results imply that the architected Cu nanolattices outperformed bulk copper by a factor of ~3 for relative densities of $\rho > 0.6$—that is, when more than 40 percent of the material was removed from a monolithic cube of the same volume.

Other Structures and Materials

Current pursuits in the field of architected structural metamaterials include efforts to develop auxetic 3D structures (i.e., materials with a negative Poisson's ratio), which are fabricated using DLW TPL (Babaee et al. 2013; Lee et al. 2012). Typical monolithic materials expand in the direction orthogonal to the loading axis when uniaxially compressed, whereas auxetic materials contract in this direction.

Pentamode materials, or 3D solids that ideally behave as fluids, have also been designed and fabricated using TPL and provide a pathway to decouple bulk and shear moduli, enabling independent wave propagation through media (Rinne et al. 2007).

Challenges of Scalability

The most significant obstacle to incorporating structural nanoarchitected metamaterials in useful technological applications is scalability, that is, the ability to manufacture either a large number of small-scale components or materials with large dimensions in a reasonable amount of time. Stochastic foams (e.g., nanoporous gold), in which the porosity distribution is random, have been explored as a possible vehicle for propagating material size effects to larger scales (Hodge et al. 2005). But these foams exhibit poor scaling of strength with relative density and are ultimately limited in the types of architecture they can create (Fleck et al. 2010).

Some technologies that could lead to scalability are roll-to-roll fabrication with nanoimprintable patterns, holographic lithography, and phase-shifting masks.

Outlook

This selective overview highlights the state of the art of some structural metamaterials with dimensions that span microns to nanometers. Experiments on nanolattices have demonstrated that unique material size effects that emerge only at the nanoscale can be effectively propagated to macroscopic dimensions and have the potential to create new classes of bulk engineered materials with unprecedented properties.

Nanoarchitected metamaterials represent a new approach to "materials by design," making it possible to create materials with previously unattainable combinations of properties—light weight and enhanced mechanical performance—as well as unique thermal, optical, acoustic, and electronic attributes. Some realistic technological advances enabled by these metamaterials are untearable and unwettable paper, tunable filters and laser sources, tissue implants generated on biodegradable scaffolds that can be implanted and absorbed by the human body, battery-powered implantable chemical sensors, and extremely insulating and superthin thermal lining for jackets and sleeping bags.

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Probabilistic risk assessment based on physical models can inform advanced hurricane risk management strategies.

An Integrated Approach to Assess and Manage Hurricane Risk in a Changing Climate

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Ning Lin

Hurricanes, with their strong winds, heavy rainfall, and storm surges, cause much damage and loss of life worldwide. Recent disasters, such as Hurricanes Katrina in 2005 and Sandy in 2012, Cyclone Nargis in 2008, and Typhoon Haiyan in 2013, underscore the significant vulnerability of the United States and the world to landfalling hurricanes. And the impacts of these storms may worsen in the coming decades because of rapid coastal development coupled with sea-level rise and possibly increasing hurricane activity due to climate change.

Major advances in hurricane risk management are urgently needed. Given the inherent uncertainties in hurricane activity, such management should be strongly informed by probabilistic risk assessment. Furthermore, hurricane risk assessment cannot rely solely on historical records: to account for projected future changes, it should integrate physical knowledge and models with observational data.

Introduction

A physically based probabilistic hurricane risk assessment framework should integrate analysis of storm activity, hazards, and risk. Because of the limitations of historical records and the complexity of the problem, Monte Carlo (MC) methods, based on numerous synthetic simulations, are often used.

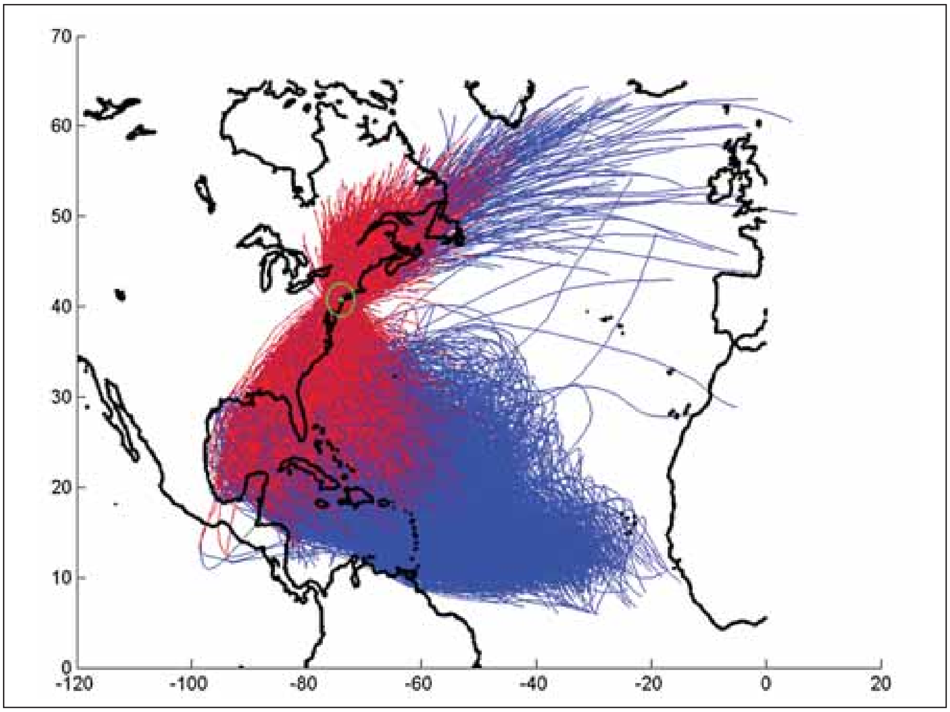

FIGURE 1 Simulation, using the Emanuel et al. (2006) model, of 5,000 synthetic storms that pass within 200 km of the Battery in New York City with a maximum wind speed greater than 21 m/s, under the observed climate of 1981–2000 and with an estimated annual frequency of 0.34. The green circle shows the 200 km radius around the Battery. Each blue curve shows a storm track, and the red portion of each track shows the 100-hour period before and during landfall (the main time period considered for hazard modelling). Longitude and latitude are shown on the axes.

In an MC approach, large numbers of synthetic but physically possible storms, characterized by their track, intensity, and size, are simulated (with their annual frequencies estimated) under observed or climate model–simulated climate conditions. Hazard models are then used to estimate the wind, surge, and rainfall-induced flooding associated with the simulated storms.

Given the estimated hazards and coastal exposure, vulnerability models can be applied to estimate storm-induced consequences (e.g., damage and/or economic losses) and thus risk. The risk assessment can in turn inform risk management.

The following sections review the main components—hurricane activity, hazards, and risk—of a physically based hurricane risk assessment framework and its application to evaluating risk mitigation strategies.

Hurricane Activity

Various MC methods have been developed to simulate storms that depict hurricane activity and climatology. Most of these methods (e.g., Hall and Sobel 2013; Toro et al. 2010; Vickery et al. 2000) create simulations based on the statistics of the historical storm records.

In my laboratory we apply the statistical-deterministic model developed by Emanuel and colleagues (2006, 2008). It simulates storm environments statistically but generates synthetic storms deterministically (with physical models). The large samples of synthetic storms generated by the model are in statistical agreement with the (albeit limited) observations. Moreover, as the synthetic hurricane environments can be generated for any given climate state, the model can simulate storms not only in current and past climates but also in projected future climates.

This model has been used to simulate storms in various ocean basins under projected climates over the 21st century to investigate how storm intensity and frequency may change with the changing climate (Emanuel 2013). It has also been used to simulate storms at city scales—for New York City (NYC; Lin et al. 2010a, 2012; Reed et al. 2015); Miami (Klima et al. 2011), Apalachee Bay (Lin et al. 2014), and Tampa (Lin and Emanuel 2015) in Florida; Galveston, Texas (Lickley et al. 2014); Cairns, Australia (Lin and Emanuel 2015); and Dubai in the Persian Gulf (Lin and Emanuel 2015). As an illustration, figure 1 shows a sample of 5,000 storms we simulated for NYC. These city-scale simulations can be used to analyze local hazards and risk.

Hurricane Hazards

Given a storm's characteristics, hazard models can be applied to estimate the wind, surge, and rainfall-induced flooding during the storm's landfall. Because large numbers of simulations are required for the MC-based risk analysis, the hazard models should be (computationally) "simple" (often there is a balance between accuracy and efficiency).

Wind

Various simple parametric methods have been developed to model the wind. In such an approach, one estimates the storm wind field using a parametric wind profile (e.g., Holland 1980; Jelesnianski et al. 1992) and adds an estimated background wind (Lin and Chavas 2012) to obtain the total wind field. My lab has recently developed a new wind profile (Chavas et al. 2015), motivated by the physical understanding that the canonical wind fields of mature hurricanes, although approximately circularly symmetric, cannot be described by a single mechanism.

Emanuel (2004) developed a physical model of the outer nonconvecting region of the storm, and Emanuel and Rotunno (2011) established an analytical profile that is physically valid only for the inner convecting region. We mathematically merged these two theoretical solutions to develop a complete wind profile for the entire domain of the storm (Chavas et al. 2015). This new physical model, evaluated and calibrated with various observational datasets, will have broad applications in hurricane hazard analysis.

Storm Surges

Storm surges, driven mainly by the storm surface wind and pressure, are also sensitive to coastal bathymetry and topography. Hydrodynamic surge models, basically solving coastal shallow water equations, include the SLOSH (Sea, Lake, and Overland Surges from Hurricanes) model (Jelesnianski et al. 1992), used by the National Hurricane Center for real-time forecasting, and the Advanced Circulation (ADCIRC) model (Westerink et al. 2008). The SLOSH model is computationally more efficient, but the ADCIRC model can better resolve the physical processes and produce results with higher resolutions.

Both the SLOSH and ADCIRC models are applied in my lab, depending on applications. Figure 2 shows that, as an example, the simulated storm surges in the NYC area from Hurricanes Irene (2011) and Sandy, using the ADCIRC model in this case, compare very well with the tidal gauge observations. In these simulations, we used high-resolution bathymetry and topography data, observed storm characteristics, as well as our new complete wind profile (Chavas et al. 2015) and a simple parametric pressure model (Holland 1980).

Rainfall

Hurricane rainfall is comparatively difficult to model because of its large spatial and temporal variation. Thus, most hurricane rainfall modelling applies full numerical weather prediction models (e.g., Lin et al. 2010b; Tuleya and DeMaria 2007). However, this approach requires large quantities of input data and has a high computational cost, so it is not effective for risk analysis.

Recently, simpler parametric models have been developed based on historical rainfall statistics (e.g., Lonfat et al. 2007; Tuleya et al. 2007) and physical

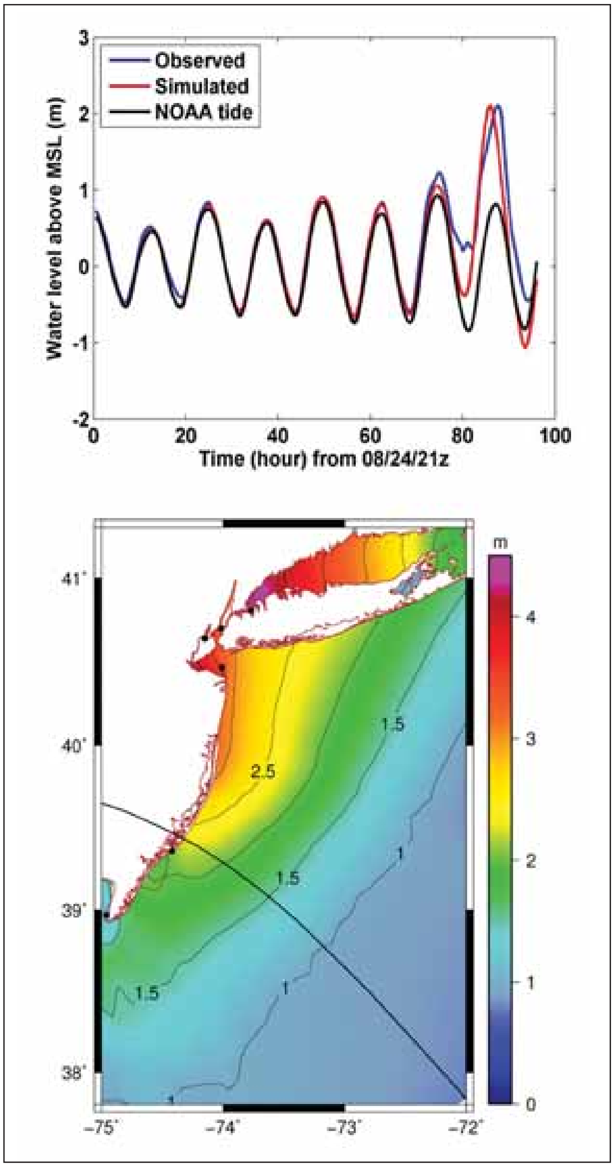

FIGURE 2 Storm surge estimation for New York City for Hurricanes Irene (above; time series of water level at the Battery) and Sandy (below; spatial distribution of the simulated peak surge; the estimated peak surge at the Battery, about 2.9 m, is close to the observed value of about 2.8 m above high tide; black curve shows the track of Sandy). MSL = mean sea level; NOAA = National Oceanic and Atmospheric Administration.

principles (e.g., Langousis and Veneziano 2009). The basic physics of hurricane rainfall is that it is determined mainly by the combination of environmental moisture and the speed of the storm updraft. The latter depends on low-level convergence due to surface friction, storm intensification, interactions with topography, and the background baroclinic state. A model that describes these processes has been shown to generate rainfall statistics comparable to the observations (Zhu et al. 2013).

Research in my lab is ongoing to evaluate and further develop this physical rainfall model, which can then be coupled with a hydrologic model (e.g., Cunha et al. 2012) to simulate inland flooding.

Hurricane Risk

Hazard models can be applied to simulated synthetic storms to generate large samples of hazards from which hazard probabilities can be estimated. For example, the ASCE building code has used such an approach to establish design wind maps (showing wind speeds for various return periods) for the entire US coast. Similarly, the Federal Emergency Management Agency (FEMA) developed flood maps depicting 100- and 500-year floodplains as a basis for the federal flood insurance policy. (Different storm and hazard models were used in these different applications.)

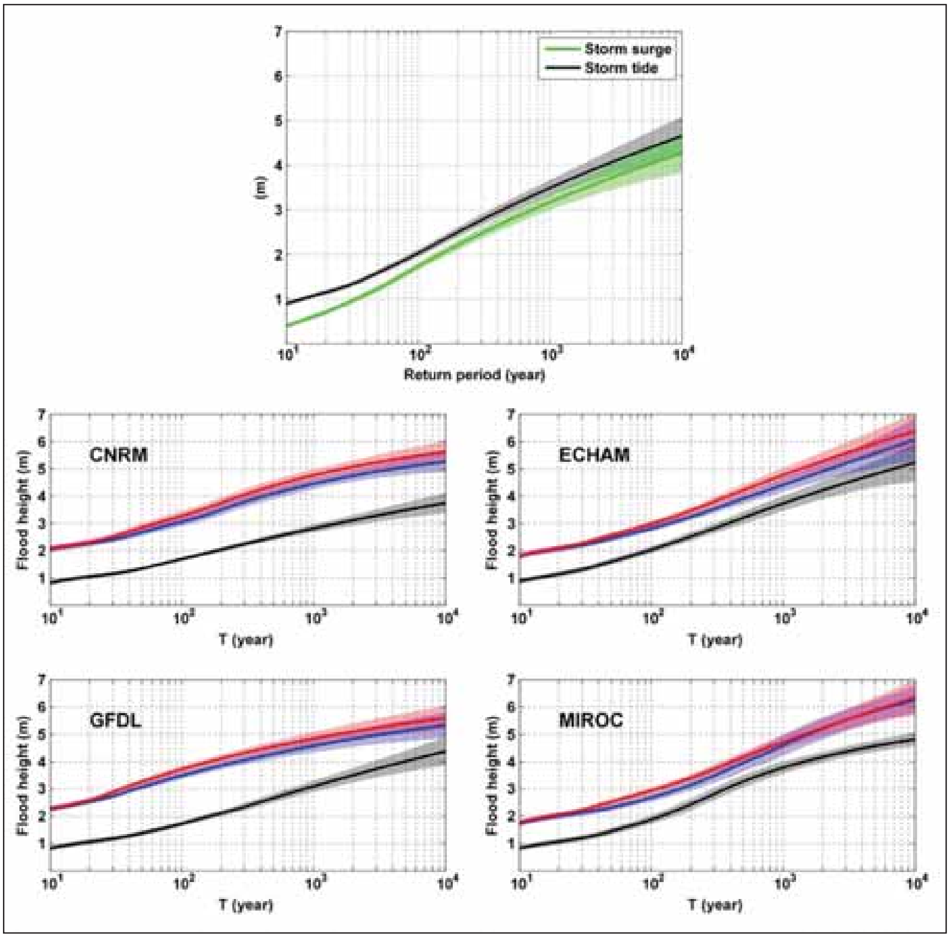

FIGURE 3 Estimated storm surge return level curves for New York City, under (top) the observed climate of 1980–2000 and (below) four climate model–estimated climates for 1980–2000 (black) and 2080–2100 (blue and, when accounting also for potential changes in storm size, red; with projected 1 meter sea level rise accounted for). Each curve is based on 5,000 synthetic storms (e.g., the curves in the top panel are based on the 5,000 storms shown in figure 1). Four climate models are applied: CNRM (CNRM-CM3; Centre National de Recherches Météorologiques, Météo-France), ECHAM (ECHAM5; Max Planck Institute), GFDL (GFDL-CM2.0; NOAA/Geophysical Fluid Dynamics Laboratory), and MIROC (MIROC3.2, Model for Interdisciplinary Research on Climate; University of Tokyo Center for Climate System Research (CCSR)/National Institute for Environmental Studies (NIES; Japan)/Frontier Research Center for Global Chance (FRCGC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC)). *Source:* Lin et al. (2012).

If the hurricane model used to generate synthetic storms draws on climate model–projected climate environments (Emanuel et al. 2008), one can estimate probabilistic hazards under future climates. We have performed such analysis for various coastal cities; for example, figure 3 shows our estimations of the storm surge level for NYC as a function of return period, under the observed current climate as well as climate model–estimated current climates and climate model–projected future climates. The results indicate a potentially significant increase of surge floods in the future due to climate change.

The hazard probabilities can also be combined with the estimated consequences of the hazards to quantify the risk. (The consequent damage/losses can be estimated with vulnerability models such as the Hazus model developed by FEMA.) The risk is often expressed by the expectation (mean) of the loss in a year (e.g., Aerts et al. 2013), but the full probabilistic distribution of the loss, if available, is more informative. In the context of climate change and coastal development, this risk is likely increasing.

To obtain a temporally integrated measure, the overall loss is also typically quantified by its present value (PV), the sum of all discounted losses occurring over a given time horizon (e.g., the next 100 years). Then the risk can be considered as the mean or, better, the probability distribution of the PV of future losses.

Benefits and Costs of Risk Mitigation Strategies

The PV also provides a convenient metric for comparing the benefit and cost of risk mitigation strategies. The benefit can be considered as the PV of the future losses prevented by mitigation, and the cost is the PV of the total cost of the mitigation (including construction and maintenance). While the cost is largely deterministic, the benefit is random.

Most studies have focused on comparing the cost and the mean of the benefit (e.g., Aerts et al. 2014). We present a more informative probabilistic cost-benefit analysis, applied to various coastal flood mitigation strategies proposed for NYC. As shown in figure 4, for each strategy we estimate the full probability distribution of the benefit and plot its exceedance probability function to compare with the cost. The crossing of the curve of the benefit exceedance probability and the line showing the cost indicates the probability that the benefit is greater than the cost. The probabilities of getting any higher or lower benefits can also be easily read from the curve.

The probabilistic benefit-cost analysis thus provides adequate information for making management decisions for any specific risk tolerance (decisions made based on the mean implicitly assume "risk neutral"). Also, this risk management analysis has relied on the physically

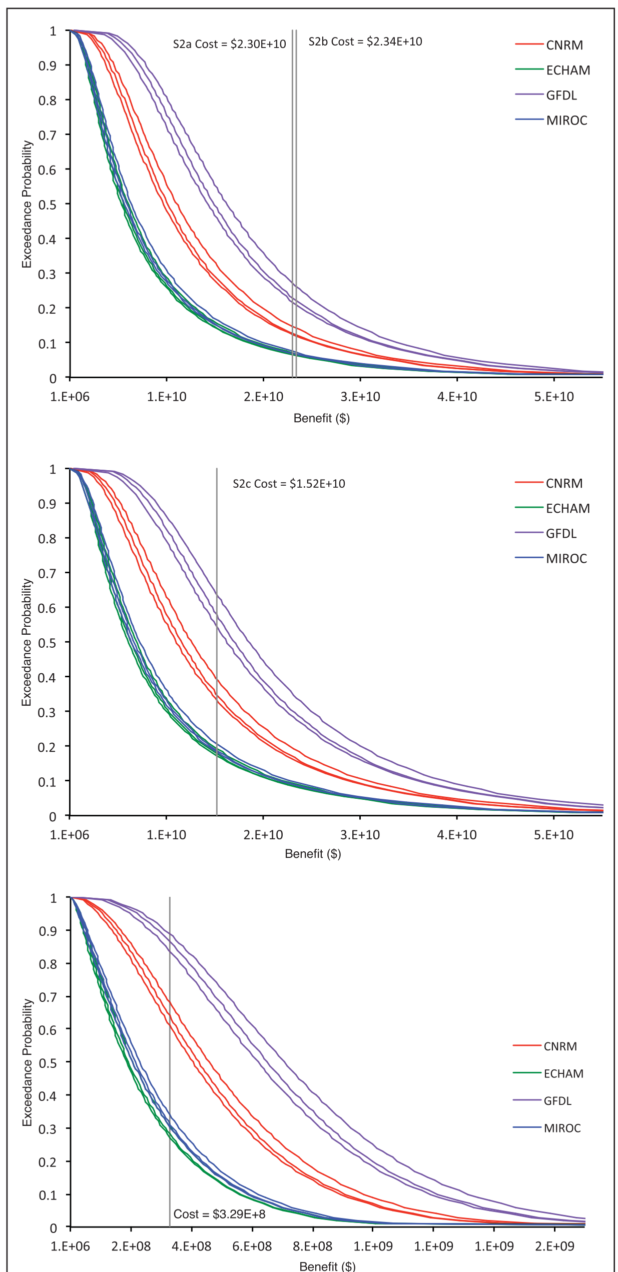

FIGURE 4 Estimated exceedance probability of the benefit (curve) compared to the cost (vertical line) for strategies S2a and S2b (top), strategy S2c (middle), and a strategy of elevating new houses on the floodplain by 6 feet (bottom) for New York City (NYC). S2a consists of three barriers to close off parts of NYC and New Jersey but preserves wetland dynamics of Jamaica Bay. S2b expands on S2a by adding a fourth barrier that closes off Jamaica Bay. S2c replaces three barriers from S2b with one large barrier in the outer NY harbor to protect a larger area. The details of these mitigation strategies are discussed in Aerts et al. (2014). The analyses account for projected coastal development and changes in storm activity and sea level over the 21st century. Current and future building stock data are obtained from the NYC Office of Emergency Management. Synthetic storm surge events are obtained from Lin et al. (2012) for the four climate models (CNRM, ECHAM, GFDL, and MIROC; see figure 3 for definitions), as shown by the return level curves in figure 3. The probabilistic sea level rise projection is based on Kopp et al. (2014); the three curves of the same color show results with sea level rise projected for the three IPCC AR5 (Intergovernmental Panel on Climate Change Fifth Assessment Report) emission scenarios (RCP 2.6, RCP 4.5, and RCP 8.5).

based risk assessment to account for the dynamic evolution of urban development, storm climatology change, and sea level rise.

Future Research

Although much remains unknown about how hurricanes, especially their frequency and size, will vary with the climate, risk assessment should continue to incorporate the state-of-the-art science to support risk management. Effective risk analysis will require more physical or physical-statistical methods for simulating synthetic storms. Hurricane rainfall models, especially those based on physics, need to be developed to estimate inland flood risk in a changing climate. Hurricane hazards are correlated (e.g., hurricane wind affects both storm surge and rainfall; coastal and inland flooding may interact), and multihazard approaches are needed to estimate how hazards will jointly evolve and how to deal with the joint risk.

In addition to engineering measures, urban planning and federal and private insurance play increasingly important roles in coastal risk mitigation. Establishing systematic and more integrated strategies may be the future direction for hurricane risk management.

Acknowledgment

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Risk management strategies that incorporate knowledge of human biases and behavior in regard to low-probability/high-impact events could reduce natural disaster losses.

Moving from Risk Assessment to Risk Reduction

An Economic Perspective on Decision Making in Natural Disasters

Jeffrey Czajkowski

Jeffrey Czajkowski is the Willis Research Network Fellow at the University of Pennsylvania Wharton Risk Management and Decision Processes Center.

A significant aim of natural disaster research is to improve the science, or the hazard assessment, of risk associated with such disasters. This goal could be achieved by, for example, enhancing the accuracy of short-term extreme weather or long-term climate forecasts or by increasing the validity of the hazard component of natural disaster catastrophe models.

It is assumed either that users of the information will fully understand the scientific data and incorporate that understanding in rational decisions based on a systematic analysis of tradeoffs between benefits and costs, or that losses will be better predicted and managed based on the enhanced scientific aspects of a catastrophe model. Yet, although hazard assessments have improved, many forms of losses from natural disasters have increased over time, associated with innumerable instances of inadequate investments in loss reduction measures and poor decision making before and after events.

As reported by the United Nations International Strategy for Disaster Reduction, "Experience has shown that a purely technical assessment of risk, however sophisticated and cutting-edge, is by itself unlikely to trigger actions that reduce risk. Successful risk assessments produce information that is targeted, authoritative, understandable, and usable" (UNISDR 2015, p. 148). Research provides empirical evidence of individuals exhibiting systematic behavioral biases and using simplified decision rules when making choices with respect to low-probability/high-impact events such as natural disasters. The findings show that such choices and the resulting behavior are significantly influenced by individual interpretation, which is dependent on how the scientific information is framed and presented, so it is essential to incorporate understanding of decision biases in the assessment and subsequent communication of natural hazard risks.

Unfortunately, little of this behavior-based knowledge has been incorporated into natural disaster risk assessment and catastrophe modelling. The use of appropriate risk management strategies based on such knowledge could reduce natural disaster losses.

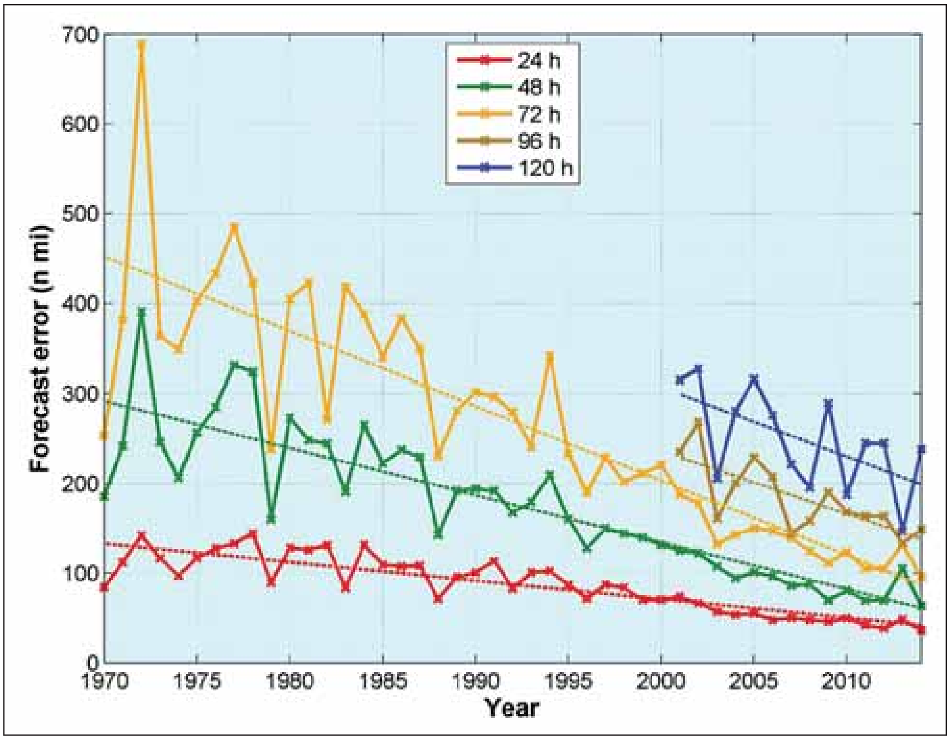

FIGURE 1 National Hurricane Center annual average official track errors as a function of forecast lead time for Atlantic Basin tropical storms and hurricanes, 1970–2014, with least squares trend lines superimposed. n mi = nautical miles. *Source:* www.nhc.noaa.gov/verification/verify5.shtml.

Introduction

Progress in Forecasting and Modelling

Recent decades have seen significant progress in the ability not only to observe and understand the weather but also to provide more accurate forecasts (Hirschberg et al. 2011; NRC 2010). This is congruently true for extreme weather events such as hurricanes, as evidenced by the National Hurricane Center's reduced annual average track forecast errors from 1970 to 2014 (figure 1). For example, the 72-hour track forecast error improved from nearly 450 nautical miles on average in 1970 down to less than 100 nautical miles in 2014, as shown by the yellow least squares trend line. These forecast improvements have been credited with a number of associated benefits, such as a substantial reduction in the number of direct fatalities thanks to more timely evacuation (Gladwin et al. 2007; Rappaport 2000, 2014).

Major advances in the science and modelling of extreme weather hazards (see Lin et al. 2012 for a discussion of storm surge modelling) have led to the widespread use of catastrophe models for natural hazard risk assessment since the early 1990s by the insurance industry. This usage has in turn led to the further implementation of natural hazard risk transfer mechanisms such as reinsurance and capital markets (Grossi and Kunreuther 2005), allowing for the relatively uneventful absorption of natural hazard economic losses by the insurance industry in recent years.

Persistent Challenges

There remain serious concerns, however. First, the evidence suggests an upward trend in economic losses from natural disasters worldwide (figure 2), to an estimated annual average of about $250 billion (UNISDR 2015). This rise is correlated with population and exposure growth in high hazard areas (UNISDR 2013, 2015), leading to more people affected by natural disasters, interdependencies in economic and social systems that increase vulnerability to disruptions, and potentially exacerbated hazard risks from climate change impacts (UNISDR 2015).

Second, reduced mortality benefits have been limited to select developed countries, largely because of a lack of capacity to forecast disasters and provide early warnings in developing countries (UNISDR 2015). Moreover, in developing countries noninsured and nondirect property and other losses, and the costs associated with recovery, are difficult to quantify and

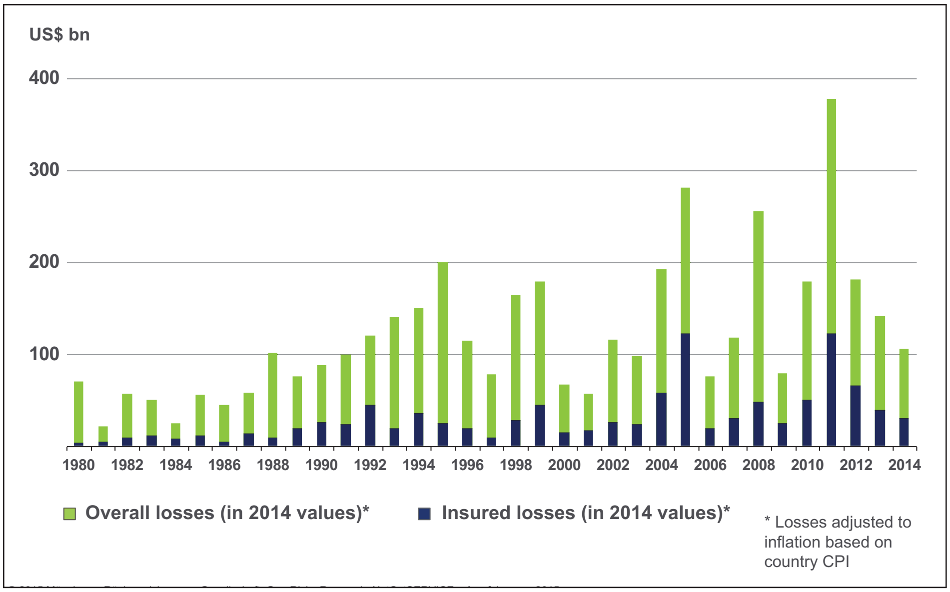

FIGURE 2 Overall and insured losses associated with worldwide natural catastrophes, in billions of dollars, 1980–2014. CPI = consumer price index. © 2015 Münchener Rückversicherungs-Gesellschaft, Geo Risks Research, NatCatSERVICE. Reprinted with permission.

hence thought to be substantially underestimated (UNISDR 2015).

Finally, even in a relatively sophisticated natural disaster risk management landscape like the United States there have been both inadequate investments in hazard-related loss reduction measures (e.g., with Hurricane Katrina in 2005 and Hurricane Sandy in 2012) and poor decision making. As an example of the latter, during the 2013 Oklahoma City tornado residents should have sheltered in place but were advised by a local meteorologist to evacuate south in their cars.

Illustrative examples show how a traditional natural hazard forecast risk context (i.e., risk "space") may be placed in a broader overview of event risk in time, importantly including behavioral implications of intertemporal decision making. The paper further describes an economic (i.e., benefit-cost) model of decision making in this risk space, highlighting potential sources of bias demonstrated in recent research.

Defining the Natural Hazard Forecast Risk Space

Natural hazard risk is defined as the probability of a natural hazard event occurrence and its expected impact (Kunreuther and Useem 2010). Thus, the concept of natural hazard risk has two key components, hazard probability and impact, each of which has an element of uncertainty associated with it. Geoff Love and Michel Jarraud of the World Meteorological Organization provide a schematic of this natural hazard risk space (figure 3), with the probability of the hazard on the y-axis and the impact on the x-axis (Love and Jarraud 2010); uncertainty is represented by the shaded shapes surrounding the three illustrative risks shown (e.g., C would have more uncertainty in impact vs. likelihood given the size, shape, and position of the circle).

Physical scientists working in the area of natural hazard forecast risk often concentrate on the likelihood of occurrence (y-axis), such as the return period for a flood event. Thus, as an illustrative example of this predisposition, only 0.6 percent of the National Oceanic and Atmospheric Administration's 2008 budget of $4 billion was directed to social science activities, which are more likely to focus on the impact side of a risk (NRC 2010).

Likewise, in a catastrophe modelling framework of combined hazard, exposure, and vulnerability components leading to loss (Grossi and Kunreuther 2005),

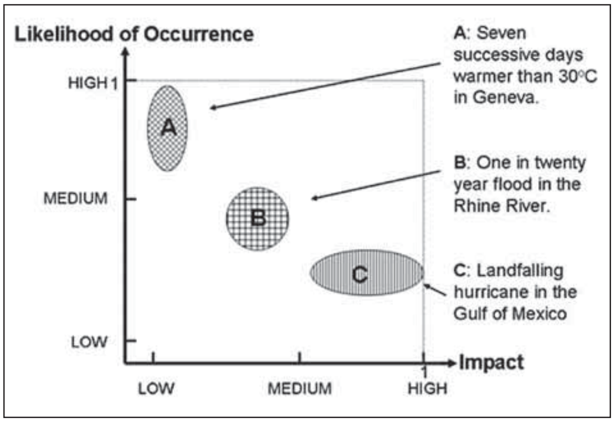

FIGURE 3 Natural hazard forecast risk space. Uncertainty is represented by the size, shape, and position of the shaded region surrounding the three risks illustrated. *Source:* Kunreuther and Useem (2010), printed and electronically reproduced by permission of Pearson Education, Inc., New York.

emphasis is typically on hazard, although the other components may significantly affect losses and hence overall risk. For example, a Risk Management Solutions study found that loss estimates could change by a factor of 4 when property exposure data gaps were filled or inaccurate information was corrected (RMS 2008).

There is a clear need to better understand the impact side of the natural hazard risk equation—including perceptions of expected impact—if overall risk reduction is the goal (Kunreuther and Useem 2010). For example, Botzen and colleagues (2015) find that in New York City flood risk perception is influenced by underestimation of hazard impact. Significantly, since the US tornado tragedies in 2011, impact-based warnings for tornadoes (figure 4) have been implemented by the National Weather Service (NWS).[1]

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BULLETIN - EAS ACTIVATION REQUESTED
TORNADO WARNING
NATIONAL WEATHER SERVICE SIOUX FALLS SD
722 PM CDT FRI OCT 4 2013

...TORNADO EMERGENCY FOR WASHTA...

THE NATIONAL WEATHER SERVICE IN SIOUX FALLS HAS ISSUED A

* TORNADO WARNING FOR...
  CHEROKEE COUNTY IN NORTHWEST IOWA...

* UNTIL 800 PM CDT

* AT 720 PM CDT...A LARGE AND EXTREMELY DANGEROUS TORNADO WAS
  LOCATED NEAR WASHTA...AND MOVING NORTHEAST AT 30 MPH.

  THIS IS A TORNADO EMERGENCY FOR WASHTA. TAKE COVER NOW. THIS
  IS A PARTICULARLY DANGEROUS SITUATION.

  THIS IS A PARTICULARLY DANGEROUS SITUATION.

  HAZARD...DAMAGING TORNADO.

  SOURCE...EMERGENCY MANAGEMENT CONFIRMED TORNADO.

  IMPACT...YOU ARE IN A LIFE THREATENING SITUATION. FLYING
           DEBRIS MAY BE DEADLY TO THOSE CAUGHT WITHOUT SHELTER.
           MOBILE HOMES WILL BE DESTROYED. CONSIDERABLE DAMAGE
           TO HOMES...BUSINESSES AND VEHICLES IS LIKELY AND
           COMPLETE DESTRUCTION IS POSSIBLE.

* THE TORNADO WILL BE NEAR...
  QUIMBY AROUND 730 PM CDT.
  CHEROKEE AROUND 745 PM CDT.
  AURELIA AROUND 750 PM CDT.

PRECAUTIONARY/PREPAREDNESS ACTIONS...

HEAVY RAINFALL MAY HIDE THIS TORNADO. DO NOT WAIT TO SEE OR HEAR
THE TORNADO. TAKE COVER NOW.

&&
LAT...LON 4259 9585 4291 9565 4291 9550 4283 9538
      4269 9539 4256 9569 4256 9577
TIME...MOT...LOC 0023Z 225DEG 27KT 4260 9567

TORNADO...OBSERVED
TORNADO DAMAGE THREAT...CATASTROPHIC
HAIL...1.50IN

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FIGURE 4 National Weather Service tornado impact–based warning example for a catastrophic tornado warning. *Source:* NWS Impact Based Warnings, www.weather.gov/impacts/#.VjyjjrerS72.

Integrated loss modelling between the physical sciences and other disciplines such as engineering and the social sciences is critical to enhance understanding of the numerous factors behind natural hazard risk (Kunreuther and Useem 2010; Morss et al. 2011; Tye et al. 2014). Integrated disciplines (e.g., physical scientists and economists) are evident in natural hazard impact assessment research on hurricane risks in coastal locations (Czajkowski and Done 2014) and on inland flooding from tropical cyclones (Czajkowski et al. 2013).[2] And a 2010 overview of the literature on integration of socioeconomic considerations in weather research cites six successful programs (NRC 2010, pp. 34–35).

[1] Information about NWS impact-based warnings is available at www.weather.gov/impacts/. For an assessment of the impact-based tool see Harrison et al. (2014).

[2] A number of recent impact-focused assessments for extreme events are available; e.g., Chavas et al. (2012), Malmstadt et al. (2009), Mendelsohn et al. (2012), Murnane and Elsner (2012), Murphy and Strobl (2010), Nordhaus (2006, 2010), Schmidt et al. (2009, 2010), Strobl (2011), and Zhai and Jiang (2014).

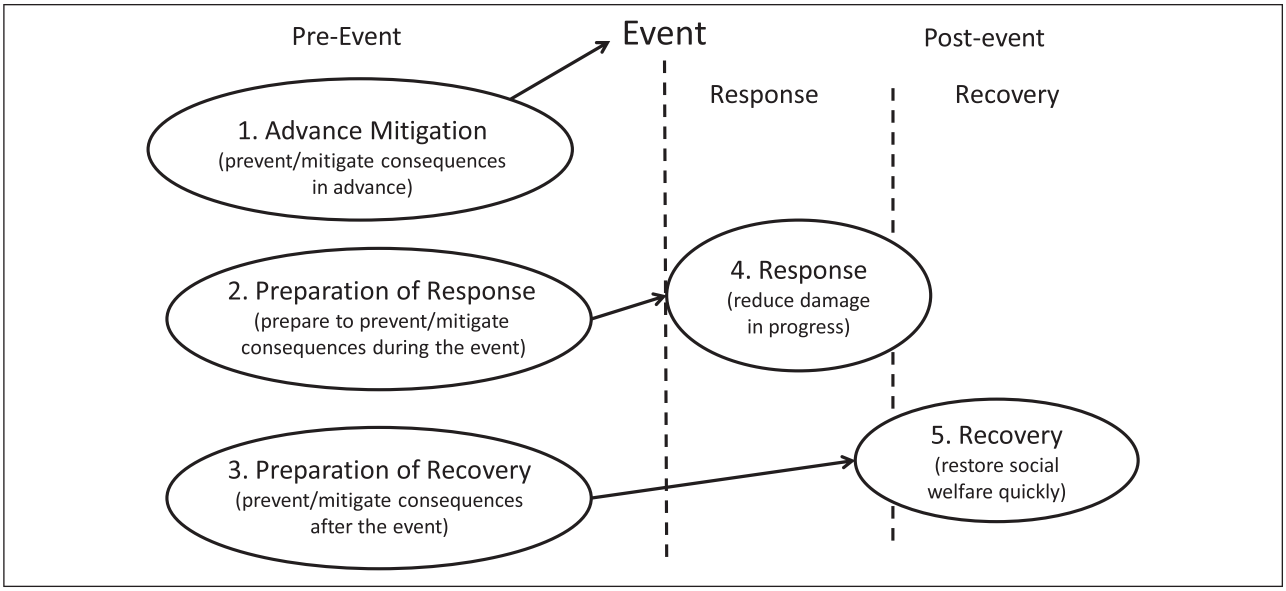

FIGURE 5 Overall timeline of natural disaster risk. *Source:* Kunreuther and Useem (2010), printed and electronically reproduced by permission of Pearson Education, Inc., New York.

Natural Hazard Forecast Risk in Time

Pre- and Postevent Planning

Forecasts of natural hazard risks are directly tied to an event, whereas the extent of overall impacts is a function of risk over time in the affected areas.

While most activity surrounding a natural hazard event is focused on the crisis management stages of preparation and response (during and immediately afterward), the socioeconomic impacts are tightly linked with the pre-event prevention, mitigation, and recovery planning activities and the postevent long-term recovery process. Narrowly focusing risk reduction efforts on the event itself will likely not support optimal total risk reduction efforts. Herman Leonard and Arnold Howitt of the Kennedy School of Government at Harvard provide a time-oriented view (figure 5) that extends to include the oft-underappreciated stages of pre-event preparation and postevent recovery (Leonard and Howitt 2010).

The ability to expand the timescale of the natural hazard risk event space to earlier and later stages is critical. For example, how would warning messages of a potential natural hazard event risk in the relatively distant future affect current pre-event preparation activities (NOAA 2015)?

Accounting for Behavioral Biases

Although expanding the timescale of the risk space is essential, interjecting the notion of time is potentially problematic given temporal behavioral biases such as underweighting the future through hyperbolic discounting[3] (Kunreuther et al. 2012). In this way of thinking, although the costs of pre-event preparation and mitigation are immediate and certain, the benefits associated with action are in the distant future and therefore uncertain in both time and return. Even if properly discounted benefits that accrued over time (i.e., at a constant and appropriate discount rate) outweighed the upfront costs, individuals would tend to disproportionately discount the future given their aversion to delayed gratification (Kunreuther et al. 2012).

Other intertemporal behavioral biases (Kunreuther et al. 2012) that could hamper optimal pre-event mitigation are myopic planning (a limited time horizon of only the next few years), underestimation of the risk (the probability or impact of a hazard), and affective forecasting errors (poor predictions of emotional states based on feelings today).[4] These biases make clear the importance of behavioral tendencies in decision making in the natural hazard risk context.

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[3] Hyperbolic discounting rapidly discounts valuations for small time periods and slowly discounts valuations for longer periods. Exponential discounting, on the other hand, discounts by a constant factor per unit delay, regardless of the length of the delay.

[4] Intertemporal bias of duration neglect (Kunreuther et al. 2012) may also exist in the postevent recovery phase, when there is a tendency to overestimate the time to recover and hence future protection would be overvalued.

Decision Making in Natural Hazard Risk Context

Intuitive vs. Deliberative Decision Making

From a rational economic perspective in the natural hazard risk space, individual decisions at a point in time are based on expected utility theory.[5] According to this theory, an individual confronted with the need for a decision with uncertain outcomes will decide based on the outcome with the greatest expected utility.

Table 1 shows the application of expected utility theory in the context of a natural disaster. When one is deciding to evacuate from a forecasted hurricane, utility (or disutility) is assigned to each possible future state (landfall hit or miss) given the possible action (stay or evacuate), and each future state is assigned a probability (p) with all probabilities summing to one. The choice of staying or evacuating is determined by selecting the action with the highest expected outcome across all possible states; in table 1, the choice is to evacuate.

In reality, however, the decision-making process is often quite complex (especially over multiple forecast periods)[6] and rarely do the people under the warning act rationally. Rather, the combination of systematic behavioral biases coupled with simplified decision rules leads to choices that differ from those predicted by expected utility theory (Kunreuther and Useem 2010; Kunreuther et al. 2012).

Kahneman (2011) highlights the difference between intuitive and deliberative thinking, documenting extensive research on intuitive biases that operate in lieu of ideal deliberative decision making and result in suboptimal choices for low-probability/high-consequence events such as natural disasters. For example, the availability bias estimates the likelihood of disaster occurrence based on the saliency of the event as opposed to objective hazard probabilities. Or protective action is not taken because the subjective probability of expected impact is below some threshold level of concern. Kunreuther and Useem (2010) discuss a host of other behavioral biases revealed by the research, many of them associated with group behavior, risk culture, fear and other emotions, and trust.[7]

TABLE 1 Evacuation payoff matrix

Outcome / Action	Landfall strike ($p = 0.3$)	Landfall miss ($p = 0.7$)	Expected utility
Stay	−2000	0	(0.3 × −2000) + (0.7 × 0) = −600
Evacuate	1500	−500	(0.3 × 1500) + (0.7 × −500) = 100

The utility of evacuating for the landfall strike of a disaster would be the avoided injuries net of the cost of evacuation; the disutility of staying would be the expected injuries or mortality; and the disutility of evacuating when no strike occurs would be the costs of evacuation. Expected utility is the summation by row of the probability of each outcome multiplied by its illustrative utility/disutility. p = probability.

Factors that Drive Positive Behavior

A considerable amount of research has sought to identify what factors drive positive behavior in this context, controlling for behavioral biases. Meyer and colleagues (2013) used a realistic simulated storm environment to better understand risk perception and decision making, and in a subsequent study they interviewed more than 2000 respondents in real time under the threat of hurricane strikes during the 2010–2012 hurricane seasons (Meyer et al. 2014). Beatty and colleagues (2015) used a big data approach to analyze water bottle sales before and after a hurricane.

In a recent review and assessment of risk communication and behavior, NOAA (2015) points to work by Mileti and colleagues (2006) that identified a number of factors and categories consistently found to matter in the context of warning response: sociodemographic (female, white, more education, and children present);

[5] Other social science theories of decision making in a natural hazard context include the psychometric paradigm of psychology (perception of hazards taking into account qualitative information [e.g., dread] rather than just statistical [i.e., probability]); the cultural theory of risk in anthropology (social and cultural influences on risk perception); the mental models approach of psychology and risk (individuals have a "mental model" of reality, influenced by social interactions and experiences, that they use as a lens to view risky situations); the protection motivation theory of psychology (people protect themselves based on their perception of severity, probability, effectiveness of protective action, and self-efficacy); and the social amplification of risk framework of geography (risks are amplified or attenuated due to individual, social, and cultural factors) (NOAA 2015).

[6] For an illustration of this decision over time from a dynamic perspective, where for each forecast period the individual may choose to evacuate or wait for an additional forecast, see Czajkowski (2011).

[7] Chapter 4, "Cognitive Constraints and Behavioral Biases," discusses these in more detail as does chapter 5, "The Five Neglects: Risks Gone Amiss," from an expected utility perspective.

personal (experience, knowledge of hazard and actions, self-efficacy, fear, risk and vulnerability perception, more resources available, large and strong social network); source/channel (environmental or social cues present, official source, in person, familiar source, multiple sources); information (specific, credible, certain, frequent, consistent, and with guidance on actions); and threat (less lead time available, greater severity, close, confirmed).

Importantly, however, little of this behavior-based knowledge has been incorporated in natural disaster risk assessment or mitigation planning. Possible approaches are briefly articulated in the next section.

Moving Forward

Despite significant advances in recent decades in observing, understanding, and forecasting extreme weather, the impacts and threats from natural disasters remain extensive. This paper has provided a definition and context for decision making in the natural disaster risk space where behavioral biases play a significant role. Efforts to reduce natural disaster risk will have to incorporate appropriate risk management strategies based on this behavior-based knowledge. The following measures are recommended based on this overview:

- Develop warning and forecast products that assess and communicate risk from the perspective of both probability and impact, including the notion of uncertainty.
- Extend the timescale of the risk forecast space to pre-event preparation/mitigation and postevent recovery planning.
- Account for the behavioral biases documented in the socioeconomic research literature when designing risk communication tools or incentivizing more proactive preparation, mitigation, and/or recovery activities.
- Extend catastrophe models to include risk perception and behavior components.

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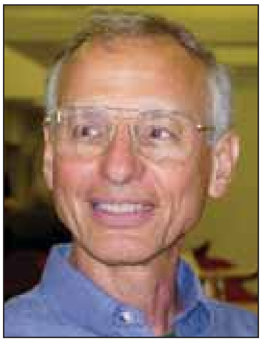
Op-ed

Energy for the Foreseeable Future

S. Fred Singer is professor emeritus at the University of Virginia and director of the Science and Environmental Policy Project.



Gerald E. Marsh is a retired physicist from Argonne National Laboratory.

Many people believe that wind and solar energy are essential for replacing nonrenewable fossil fuels. They also believe that wind and solar are unique in providing energy that's carbon-free and inexhaustible. A closer look shows that such beliefs are based on illusions and wishful thinking.

About half of the carbon dioxide (CO_2) put into the atmosphere by humans is from the production of electricity by burning fossil fuels. Electricity from nuclear fission produces essentially no CO_2 and has none of the disadvantages of solar/wind (described below). Opposition to nuclear power is based on irrational fears and misleading cost comparisons.

Although it appears at first glance that solar, wind, and nuclear sources of energy do not emit CO_2, this is not quite true. All require equipment manufacture that involves CO_2 emission; a rough measure is given by comparing the relative costs of construction as well as operation and maintenance (O&M). But caution must be exercised here: a nuclear plant has a much longer life (60 years and more). Because of limited experience there is inadequate information about corresponding lifetimes and O&M costs for solar/wind.

A major problem for solar/wind is intermittency, which is partially overcome by providing "stand-by" power—mostly from fossil fuels. Nuclear also has special problems (e.g., the care and disposal of spent fuel) that raise the cost and make comparisons rather difficult and also somewhat arbitrary, especially since the "externalities" associated with fossil fuels (e.g., coal plant waste disposal and health costs associated with coal) are rarely counted.

There is general agreement that both solar and wind energy are truly inexhaustible and satisfy the principle of sustainability. However, both are very dilute sources of energy and require large land areas, favorable locations, and the transmission of electric power. In contrast, nuclear power plants have a comparatively tiny footprint and can be sited wherever cooling water is nearby.

Moreover, nuclear energy is also, for all practical purposes, inexhaustible. Uranium is not in short supply, as many assume; this is true only for high-grade ores, the only ones worth mining at current market prices.

About 0.7 percent of natural uranium is in the form of the fissionable U-235 isotope; the remainder is inert U-238. For use in power reactors the uranium fuel must be enriched in U-235 to at least the 2 percent level (for weapons, the required level is 80 percent or more).

Currently, low enriched uranium is cheap enough to justify "once-through" use in light water power reactors; fuel rods are replaced after a fraction of the energy contained in them is "burnt up." Fissionable plutonium (Pu) is created during burnup (from the U-238 in the fuel rods) and contributes to the generation of electric power. The spent fuel contains U-238, radioactive fission products with lifetimes measured only in centuries, and small amounts of long-lived radioactive Pu isotopes and other heavy elements. As every nuclear engineer knows, this spent fuel is itself an important potential resource. Most of it can be transformed into valuable reactor fuel for fast-neutron reactors, enlarging the useful uranium resource by a factor of about 100. If used in the "breeder" mode, such reactors can make uranium resources truly inexhaustible.

Nuclear fusion, the energy source that powers the Sun, has been the "holy grail" of plasma physicists, who after decades of research have not yet been successful in building a stable fusion reactor (the hydrogen bomb is an example of unstable fusion). In a hybrid fusion-fission design, fusion could be a source of neutrons for creating fissionable material for reactor fuel.

So why is this country not moving full speed ahead with all forms of nuclear to make it the primary source of energy for generating heat and electricity? Are precious time and dollars being wasted on marginal improvements to solar photovoltaic and wind technology?

What seems to be holding back the adoption of nuclear energy is public concern about cost, safety, proliferation, and disposal of spent fuel. We briefly address these concerns.

Cost: Growing scarcity of coal and a trend toward factory-assembled modular nuclear reactors reduce existing cost differentials—and may even reverse them.

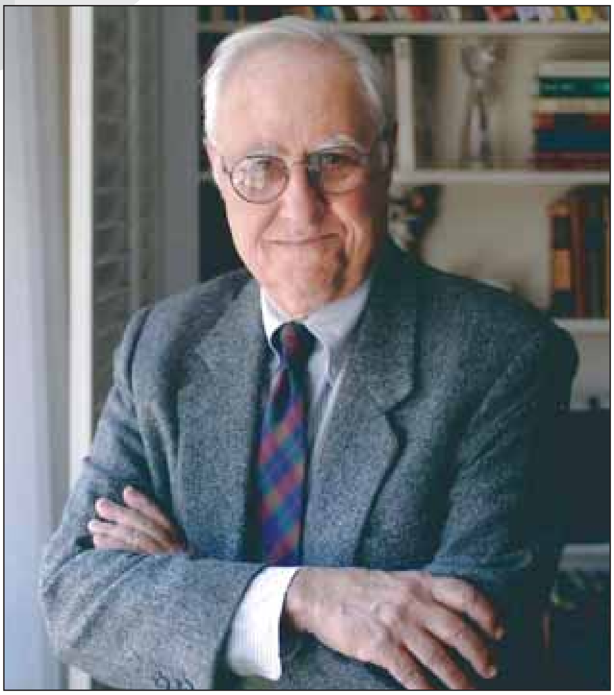
Safety: There have never been lives lost in commercial nuclear accidents. Proper design is further improving safety by reducing the number of valves and pipes and relying on gravity in inherently safe designs.

Nuclear proliferation: Much has changed in recent decades. There is no longer a nuclear duopoly. If North Korea and Iran can build weapons—and delivery systems—it may be time to rethink the international nonproliferation regime.

Disposal of spent reactor fuel: There are no real technical problems. The containment time for a waste repository is reduced to less than 500 years by using reactor designs that burn up much of what is currently called "waste." Reprocessing works, but has been discouraged because of historic concerns about proliferation based on plutonium. US reprocessing of spent fuel would make nuclear truly sustainable and eliminate the long-term waste problem, without contributing to proliferation.

An Interview with . . .

Sam Florman



Samuel C. Florman (NAE) is a civil engineer, retired general contractor, and author.

RON LATANISION (RML): I want to begin by saying how much we appreciate the fact that we are now finally interviewing the man who has had more to do with this column than anyone else, beginning with our very first interview, with Richard Blanco.[1] I've been trying to think of what word best describes your influence.

SAMUEL C. FLORMAN: I've been reading about the science advisor to the president. Why don't we just say I'm one of your many advisors?

RML: When you say the president's science advisor, do you mean John Holdren in particular or do you mean the community of advisors?

FLORMAN: The whole history of it—including President Nixon bouncing the advisor and shutting down the office—because in anticipation of this call I started thinking about engineers and what we should be doing. Giving advice certainly. We don't hear much about it, but Holdren is there, as well as a whole crew of admirable people. Incidentally, he's called the *science* advisor. We could talk a good while about the use of the word science when they really mean science and technology, science and engineering, and sometimes it should be engineering and incidentally science.

RML: That's an interesting point; let's come back to that, because I want to ask your thoughts on science and engineers in public life. But let's begin with a bit of personal history. You've had a home in Manhattan virtually all your life, is that right? Maybe you can give us a short biographical sketch.

FLORMAN: At this very moment living in Manhattan is a special thrill and a special annoyance. The pope is going to be here in a few days, and it looks like the whole police force of New York is at our front door and we're getting notices of how many streets are going to be closed.

We've actually had a pope here once before, and President Johnson and most of the other presidents right up to Obama. My wife and I live next to a transverse road through Central Park, and with ABC Studios and Lincoln Center to the West and the United Nations and ritzy neighborhoods to the East, this can sometimes be exciting. And of course it can be a nuisance. New York City is certainly dynamic.

As far as our profession is concerned, this city is a natural breeding place for engineers, especially for civil engineers. It's almost like we live in the middle of a construction project. As a kid I was what we call a "sidewalk superintendent" all over town, and in addition right outside my window for a couple of years I had an apartment house under construction. In those days steel beams were attached with red hot rivets—today we use high-tension bolts—and the workers would sometimes toss those rivets long distances from the place where they were heated to the men who would catch them in a metal container and then hammer them into place. What a thrill!

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[1] Poet-engineer Richard Blanco, interviewed for the fall 2014 issue of the *Bridge*, cited Sam Florman's book *The Existential Pleasures of Engineering* as a significant influence in his decision to become an engineer.

And then there was the miracle of New York City's water supply. The Academy publication *A Century of Innovation* (2003) described the many engineering achievements that have transformed our lives, and I was asked to write something about how pure water was provided for huge metropolises. This reminded me of the time I was with my family at a fancy restaurant, and the waiter wanted to bring us bottled water with the name of some European spa on the bottle. My father said, "No thanks, we will have La Guardia cocktails." The waiter knew this meant we wanted New York City tap water. Then my father launched into a dissertation on the wonders of water in New York City being brought down from the mountains, through fantastic tunnels and culverts and viaducts. What a fabulous engineering accomplishment that was: to be here with millions of people, nothing around us but salt water and a contaminated river, and all this fresh water coming in.

So I would say that New York was a great place for getting a youngster to think about an engineering career. Of course I've heard about kids out on farms who tinkered with things—I guess you never know where the inclination toward engineering might come from.

RML: Am I correct that your only departure from Manhattan was during your undergraduate study at Dartmouth?

FLORMAN: Well, sort of, except that Pearl Harbor occurred during my senior year in high school, so my early places of residence were pretty much established by the events of World War II. I was very fortunate in choosing to go to Dartmouth, not only because I had one year of wonderful civilian college life—and because Dartmouth's Thayer School of Engineering encouraged me to think about the place of liberal arts in engineering education—but also because Dartmouth happened to have the largest Navy V-12 program in the nation. I enrolled in that program shortly after arriving on campus, and after that one year of civilian life I was called to active duty, which meant putting on a uniform and being subject to military discipline but continuing with my education. Along with the other V-12 enlistees in my class who were studying engineering, I stayed at Dartmouth until early 1945. In 2½ years we had earned enough credits to receive a degree. Then off we went to Officer Training School in Rhode Island, commissioned as ensigns in the Navy's Civil Engineers Corps, given a couple of months of military training, then sent off to the Philippines to join the Seabees (US Naval Construction Battalions) being mustered for the invasion of Japan. We arrived in Leyte Gulf one day before a surrender agreement was signed by the Japanese. You could say that was fortunate timing, although there's a touch of guilt that goes with being spared the action experienced by others. In any event, I spent the better part of a year in the Pacific on the island of Truk mostly rebuilding—with Japanese workers, incidentally—the facilities that had been bombed.

After returning home and leaving the Navy I went to Columbia for a year, and then I worked a bit for a house builder. But I still had some wanderlust so I got a six-month job as a construction engineer in Venezuela, where the oilfields were being developed. Then I took the money I made and traveled around Europe 'til the money ran out. After that I came home and settled down. I've been here in New York ever since—except for such tourist travel as my wife and I have been able to squeeze in. And I guess I should mention a getaway cabin by a lake in Putnam County, just 50 miles from Manhattan but it feels like another world.

RML: You got a bachelor's degree in civil engineering at Dartmouth, and then a master's in English literature from Columbia. That's an unusual combination, at least for an engineer.

An engineer should be a totally educated individual prepared to take on the most pressing problems of our civilization.

FLORMAN: Well, the concept behind the Thayer School of Engineering at Dartmouth came from Sylvanus Thayer, also known as the Father of West Point. Thayer studied at Dartmouth and then at West Point, graduating in 1808, and when he was put in charge of the Academy in 1817, he brought with him respect for France's École Polytechnique, where education for leadership was the tradition. In his older years he contributed funds for the founding of an engineering school at Dartmouth, and the concept of this school was that in order to be a top-notch engineer, you had to be a broadly educated individual prepared to take on the most pressing problems of civilized society. The school opened in 1871, and in the beginning students were obliged to take four years in college, receiving a basic bachelor of arts degree, and then spend two years in the engineering school before they could graduate with a degree in engineering. Eventually Dartmouth cut that back to a total of five years instead of six—BA degree after the fourth year plus BE after the fifth. And of course many graduates go on to advanced degrees. So, when I took a master of arts degree in literature, I was in a way honoring the Thayer tradition.

I am supportive of the idea that engineers should be in public office.

CAMERON FLETCHER (CHF): There is increasing discussion of expanding engineering education to include some of the liberal arts. What do you think it would take to make that happen at other schools?

FLORMAN: As far as expanding the requirement for a basic engineering degree, a few years ago the dean of one of the largest engineering schools told me that the parents who pay the tuition are mostly not at all happy with the idea of adding a fifth year for the basic degree. However, currently there is considerable pressure to add more liberal arts courses into the basic engineering program. I happen to favor the Thayer program or equivalent, but I'm not privy to the conclaves where such decisions are made.

RML: Many of the decisions that are made in the interest of the public are made by people who have no training in science or engineering or technology. I'm curious: Given the background that you have in engineering and your interest and involvement in construction with KBF, where you were a chairman, have you ever thought about public life as a career?

FLORMAN: I guess everybody thinks about that—you look at the politicians and you say "I can do better." But thinking realistically of public office for myself I would have to say "No, no, no, and no." I get along fine with most people, but don't put me before a rambunctious crowd and don't ask me to debate with clever opponents or joust with professional journalists.

I'm supportive of the idea that engineers should be in public office. But exactly how this works out in the real world . . . well, it's not clear. Our two engineer presidents have been Herbert Hoover and Jimmy Carter. Tom Wicker, a respected journalist of the late 1900s, noted that Mr. Carter used an "engineer's approach of devising 'comprehensive' programs on this subject or that, but repeatedly failed to mobilize public opinion in their support." Yet many apparently natural politicians, dynamic individuals who are able to mobilize public opinion, are often not clear thinkers nor trustworthy leaders.

CHF: What types of roles for engineers in public life do you think might be meaningful, relevant, useful?

FLORMAN: Well, we can't give up on the idea of political leadership. I've mentioned the École Polytechnique in France, where engineering and science have been the foundation for going into public life. When doing research for a book that I wrote in 1997 I found that the presidents of several nations including Chile, Peru, and the Philippines were engineers. Jiang Zemin, president of China (1993–2003), was an electrical engineer who rose to political power through the post of minister of electronics industries. He had recently told an American visitor that although he no longer used his engineering actively, it helped him not only in his thinking and understanding of commercial and industrial projects in his country but also in systemizing his thinking about the world. So I'm reluctant to give up on the idea of engineers as political leaders.

But while we're thinking about engineers seeking office or being in office because they're so well informed and smart, somehow the advisory position doesn't sound very romantic or dramatic. Yet it's very important. All the key people in government, all the politicians, rely on advisors who we may not read about in the newspapers but often play a critical role.

There's a very good play that was here in New York recently—based on a couple of highly praised books: *Wolf Hall* and *Bring Up the Bodies*—about Henry VIII and his advisor Thomas Cromwell. Very dramatic. Cromwell, as an advisor, really dominated the history of his time, doing more than advising, playing a critical role in the decision-making process.

RML: There's a line in your book, *The Existential Pleasures of Engineering*, in which you describe politics as "good objectives competing for limited resources." I think that's an apt description, particularly when, as an engineer, I look at things such as infrastructure in the United States. We've had bridges that have failed, sometimes spectacularly and with loss of life. We have airports that are described as third world, and water distribution systems, as in the city of Manhattan, that are more than a century old.

From an engineering perspective, there's no doubt to me that our infrastructure needs some attention and updating, and yet we seem to have little movement on that from Congress. Is that the case? These are good objectives but with limited resources. And if that is the case how do we prioritize resources to deal with things that are fundamental to the way we function in this country?

FLORMAN: It is very much the case, and it's hard to understand because most people agree that bridges should be safe and dams shouldn't leak or levies disintegrate. Industry, certainly my industry, is waiting, waiting, waiting for the work to be financed. And the labor unions are all for it. What's holding it back?

One is inclined to refer to the Great Smog of '52, the air-pollution event that struck London during a period of cold weather in December of that year. The problem was obvious to all, but the danger had been ignored. The air in London was awful—coal-fired power stations, coal-heated homes, polluting vehicle exhaust. The city was renowned for its "pea-soupers." The '52 disaster was at first taken in stride. But in the ensuing weeks statistics compiled by medical services found that the fog had killed 4,000 people, possibly several times that number. After that event the public mood was completely changed. Regulations were imposed and laws were passed. Reflecting on the event at the 1962 international Conference on the Technological Order, Aldous Huxley observed: "Evidently we have to have a great many tremendous kicks in the pants before we learn anything."[2]

RML: We don't seem to have the political will to make some of this happen.

FLORMAN: That's true. Politics is a funny thing. Newt Gingrich was leader of the Republicans in Congress at a time when members of his party were arguing for cutting the budget, and he said "Fine, let's cut the budget, but not for science and industry." He persuaded his party to work with the Democrats to double the budget of the National Institutes of Health. And all of the science and technical parts of government were funded at a time when many other aspects of the budget were being cut.

So it can be done, and everybody is calling for cooperation between the parties for the sake of the country. Let's just hope common sense will prevail.

Everybody is calling for cooperation between the parties for the sake of the country. Let's hope common sense will prevail.

RML: In addition to your books, you have written for the *New York Times* and *Harper's*.

FLORMAN: At *Harper's* I was a contributing editor; at the *New York Times* I've had a variety of assignments—an essay in the Sunday magazine section, an op-ed, a couple of columns for the real estate section, and what I've really enjoyed the most is the book review section. I wrote eight or nine book reviews. That was fun, especially the front page review of Tracy Kidder's Pulitzer Prize winner *The Soul of a New Machine*. And for 15 years I wrote a regular column for *Technology Review*.

But Bob Lucky has done a world's record number of columns for *IEEE Spectrum* over a period of many years.

RML: I know him. When I was at MIT he was a frequent visitor to the Materials Science Department. We had people in the department who were interested in integrative circuits and crystal growth and the kinds of things that were of interest to Bob and his colleagues at Bell Labs. I remember that he always spoke well and had a good sense of humor.

CHF: As evident in the title of the published collection of his columns: *Lucky Strikes…Again*. Henry Petroski is another engineer writer, and he spoke glowingly of you, Sam.

FLORMAN: If we ever have a club, Henry is the king and the emperor of engineer writers. I have a shelf full of his excellent books.

[2] Huxley A. 1962. Technology and Culture 3(4):636–642. Proceedings of the Encyclopaedia Britannica Conference on the Technological Order.

RML: The interesting thing is that you and Henry are both civil engineers. My sense is that the people in the engineering community with the most perspective and sensitivity to social issues seem to be civil engineers. That was true at MIT, where I remember people like Joe Sussman in the Civil Engineering Department. He really got very involved in public policy. His sense of the social value of what he is doing was enormous.

Maybe that is because civil engineers build systems that serve society—buildings and schools and apartments. There is also this dimension of a deep concern about the common good that has always struck me as being typical of civil engineers. Am I off-base or do you see it?

FLORMAN: No, you are very much on. As a matter of fact, historically, civil engineers *were* engineering until the mechanicals came along and identified themselves as a new and different group, and then all the other specialties followed. The civil engineer John Roebling, who designed the Brooklyn Bridge, was a student of philosophy.

RML: That is another common sort of factor here. Henry Petroski, in addition to teaching civil engineering, is a history professor. And you have not only a degree in civil engineering but also one in English literature. Literature and writing must have been a very high priority or very high interest to you at an early stage.

FLORMAN: Yes, and part of the answer is down the street here: the Ethical Culture Fieldston School. It has been a very progressive school from way back.

We want to do the right thing, but engineers and the public can't always agree on the right thing to do.

CHF: You've been associated with engineering ethics, and we published a piece that you wrote for the *Bridge* back in 2002. We're actually devoting an issue of the *Bridge* in 2017 to engineering ethics. What's your take on the current status of engineering ethics? What do you think are the biggest challenges for engineering ethics right now and where has the greatest progress been made?

FLORMAN: Engineering societies are concerned about ethics, and this concern leads to formalized codes and standards. Those have changed and continue to change because what we think is proper ethically for engineers is inevitably affected by what society values. Since society values safety we begin to put in place new laws, new rules, even new organizations to oversee compliance with these new standards. But standards have a way of changing.

It used to be people would say the Constitution gives you independence. For example, people once were concerned about the engines in steamboats blowing up and people being killed, and some politician of the day said, "You get on the boat, you check out the engine yourself to make sure the engine is proper. You can't tell people what kind of an engine to put in their boat!" The thinking has changed, and with it the role of the engineer and the role of government have come to be generally accepted.

Now, that doesn't mean that engineers who work for oil companies may or may not as individuals have opinions about where and how much oil should be developed, or where drilling is proper. During World War II IEEE had questionnaires for their members, and one of the questions was, "How do you feel about working on armaments?" For some engineers the answer was, "Sure, armaments are a part of life. I'm willing to work." For others, well, all right, maybe they would work, it was patriotic, but they really didn't like it—"We shouldn't be devoting our technical knowledge to ever more horrifying weapons, ending up with the H-bomb."

So, ethics… engineers sometimes are in the middle of situations where community standards are not at all clear. Take the automobile—the Pinto was a famous case. We learn that an automobile has a defect, and some people die because of it, and everybody is outraged. If you spend more money on an automobile you can make it safer and safer and safer. You could make it like a tank and nobody would ever be killed. Yet at the same time people say, "We want cheap automobiles, we want automobiles that are available for all citizens." So we go back and forth; these matters are not simple. Similarly, if we want to save the environment, some people say "we'll take care of that later on, right now we can't afford it," or "who knows what the danger really is."

I think we're all agreed we want to do the right thing, but then it turns out that engineers and the public can't agree on the right thing to do. Or engineers can't agree among themselves. That doesn't mean that we shouldn't keep trying, that we shouldn't consider all aspects.

Certainly engineers should be committed to being careful and diligent so that we don't have engineering mistakes from laziness or, I fear, sometimes greed. As we go along we have no choice but to be bound by current laws and regulations of which there are many thousands.

So ethics are very important, if sometimes difficult to define or agree on. I hate to see young engineers coming out of school and going to work and immediately becoming hostile because they don't like something that the industry is manufacturing. You want your engineers to be enthusiastic about what they're doing. Neither do I like to hear an engineer-executive say that his loyalty is to his stockholders, not to the public. But it's not a simple matter, which is exactly why we should be working on it and having meetings and having issues of an important publication devoted to it. Incidentally, the article I wrote for the *Bridge* back in 2002 was titled "Engineering Ethics: The Conversation without End."

New York by Gehry

RML: Let's talk about KBF. You were chair of the general construction corporation Kreisler Borg Florman. You have a number of projects that bear the name of your firm in terms of the construction activity, but one that particularly intrigues me is called New York by Gehry, a 76-story apartment building in Manhattan. Could you tell us a little about KBF and New York by Gehry?

FLORMAN: There's some confusion in the public's mind, even good friends of mine, when they see our sign, Kreisler Borg Florman, up on a building, like New York by Gehry. We're the project manager: we build the building in the sense that we get the different contractors together, we hire the plumber, electrician, we have people of our own doing work and expert superintendents and supervision, and we schedule and we oversee the money flow. Yes, we are the builder—we are professionals—but we are not the "owner," who is usually a private developer, a government agency, or a private institution. Nor are we the architect, nor the various design engineers who prepare the drawings and specifications.

The owner puts up the money (in this case some $600 million) or arranges for the financing. Sometimes the developer wants his sign up there, and sometimes not, because communities are not always thrilled to see buildings going up in certain locations.

In the case of New York by Gehry, Bruce Ratner was the developer. This building is on the Manhattan side of the Brooklyn Bridge, in a very interesting part of town near Greenwich Village, a somewhat artsy part of town and an active community. Certain members of this community didn't want a huge building going up there, so Ratner worked with the local people, and lo and behold four stories of this building are devoted to a school, for the city as a whole and for that part of the city in particular. And one floor is devoted to a hospital to provide healthcare facilities. And then, for a variety of reasons, one of which was to help get approval from artistic people who might have objected to the building, Ratner hired Gehry, who has done some fabulous museums and buildings all over the world that have gotten attention, and that was a big plus.

I think that this building is quite beautiful. Technologically it's not different from most tall buildings, but artistically there's a stainless steel covering in the form of waves, so that when you look at it it's not a flat building with brick or plain metal plates, but instead you see this ripple effect. Some people are not sure they like it, but I think it's very striking, very handsome. And a delight to build.

But along came the financial crisis—the worst since the Great Depression—and when we were about halfway up, at the 40th floor, we were told to stop work. It was a difficult time for the New York construction industry and of course for the nation. Happily the unions came in, not only for this building but for several under construction in the city, and negotiated some reduction in wages. Also, Ratner met with his financial associates, and took such actions as they thought appropriate, and after a short delay—a tense time—we were told to go ahead and get the building finished. It was nice to have this as one of the final jobs in KBF's 60-year career as we decided to close down.

We were disappointed with the behavior of a couple of organizations once they knew that we were retiring from the scene, but Ratner was as fair and decent as he could be. And looking back over all these years in what is considered to be a tough industry—and what happens to be (with the exception of restaurants) the most failure-prone industry in the nation—I am overwhelmed by the memories of fairness, goodwill, and indeed kindness that came my way.

RML: Are your children and grandchildren interested in engineering or likely to pursue engineering?

FLORMAN: We have two sons and five granddaughters. The sons spent some time as teenagers working as construction laborers, but grew up to be one doctor and one lawyer, which pleases their parents very much. Among the five granddaughters, the oldest has just graduated from law school and I think this very week is starting her job with a law firm. I don't believe her two sisters in college are on the scientific or engineering track, but I'm holding my breath.

The two younger granddaughters are now a junior and senior in high school, the same school their parents went to, the same school I went to—a very fine school. As young women of today they are very much into science and even engineering, which is being introduced in the high school. So check back with me in a couple of years and let's see when they get to college which way they go.

Engineers are smart, and we're energetic, so let's share our good impulses for the public good.

RML: They must be in a high school that is emphasizing STEM education.

FLORMAN: Yes, and I've met a couple of the teachers engaged in this new enterprise. Of course you know that STEM in some places is being converted to STEAM—the A is for the arts, to make sure that liberal education doesn't get left out in the cold.

RML: I think that's a very worthwhile objective.

CHF: As we wrap up our conversation, Sam, what messages would you like to convey to the *Bridge* readership?

FLORMAN: I guess a final message should be inspirational. I know that we're all proud of our free enterprise democracy and of the engineering skills that contribute so much to our worthy society. But beyond our personal efforts there is the communal endeavor that is vital to our society's well-being. The NAE is committed to advising the federal government, sponsoring engineering programs, encouraging education and research, recognizing superior achievements, and such worthy causes. I think that we all have a responsibility to share in these efforts. I think that engineers as a profession are committed to go into society to create things in the public interest, and to serve with groups with worthy objectives. It has been a pleasure and a privilege for me to serve on the board of the Hall of Science here in New York, and a school board, a hospital board, and the board of overseers of my engineering school, and on committees at the National Academies. I think we all owe it. And darned if we don't enjoy it when we get involved.

And beyond our own communities and even beyond our own nation, I'm happy to see that engineers are more and more committing themselves and their efforts to the public good in the widest sense, on an international scale. I used to be irked that there were Doctors Without Borders and other organizations that go out and help people in the world, without identifiable participation by engineers. Only belatedly is there an organization established called Engineers Without Borders. Engineers by and large are smart, and energetic, so let's share our good impulses for the public good. Our government and those of many other nations band together for international rescue missions in cases of disaster. And charitable organizations support marvellous efforts to relieve poverty and cure disease. Some engineers—often young engineers—are valuable participants in such enterprise. I can't claim to have participated in such efforts myself—except for small contributions—but you've asked me for a message to the *Bridge* readership.

And thinking of the *Bridge* and of the Academy, let's not forget the good folks in Washington, the staff, arranging the meetings, distributing the documents, bringing order to the enterprises that have to be efficiently managed to be effective. And publishing important materials. Please give those folks my good wishes—and to you folks who are putting out what I think is a very important publication—bravo! And Ron and Cameron, thanks for the invitation to chat about good and important things. We haven't solved all the world's problems, but we're working on them.

NAE News and Notes

NAE Newsmakers

Kyle T. Alfriend, TEES Distinguished Research Chair and professor of aerospace engineering, Texas A&M University–College Station, and **Ben T. Zinn**, David S. Lewis Jr. Chair and Regents Professor, Georgia Institute of Technology, have been named **Honorary Fellows** by the American Institute of Aeronautics and Astronautics.

B. Jayant Baliga, distinguished university professor of electrical engineering at North Carolina State University, has been chosen for induction into the National Inventors Hall of Fame for his invention of the insulated gate bipolar transistor, a power semiconductor device used as an electronic switch around the world in all sectors of the economy, ranging from transportation to consumer appliances to factory robots and medical devices in hospitals. He will be inducted at a May 2016 ceremony in Washington, DC.

Japan's largest IT society, the Information Processing Society of Japan (IPSJ), honored NVIDIA Corporation's chief scientist and senior vice president of research **William J. Dally** with the **Funai Achievement Award** for his extraordinary achievements in the field of computer science and education. Dally is the first non-Japanese scientist to receive the award since 2003.

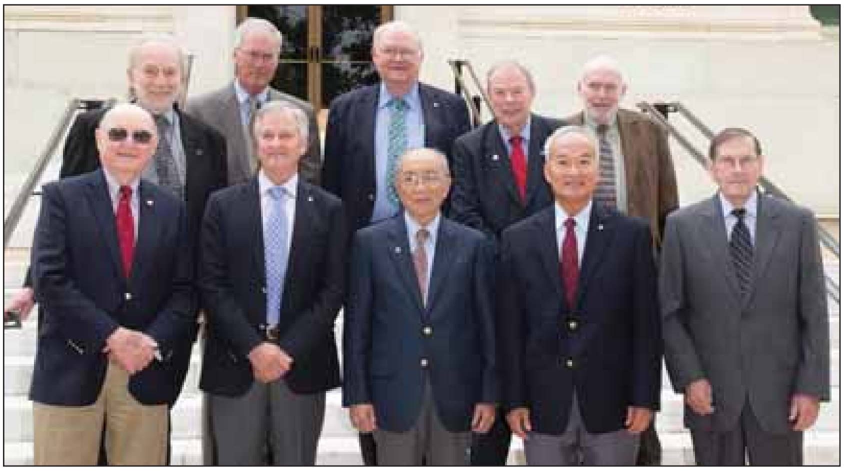
G. David Forney, Jr., adjunct professor in MIT's Department of Electrical Engineering and Computer Science and Laboratory of Information and Decision Systems (LIDS), has been selected by the Institute of Electrical and Electronics Engineers (IEEE) to receive its highest award, the **IEEE Medal of Honor**. He is being recognized "For pioneering contributions to the theory of error-correcting codes and the development of reliable high-speed data communications." The medal will be presented at the IEEE Honors Ceremony in New York on June 18, 2016.

The Society of Motion Picture and Television Engineers (SMPTE), a worldwide leader in motion-imaging standards and education for the communications, media, entertainment, and technology industries, has announced its **2015 SMPTE Fellows**. This honor is conferred on individuals who have, through their proficiency and contributions to the industries, attained an outstanding rank among members of the society. **Larry J. Hornbeck**, solid-state physicist and TI Fellow Emeritus at Texas Instruments, was chosen based on his 40-year research and development career developing microdisplays. New fellows were inducted on October 28 in Los Angeles.

Sang Yup Lee, distinguished professor, dean, director, and Division of Engineering Fellow, Korea Advanced Institute of Science & Technology (KAIST), was awarded the **Order of Service Merit in Red Stripes** on the 50th anniversary of Invention Day on April 19. He received the medal for his contributions to the empowerment of the country's biochemical industry and the birth of systems metabolic engineering by creating a number of widely appreciated source technologies for microbial production of chemicals.

The UK Institution of Engineering and Technology (IET) has awarded **Asad M. Madni** its 2015 **J.J. Thomson Medal**. The medal was inaugurated in 1976 and is awarded to an individual who has made major and distinguished contributions in electronics. Dr. Madni "has been honored for his distinguished career, spanning four decades, which has produced seminal contributions to the development and commercialization of 'intelligent' sensors, systems, instrumentation, and signal processing." He received the medal during the IET Achievement Awards Ceremony on November 18 in London.

2015 Annual Meeting



Anniversary members: *front row, l to r:* Raymond Decker (35th), Ron Latanision (30th), Norman Li (25th), Alfred Cho (30th), Herb Richardson (35th); *back row, l to r:* Arthur Heuer (25th), Paul Gray (25th), Loring Wyllie (25th), Norman Scott (25th), Yale Patt (class of 2014).

NAE members, foreign members, and guests gathered in Washington in October for the 51st NAE Annual Meeting. The meeting began on Saturday afternoon, October 3, with an orientation session for 67 new members and 12 new foreign members in the NAS Building on Constitution Avenue, followed by their dinner that evening with the NAE Council in the Great Hall.

NAE chair **Charles O. Holliday, Jr.**, opened the public session on Sunday, October 4, with brief remarks encouraging the new members to be actively engaged in NAE outreach. President **C. D. Mote, Jr.,** then delivered his annual address, titled "Strategic Plan Goals and Grand Challenges for Engineering." He talked about the need for improving the demographics of the NAE membership, attracting industry collaboration, better communicating what engineering is to the public, promoting competitive engineering talent in the US workforce, engaging globally in the innovation environment, and advising the nation on technological and societal challenges with our sister academies of sciences and medicine. He noted that the theme for this year's meeting, the Grand Challenges for Engineering, is a highlight of NAE global engagement and talked about rapidly growing national and international interest in events and programs devoted to the challenges. The text of his address is reproduced on pages 74–79 and available on the NAE website (www.nae.edu).

The induction of the NAE Class of 2015 followed President Mote's address, with introductions by NAE executive officer **Alton D. Romig, Jr**. The program continued with the presentation of the 2015 Founders and Bueche Awards. The 2015 **Simon Ramo Founders Award** was presented to **Linda P.B. Katehi**,

Class of 2015.

E4U2 Winners.

chancellor, University of California, Davis, "for visionary leadership in engineering research, entrepreneurship, and education, and for national advocacy of higher education as a major driver of the US economy." **William F. Banholzer**, research professor, chemical and biological engineering, University of Wisconsin–Madison, received the **Arthur M. Bueche Award** "for his extraordinary record of new products commercialization and improvement in university-industry relationships through innovative intellectual property treatment and joint industry-academic funding."

The **Bernard M. Gordon Prize for Innovation in Engineering and Technology Education Lecture** featured the two 2015 winners: Simon Pitts, director, Gordon Institute of Engineering Leadership (GEL) and professor of practice in engineering leadership, and Michael B. Silevitch, Robert D. Black Professor of Electrical and Computer Engineering, both at Northeastern University.

Dr. Pitts delivered the lecture. He described the GEL Graduate Program and explained why it is imperative to enhance the engineering leadership capability of early career engineers in order to improve overall US competitiveness. He identified significant "gaps" between the needs of practicing engineering leaders and the output of conventional engineering education and then shared the methods used by the GEL program to close these gaps. The GEL integrated curriculum uses both experiential and project-based learning to inculcate the knowledge, skills, and attitude needed to lead engineering teams, developing

(1) the ability to lead diverse teams of engineers with different personalities, cultures, discipline expertise, worldviews, motivation levels, and sensitivities; and

(2) the capability to technically lead projects by integrating engineers (and nonengineers) on the team to move projects from the concept stage to commercial success.

He presented survey feedback from past students confirming the efficacy of the program: 90 percent of respondents said the program was either their most important experience yet (52 percent) in improving engineering leadership capability or essential to development (38 percent). Industry recognition is equally positive: half of the students are promoted by their company within one year of completion, and two thirds at the two-year mark.

After a break, Dr. Mote introduced the three plenary speakers: **Robert S. Langer**, David H. Koch Institute Professor, Massachusetts Institute of Technology; Dawn C. Meyerriecks, deputy director, Directorate of Science and Technology, Central Intelligence Agency; and Thomas C. Katsouleas, executive vice president and provost, University of Virginia. They addressed, respectively, two of the Grand Challenges—engineering better medicine, security and cyberspace—and provided an overview and update of the Grand Challenge Scholars Program.

The Sunday program concluded with the presentation of the award winners of the second Engineering for You Video Contest (E4U2) on the NAE Grand Challenges for Engineering. The Texas Student Television Digital Media Team—Jason Weilee, Carson Taylor, and Ridge Liu—won the Best Video Overall award for their video "The Personalized Teacher," which addressed the challenge of advanced personalized learning using a play-

Forum panel and moderator..

ful, rhyming narration reminiscent of Dr. Seuss. The team showed how alleviating one challenge created a stronger foundation for solving the other grand challenges. The Best Video Overall award includes a $25,000 prize. Awards of $5,000 were given to the winners in the following categories:

- Middle School and Younger: "Engineering for You" by Maksim Tonyushkin
- High School: "Making Solar Panels More Affordable" by Hans Voegeli
- Tertiary Education: "Our Future Shines Above" by Instituto Tecnológico y de Estudios Superiores de Monterrey (ITESM), Querétaro campus
- General Public: "Virtual Reality: The Next Technological Frontier" by Bonny Eagle Robotics Team #133
- People's Choice: "Water Is Our Future" by Tyler Su

The day ended with a reception for members and their guests.

At the annual business session for members on Monday morning, Dr. Mote spoke about the NAE and answered questions from members. The business session was followed by the forum, "NAE Grand Challenges for Engineering: Imperatives, Prospects, and Priorities," in which a distinguished panel of former members of the Grand Challenges committee discussed their impact and how solutions will improve the lives of people and society. The panelists were **Alec N. Broers**, member of the UK House of Lords; **Farouk El-Baz**, professor, Center for Remote Sensing, Boston University; **Wesley Harris**, Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology; Calestous Juma (NAS), professor of practice of international development, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University; **Dean Kamen**, president, DEKA Research and Development Corporation; Robert H. Socolow, professor of mechanical and aerospace engineering, Princeton Environmental Institute, Princeton University; and Jackie Ying, executive director, Institute of Bioengineering and Nanotechnology (Singapore). Dan Vergano, science reporter, *BuzzFeed News*, moderated the discussion, exploring the many questions surrounding the impact of the Grand Challenges and possible next steps.

Sunday's induction ceremony, award ceremonies, plenary speeches, and Monday's forum were all recorded and are available on the NAE website (www.nae.edu).

On Monday afternoon, members and foreign members participated in NAE section meetings at the NAS Building and Keck Center. The Annual Meeting concluded with the reception and dinner dance, with music provided by the Odyssey Band, at the JW Marriott.

The next annual meeting is scheduled for October 9–10, 2016, in Washington, DC—save the date.

Remarks by NAE Chair Charles O. Holliday, Jr.

Charles O. Holliday, Jr.

Congratulations to all the new members today. Let's give them a big round of applause. And congratulations to the family members and friends, whether in this room today or with us in spirit, who were so important to the accomplishments that got you here today. They get a bigger round of applause.

For the family members, you might not know exactly what has to happen for those selected to walk across this stage in a few minutes. You can't apply for this position; you have to be recognized by a peer in the National Academy of Engineering—and they're not supposed to tell you they're nominating you. They do a lot of research on you to make sure you have the qualifications. They find multiple other members who will second that, and when you've met all those qualifications you're just starting the process. It's a rigorous hurdle, and only one in nine nominees actually walks across this stage. So it's a very special accomplishment, and I want you to know what your family member or friend went through to be here today.

For the new members, you will have many opportunities to serve in formal processes in the National Academy of Engineering. You heard about it in the orientation yesterday, about committees and workshops and serving as an officer, and I highly encourage you to do those things. But I'm going to talk about something else today, and that is the informal processes.

There will be two changes to your life after you walk across this stage, and I urge you to take advantage of them as an opportunity. Don't think of this as an obligation. Think of it as an opportunity that now occurs every day of the rest of your life and that didn't exist before today.

First, you have had a "brand" extension. Usually when you think about brands you think Coca-Cola, IBM, Google…. I'm talking about your personal brand. You've got a great personal brand already or you wouldn't be here; you have a great list of accomplishments. But after today there's one more called *member, National Academy of Engineering*. And that's very special.

I urge you to think about that as you're advertising your brand. The way we advertise our brands as individuals is we introduce ourselves to somebody we don't know, or we get reacquainted with a friend we haven't seen in a long time, and we say, "I'm a member of the National Academy of Engineering." If they're an engineer or focused on technology, they'll probably know what you're talking about. If they don't, they'll probably say "that's very nice"—and then you have an opportunity to tell them what the National Academy of Engineering is about and you can advance our brand.

We serve the nation in everything engineering and technology. Our roots go back to President Abraham Lincoln, who understood that the nation needed advice on engineering and technology and that it should not come from politicians. For some reason, he had this idea that politicians might look at engineering and technology with a political eye and be biased. After being in this town for a day, I'm sure you know that could never happen.

He also knew that if we were paid, we might not be quite so objective either, so we don't get paid for our work.

We are credible. We bring that to the world. It's at the federal level by our charter but it can be at the city level, the state level, or anywhere in the world as we go forward. I urge you to keep that in mind.

You also have another obligation and an expectation that you might not have anticipated. When you say, "I'm a member of the National Academy of Engineering," people think you know what you're talking about. You know your technology. But they also expect you to be able to explain it in a way that they can understand it. I don't mean talk down to them, but explain it in a way that's meaningful for them. And that is another expectation you have going forward.

I will close with a short story that exemplifies this much better than I could ever have guessed as I was preparing this talk. Just 10 days ago I was in New York at the United Nations. A few people were in town—the pope, President Obama, some of his buddies (or not) from around the world. I was invited to a dinner to honor the pope. Since the pope was actually speaking at

Madison Square Garden, holding Mass that night, I didn't think he was going to be at the dinner. I was pretty sure he had another gig so it wasn't going to happen.

But it turned out the dinner was to honor the scientists and engineers who, many months earlier, had met with the pope to explain global warming and climate change. They explained it to him in such a way that, with all the different issues he could take up, he moved this one up on his agenda.

The leader of the group of scientists and engineers described the process they used to prepare to talk to the pope. They researched over 700 papers—hundreds of thousands of pages of data about global warming and climate change. They condensed all that to a couple thousand pages and a big stack of charts, and as they were going in to meet the pope the leader asked, "How much time do I have? How many charts can I show?" The response was, "You can say two sentences." And he said, "You don't understand—" "No. Two sentences."

Think about this. From your discipline, you have a chance to talk to the pope, or anybody else, and you have only two sentences to explain your life's work, those 700 documents.

Now, I will not get this perfectly right, but this man's two sentences were: "Your Holiness, global warming and climate change is real and it's bad for the world." Second sentence: "Your Holiness, the three billion poorest people in the world will be the most impacted by this result." Period. Those were his two sentences.

I think the pope had a few questions, but if you look back at what he said in New York last week, he said those two sentences a lot of times, over and over.

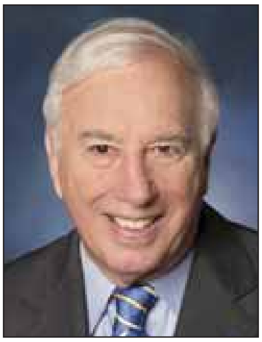
Maybe you can't get your lifetime's work down to two sentences, but if the pope were challenging you, you would probably find a way.

My challenge to you today is to get up and serve. Take the opportunities. Find ways to explain what you know about science and technology in a way that everybody can understand.

You can make a real difference. And we can take this organization forward.

Thank you very much.

NAE Strategic Plan Goals and Grand Challenges for Engineering: Remarks by NAE President C. D. Mote, Jr.



C. D. Mote, Jr.

I am honored to welcome all our members, foreign members, special friends, and guests to this 51st annual meeting of the National Academy of Engineering. I offer my warmest welcome to our newly elected members and foreign members and assure you that this induction day will be one that you will remember. And a special welcome is extended to all our spouses who have put up with us so graciously and make our work at the academy possible.

A Year to Remember

This past year has been one to remember for the NAE and for the entire academy complex. Our 50th anniversary was highlighted at our 2014 annual meeting, and in July of this year the academy complex experienced its greatest transformation since the NAE was founded in 1964 when it welcomed the new National Academy of Medicine, created from the Institute of Medicine. The three academies also adopted a new brand: *The National Academies of Sciences, Engineering, and Medicine*. Each academy retains its identity, but an identity for the complex prepares us to participate more effectively in today's global environment.

In February the NAE, along with the University of Southern California's Viterbi School of Engineering and the MacGyver Foundation, launched *The Next MacGyver* initiative, with the backing of the White House. In the TV series of 1992, secret agent MacGyver solved complex problems using keen knowledge of engineering and sciences, his Swiss Army knife, and extraordinary cleverness. Of course, he was dashing—very engineer-like. The Next MacGyver initiative seeks to place a female engineer as the lead superhero in a primetime TV series. A crowd-sourcing initiative that solicited ideas for a series story line befitting a female engineer led to 5 winners. NAE member Wanda Austin, a superhero herself, served as one of the judges. Each winner has been assigned a top Hollywood producer of TV programs[1] to lead in developing a new TV series. Over the next year when you see a TV series with a female engineer as the lead superhero, she is likely to be an NAE *Next MacGyver*.

In addition to celebrating our 50th anniversary, at the 2014 annual meeting we together began the process of creating our first new strategic plan since the one that was approved on October 2, 1999.[2] Our goal was to draft a five-year plan focusing on the priority use of our resources. We received invaluable inputs from the membership, held a council retreat that was supported generously by IBM's planning services, discussed the plan at every council meeting, and the council adopted it on August 3.[3] Thank you all for your participation.

This Year's Annual Meeting

At this annual meeting I have two charges. First, I wish to speak briefly about what underpins the goals of the plan and why they are critical to the NAE. Then I will speak about the theme for this annual meeting, the *NAE Grand Challenges for Engineering*, an ever-expanding movement.

Strategic Plan Goals

The strategic plan sets forth the mission, vision, and six 5-year goals for academy organization and engagement; recommends actions to support each goal; and establishes metrics and milestones for measuring progress on them. Because time is fleeting, we are already moving forward with their implementation. While we may not complete all of them within five years, good progress will be made because they have our attention.

Goal 1. Membership Representation: Increase the representation of business, female, younger, foreign, and underrepresented minority members.

There are serious demographic issues facing the NAE. One is the need to ensure that the "practice of engineering" voice remains primary in the NAE's advice to government. The academy was created principally to ensure this voice. However, the decreasing representation of business members in the academy is challenging our connection to the business and industry sectors. Historically, our business members have been our primary contacts to their companies.

At the founding of the NAE in 1964 about 70 percent of its members were in the business of engineering, but that number has decreased to 37 percent today. And without immediate steps it will continue to decline, because business members are more concentrated among our older members. In short, more members are leaving the NAE than are entering. Our recognition of this problem is long-standing, but so too has been our ineffectiveness in dealing with it. Now we must address business representation in the election of new members with determination before it drops below a tipping point making recruitment of nominations from business too difficult. The peer committees and the Committee on Membership have taken on this charge beginning with the 2016 election cycle, and I applaud their appreciation of the problem and their determination to address it. This is a solvable problem.

The fractions of women and underrepresented minorities among our new members also remain too small despite our efforts to incentivize their nominations. The Membership Policy Committee and the Committee on Membership will continue their efforts to propose policies and implementations that will rebalance their highly qualified representation. The time has come to show demonstrable change here too.

Our effectiveness in serving the nation calls for us to improve our identification of highly qualified foreign member candidates, inspire their nomination, and elect those that meet our qualifications, especially candidates from countries and regions where the NAE has few foreign members. I am pleased to report that this year over 10 percent of the foreign member nominees would, if elected, be the first in the NAE from their country.

Goal 2. Industry Collaboration: Increase the value of the NAE to industry.

Leaders from industry have long been major contributors to the NAE's advice to government. Yet, despite this legacy, there is general agreement that the value of the NAE to industry is not high enough.

Historically, the academy's link to industry came through NAE business members who were highly placed and prominent in their com-

[1] Such as *Madam Secretary*, *Star Trek*, *Hawaii Five-O*, and *CSI: Cyber*.

[2] The 1999 plan was amended twice, to add international affairs in October 2005 and engineering education in October 2006.

[3] Members can find the plan at https://www.nae.edu/14102.aspx?Redirect=142618.

panies and industry sectors. They inspired, and in many cases recruited, colleagues and companies to participate with the NAE. Today, those links, like the number of business members, are not what they were earlier and must be regenerated. Goals 1 and 2 are related.

In addition to the all-important human interface of NAE members with industry, we must present and communicate the value of NAE to large and small firms alike. Meetings and communications with industry leaders will help us reorient our efforts to fulfill this goal. Through these engagements and others with your help, we will reconnect to industry.

Goal 3. Public Understanding: Demonstrate to the public how engineering creates a better quality of life.

In the Lincoln-Douglas debate of 1858, Abraham Lincoln said, "Public sentiment is everything. With public sentiment, nothing can fail. Without it, nothing can succeed." Because every public opinion poll verifies that the public has no correct "sentiment" about engineering, today we might ask, "How can engineering succeed?" Good question!

Communication, communication, communication is the problem and the answer. The problem is, what is communicated to the public about engineering is often wrong by omission or misrepresentation. For instance, take three of the greatest engineering feats of this century: the Mars and Pluto missions and the Large Hadron Collider. All publicity about them is essentially silent on engineering. But how many people do we all know who were inspired to engineering because of the Moon mission and space exploration?

It is also time to hit the replace button when the word "technology" is used to represent "engineering." Technology is an outcome, it is not engineering.

The collective silence of the engineering community about the correct public understanding of engineering begets its invisibility. If the public hears nothing about engineering, how can it ever develop a positive sentiment? Those who understand engineering can correct this problem if enough of us decide to do so. I believe that one of my responsibilities to you, and to the public and the nation, is to advocate for the correct use of the word "engineering."

Introducing engineering to K–12 students through in-school and after-school programs, like four-year engineering curricula in high school and FIRST Robotics competitions for 6- to 18-year-olds, and inspiring students through an Advanced Placement examination—measures like these bring engineering forward to young people, to their parents, and to schools too. The Grand Challenges for Engineering also inspire young people and the public generally about what engineering does for people and society.

Goal 4. Ensuring Engineering Talent: Promote and inspire highly competitive engineering talent in the US workforce.

Talent is the coin of the global realm. Every country, every company, every organization is seeking talent in engineering. Nine of the top ten highest-paid midcareer salary positions in the United States are in engineering,[4] and all of the top ten highest-paid early-career salaries are in engineering.

Ensuring a globally competitive engineering workforce is mandatory for the security, health, prosperity, and future of our nation, if not most nations. The future cries out for a competitive engineering workforce.

The NAE serves as a resource for educators, employers, professional societies, and the government as they carry out their critical roles to educate, train, employ, and develop the engineering workforce. We support K–12 and out-of-school efforts to expose students early on to engineering concepts, practices, and "habits of mind." We promote advances in engineering education, like experiential learning through programs such as Engineers Without Borders, interdisciplinary study through programs like the rapidly expanding Grand Challenge Scholars Program, multidisciplinary studies (in the sciences, arts, mathematics, languages, humanities, public policy, and so on), and many others.

Goal 5. Global Engagement: Engage globally in support of national interests.

Globalization is the defining construct of the 21st century innovation environment. This environment requires partnerships to assemble expert talents and facilities in order to accelerate desired outcomes—be they products, research, discoveries, or others—while adapting to a constantly changing global environment. Change is accelerating, and we are reminded virtually daily that any advantages of innovation and information we possess cannot be protected. We live in a "use it or lose it" world, where the need is to "use

[4] According to the 2014–2015 Payscale College Salary Report.

it" quickly to derive benefit from it before others do so ahead of us.

Support of US national interests in the global environment requires the NAE to take a leadership role and engage with international academies and organizations on appropriate issues. Here are examples of global engagement that are already under way:

- The Global Grand Challenges Summits, which are a partnership between the Royal Academy of Engineering, the Chinese Academy of Engineering, and the US National Academy of Engineering to accelerate global engagement on the Grand Challenges.
- Promotion and expansion of the Grand Challenge Scholars Program and related programs that bring global attention, preparation, and talent to Grand Challenge–level problems.
- Increased foreign membership, especially in countries with few foreign members, to support the global engagement of the NAE.
- Greater foreign member involvement in services to the NAE through their nomination, service on committees, and international programs like the bilateral Frontiers of Engineering symposia.
- And NAE member services to other academies and countries on their prize selection committees, research review committees, and government advisory committees.

Goal 6. Effective Advising: Together with our sister academies of sciences and medicine, enhance effective advice to the nation on technological and societal challenges.

Though nothing in the charter of the three academies stipulates how advice will be rendered to the government, it is provided through studies, roundtables, workshops, and other mechanisms of our creation. The current methods are criticized sufficiently to suggest that other means of providing advice should be explored.

Increasing the effectiveness of our advice is the goal. For instance, a stronger connection between the academies and policymakers, a more assertive commitment to engaging sponsors and stakeholders following completion of studies, and engagement of the NAE membership in the dissemination of advice may lead to more effective advising. All will be explored.

We must ensure that members who participate in studies, or nominate others, hear back from us on the outcomes of their efforts on our behalf. Such efforts are fundamental to our raison d'être.

Identifying timely issues of critical engineering importance by enlisting member input and developing proposals to fund studies of them are also essential to this goal.

Grand Challenges for Engineering

The theme for this annual meeting is the NAE Grand Challenges for Engineering, a highlight of our global engagement goal. This topic has been picking up speed since the challenges were introduced in 2008.

For a quick history, the Grand Challenges for Engineering were proposed by a committee of 18 distinguished engineers, scientists, entrepreneurs, and visionaries who set out to identify the most critical, yet tractable engineering system challenges that must be tackled successfully in this century for continuation of life on the planet as we know it. The committee received thousands of inputs from around the world, and more than 50 subject matter experts reviewed its report, making it among the most reviewed of all academy studies. A list of 14 Grand Challenges for Engineering[5] was published in 2008. They were not ranked in importance or on the likelihood of their solution. No implementation plan or direction toward resolution was offered. NSF funded the study and publication of the report, but there was no follow-up support. In short, the grand challenges for the engineering needed to save the planet for people and society in this century kicked off from a "standing start." So the challenges were "grand" in more ways than fourteen.

Engineering has long gravitated to great human needs: navigation of the oceans, travel to the moon and back, Earth exploration, national security, industrial and agricultural revolutions, communications, and transportation, to name a few. But to my knowledge this is the first time a committee has voluntarily set out challenges for the survival of the planet, had them picked up at the grass-roots level, and found interest in them accelerating seven years later. It is a phenomenon.

[5] The 14 NAE Grand Challenges for Engineering are to make solar energy economical, provide energy from fusion, develop carbon sequestration methods, manage the nitrogen cycle, provide access to clean water, restore and improve urban infrastructure, advance health informatics, engineer better medicines, reverse-engineer the brain, prevent nuclear terror, secure cyberspace, enhance virtual reality, advance personalized learning, and engineer the tools of scientific discovery.

In 2010 a plan to prepare students to think about careers devoted to the challenges (and problems like them) was put forward by Thomas Katsouleas, then dean of the Pratt School of Engineering at Duke; Richard Miller, president of Franklin W. Olin College of Engineering; and Yannis Yortsos, dean of the Viterbi School of Engineering at USC. Former NAE president Charles Vest, who was enthusiastic about the Grand Challenges, was supportive of their initiative from the start. The Grand Challenge Scholars Program was the first organizational effort to prepare talent for, and present a vision directed to, achieving solutions to the challenges on a global scale. You will hear about the founding and expansion of this program both nationally and globally from Tom Katsouleas during his plenary remarks later today.

The 2nd organizational effort was the Global Grand Challenges Summit, first held in London in March 2013, cosponsored by the Royal Academy of Engineering, Chinese Academy of Engineering, and NAE in their first joint effort. The 2nd Global Grand Challenges Summit was just held in Beijing, September 13–16, with over 800 attendees invited by our three academies, including large numbers of students, and a competition for university students to develop a business plan for a start-up based on the Grand Challenges. The summit topics were sustainability, urban infrastructure, health, joy of living, energy, education, security, and resilience.

At the Beijing summit, the three academies and FIRST Robotics, founded by Dean Kamen (FIRST stands for "For Inspiration and Recognition of Science and Technology"), announced a collaboration to begin in 2017 at the 3rd Global Grand Challenges Summit, which will be hosted by the NAE in the United States. FIRST Robotics reaches hundreds of thousands of 6- to 18-year-old students through its nearly 50,000 competitions in 83 countries. In this new collaboration, FIRST, with the participation of the academies, will select Grand Challenge competition goals for its championship robotics competition, which will take place immediately after the summit. The university student competition that has preceded both summits to date will continue. In this way the Grand Challenges for Engineering will be exposed to millions of new people—students, parents, sponsors, governments, corporations, and mentors—including the young people we need to inspire to conquer them. This is another effort that moves the Grand Challenges for Engineering to an even more grand scale.

The accelerating momentum of the Grand Challenges for Engineering, now seven years after their introduction, is more akin to that of an international movement than a project. And that's in large part because these challenges are relevant to everyone, and are not targeted to a country or company.

Now is a good time for introspection and reflection on the Grand Challenges for Engineering. How are they doing? What else should we be doing? Have changing global circumstances called for rethinking the challenges or how we are going about them? Hence the theme of this meeting.

Plenary Presentations

Today we will be treated to extraordinary plenary lectures devoted to the Grand Challenges. Dr. Robert Langer of MIT will speak about his renowned lifelong work on the challenge to "Engineer Better Medicines." Later this month, Queen Elizabeth will personally present him with the 2015 Queen Elizabeth Prize for Engineering at Buckingham Palace for his work. Then Ms. Dawn C. Meyerriecks, CIA deputy director for science and technology and a specialist on cybersecurity, will speak on the grand challenge to "Secure Cyberspace," a topic on everyone's mind. Is it possible?

And because solutions to the Grand Challenges depend on inspiring the next generations of bright, young talent to engage in them, Dr. Thomas Katsouleas will describe the Grand Challenge Scholars Program. From his remarks you will understand the educational experience of the participating students and the attraction of programs around the world to prepare them for the Grand Challenges and problems like them.

Monday Morning Panel

Tomorrow morning from 9:30 to 12:30 in this auditorium, we are fortunate to have seven members of the original 2008 Grand Challenges for Engineering committee here for a panel moderated by Dan Vergano of Buzzfeed News. I thank them in advance for coming from around the world to participate in this panel. Their remarks on the challenges will be wide-ranging, retrospective, and prospective, and will put ideas on the table for discussion, including your questions. What should be the next steps?

This may be the first time in history that a panel of experts has put forward a set of recommendations for the planet and, just seven years later, actually seen its recommendations propelling growing global, grass-roots movements that are impacting not only engineering education but also, most importantly, the way people are thinking about the future and the role of engineering in it. Everywhere you turn today “the grand challenges for this and that” are appearing. This is a rare circumstance.

Video Competition

Many of you will recall the Engineering for You video competition last year that highlighted engineering contributions to people and society. Because of its success, and with the generous sponsorship of the ExxonMobil Foundation and its president Suzanne McCarron, we extended the competition to 2015, with a call for videos highlighting engineering contributions to solutions for the Grand Challenges. The 1- to 2-minute winning videos in the contestant categories will be shown today interspersed in the program, and the Grand Prize–winning video will be shown at the end of the day when the category winners receive their awards. You will enjoy them.

Concluding Remarks

I do hope that you enjoy this annual meeting and that the program inspires takeaway thoughts about the NAE’s new strategic goals and the imperatives of the Grand Challenges.

Thank you for the privilege of serving as your president. I always look forward to our work together to make our Academy services as broadly effective, fulfilling, and, yes, fun as possible.

In closing, I offer the counsel attributed to President Abraham Lincoln among many others: “The best way to predict the future is to create it.”

And so engineering will, as it always has.

2015 Simon Ramo Founders Award Acceptance Remarks by Linda P.B. Katehi

NAE chair Charles O. Holliday, Jr., Simon Ramo Founders Award recipient Linda P.B. Katehi, NAE president C. D. Mote, Jr., and Gerald E. Galloway, Jr., 2015 Award Committee chair.

The 2015 Simon Ramo Founders Award was presented to Linda P.B. Katehi, chancellor, University of California, Davis, “for visionary leadership in engineering research, entrepreneurship, and education, and for national advocacy of higher education as a major driver of the US economy.”

It is a tremendous honor to be here today with so many accomplished professionals and to receive the 2015 Simon Ramo Founders Award of the National Academy of Engineering.

Herbert Hoover, the only engineer to serve as president of the United States, called engineering a great profession, and I can tell you he was certainly correct.

“There is the satisfaction of watching a figment of the imagination emerge through the aid of science to a plan on paper,” he said. “Then it moves to realization into stone or metal or energy. Then it brings homes to men and women. Then it elevates the standard of living and adds to the comforts of life. This is the engineer’s high privilege.”

For me, it has always felt like a privilege to be an engineer. And to be recognized and appreciated by one’s peers in this way is a truly wonderful feeling.

I wanted to be an engineer ever since I was a young girl watching America’s first moon landing on a neighbor’s television set in my little village on an island off the coast of Greece.

I’m not sure I could have told you exactly what an engineer did, but when I saw those calm, self-assured scientists at Mission Control managing the Apollo 11 spacecraft from the ground—everything so precise and perfect—I was inspired. It took my breath away!

The astronauts were brave, courageous pilots and technicians. But it was those brilliant engineers who did so much to make that historic mission a success and put a man on the moon. Apollo 11 and the engineers who planned it opened a universe of possibilities for the nation and for so many young boys and girls who were inspired by what they saw on TV just like me.

As the first woman to receive this award, I am extremely proud and grateful. There were challenges along the way, but the work and the search for answers always saw me through. And I know, as our field becomes more diverse, there will be other women and members of underrepresented groups to win this and other awards.

Throughout my career, and especially now as chancellor at the University of California, Davis, I have had many opportunities to mentor women engineers. Many of them were inspired to enter the field by some of the same reasons as me. It may not have been the Apollo mission that drove them, but hands-on science and the search for innovative solutions to advance humankind make for exciting and gratifying work.

As all of you appreciate, engineers are innovators. We solve problems. We find solutions where solutions can be elusive. Across all the engineering disciplines represented by the NAE, we help the world overcome obstacles and adversity. We find new ways to treat disease and supply water, energy, and other vital resources to people, cities, and farms. We design bridges, dams, and airports. We design communication networks and defense systems that keep people safe.

In my own case, much of the research I have done over my career has focused on the development and characterization of planar and highly integrated circuits and antennas, with emphasis on high-frequency effects. My colleagues and I were fortunate enough to achieve some important breakthroughs and launch companies that created jobs and sparked economic development.

Unfortunately, I don't believe the general public is fully aware of the extraordinary role that innovation—much of it from engineers—has played in creating economic opportunity and prosperity in America and around the world.

According to the US Department of Commerce, since the 1940s two thirds of America's economic growth is attributable to growing productivity that results from innovation, much of it advanced by engineers like you. From the different subdisciplines of chemical, civil, electrical, and mechanical engineering have come discoveries and technological advances that have changed the face of the world.

We have collectively come up with innovations that have improved the quality of life for hundreds of millions of people and created untold economic benefits across our planet. From the environment to energy, from cybersecurity to clean water, from public health to transportation and national security, engineers have been at the forefront of countless monumental steps forward for civilization.

And we know that locked inside those steps have been powerful drivers of economic growth and development. To cite just one example, the Brookings Institution reported a few years ago that each 10 percentage point increase in broadband participation adds 1.3 percent to the gross domestic product of a high-income nation such as the United States. That translates into billions and billions of dollars.

Advances achieved by electrical engineers in digital technology have enabled people to use new tools such as GIS mapping, telemedicine, virtual reality, online gaming, supercomputing, video on demand, video conferencing, and so much more.

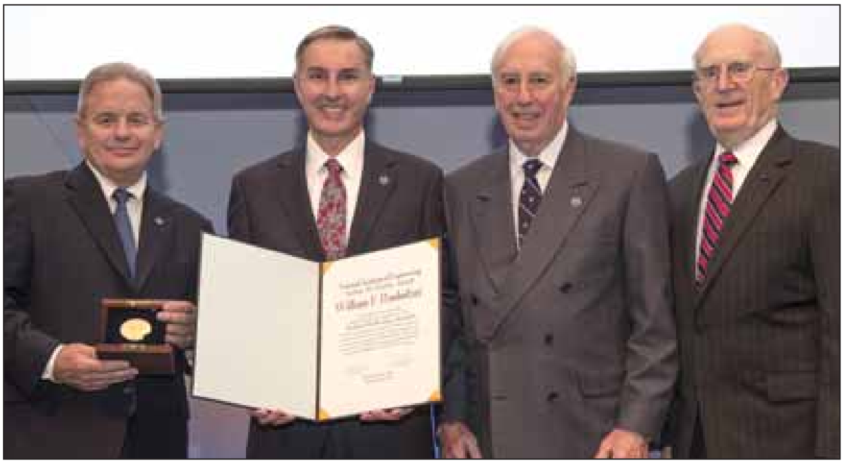
These tools drive our economy just as computer engineers drove our economy by pioneering the Internet and so many of the communication advances vital to small and large companies alike. Engineering breakthroughs have created whole new industries and opened up new careers for millions of people everywhere.

So there is no question engineers play a profound role in coming up with the products, breakthroughs, and discoveries that build companies, create jobs, improve our quality of life, and keep America competitive and economically robust.

By advocating on behalf of engineers since its creation in 1964, the National Academy of Engineering has been central to many of these innovations. By advancing our profession, you have advanced the well-being and economic health of our nation and of the people who live there.

I thank the NAE and its members for the extraordinary work you do. I thank you again for this wonderful honor. I will treasure it always. I also thank my wonderful and supportive husband and children, who are here with me today, and who have been such a big part of my life and my career.

2015 Arthur M. Bueche Award Acceptance Remarks by William F. Banholzer



NAE Chair Charles O. Holliday, Jr., Bueche Award recipient William F. Banholzer, NAE President C. D. Mote, Jr., and Gerald E. Galloway, Jr., 2015 Award Committee chair.

The 2015 Arthur M. Bueche Award was presented to William F. Banholzer, research professor, chemical and biological engineering, University of Wisconsin–Madison, "for his extraordinary record of new products commercialization and improvement in university-industry relationships through innovative intellectual property treatment and joint industry-academic funding."

Practical vs. Possible, Engineers Must Lead the Way

Receiving NAE's Arthur M. Bueche Award is a great honor and one that holds personal significance for me. I began my career at GE's Central Research Lab. On my first day I showed up at the main reception area. Just off the lobby hung portraits of the current and former directors of the lab. I still recall the awe and I must admit intimidation I felt passing by the images of such legendary figure as Whittney, Collidge, Suits, and of course Art Bueche. I wondered how I would measure up. Over the years my colleagues shared many stories on the profound impact Art had, not only within GE but on research leadership in general.

Art was a tireless advocate for the research triangle—government, academia, and industry—working together for the benefit of society. He once wrote, "Our business in industrial research is the idea business.… If we don't make it possible for people to get, develop, expand, and apply good new ideas *for the benefit of society* no one else will." Art believed that our role as engineers was to better society. Not better ourselves. Not better our profession. Better society. We always emphasize impact at the NAE—in fact it is a prime consideration for membership. But sometime I fear we view papers and citations as impact. I feel Art expected more.

How do we move from idea to impact? To answer this we must understand the difference between invention and innovation. This can be complicated and confusing. For instance, ask any person on the street who invented the light bulb or the telephone and you will get the answers Thomas Edison and Alexander Graham Bell. But the fact is these men did not invent these technologies. Edison was not the first to produce light from a filament. He was, however, the one who designed a system that allowed the filament to survive long enough to be practical. Bell was not the first to transmit sound over a wire. What he did was to design a practical device that utilized the science. We associate these men with these technologies because they made them practical. They found a way to make an idea accessible, reliable, and affordable.

Simply put, *innovation* is perfecting an invention to a point where it adds value to society—a value that people are willing to pay to possess. Certainly research based on curiosity is the starting line. Invention is the shotgun start. But innovation—that is where the race is won. And winning the race is challenging… getting to the finish line is hard, and never more difficult than in today's world.

What do I mean by that? You might ask, Isn't it easier to be an engineer today? We have so many more tools at our disposal. I would argue that it is most definitely harder. Today's inventors feel a crushing pressure to demonstrate an immediate, game-changing application of their discoveries. This pressure starts at funding agencies. Unfortunately, this has the potential to result in failure to exercise what I call "engineering discipline."

There is an immense difference between what is possible and what is practical. People sometimes extrapolate results, thus making exaggerated claims. As engineers, we must do a better job explaining the difference between discoveries that offer practical solutions and those that are only possible. The pressure to find an expedient technological solution cannot substitute for engineering judgment. Let me give you two examples to help clarify what I mean.

"It is 500 times thinner than the best filter on the market today and a thousand times stronger. The energy that's required and the pressure that's required to filter salt is approximately 100 times less."

This was a recent quote describing the use of graphene to desalinate water. Clean water, a real world challenge, combined with graphene, a sexy, Nobel prizing–winning material, and reduced energy use—makes for a great headline. So what is the issue? The issue is a little thing called thermodynamics. . . .

We have been very successful at reducing the energy requirements for desalination, using reverse osmosis. But our ability to further reduce that energy requirement is fundamentally constrained. The minimum work required to overcome the entropy created when salt dissolves in water defines energy entitlement. Claims that graphene or carbon nanotubes have properties that make water move more rapidly through them have incorrectly been extrapolated to conclude that this can dramatically reduce the energy required for desalination. Desalination is simply not a filtration problem, it is a thermodynamic one. Today's systems are within a factor of 2–4 of this nonnegotiable limit. The quote above is regrettable because it is so clearly wrong. There is simply no 100x reduction in energy possible.

More recently, a novel process was discovered in which light from blue LEDs drives a particular chemical transformation. The inventor of the process has publicly stated that it might be useful for the production of commodity chemicals. The suggestion that LEDs could be used to manufacture commodity chemicals should raise some immediate concern. The problem? The cost of photons.

Isobutyl alcohol is an example of a commodity chemical that has been synthesized using this LED process. But isobutyl alcohol has a market value of approximately 26¢/mole. And photons cost 2¢/mole at a power cost of 9¢/kWh. No more than 11 photons per molecule of product can be consumed before the electricity alone costs more than the product is worth. Add to this the fact that absorption by dyes used in this process has been shown to be a low-probability event, requiring thousands of photons per excitation. In fact this experiment took 96 hours! Elevating this albeit novel and interesting chemistry to the level of commercial significance is another example of a serious lack of engineering judgment.

I wish these were isolated examples. Unfortunately they are not. *As engineers we must do a better job understanding, communicating, and standing firmly behind the difference between the subset of discoveries that offer practical solutions—INNOVATIONS—from those that are simply untested inventions.* The best way to maintain this accountability is to continue to uphold the strong, open connections between government, academic, and industrial science and engineering.

There is one additional responsibility that the research triangle has: the responsibility to work safely. In industry even fierce competitors collaborate where safety is concerned because providing a safe workplace is a nonnegotiable prerequisite for a license to operate. Sadly, research in our universities has not always had the same emphasis on safe operating practices.

The industrial world owes it to their academic partners, the developers of our future scientists and engineers, to share best practices in safe operation and to demand it of the academic workplace. One of my proudest moments at Dow was the creation of the Dow Lab Safety Academy, an Internet-based training tool that allows colleges and universities access to the same safety training and knowledge that Dow scientists and engineers use. I encourage you all to join in my crusade to improve the safety practices at our academic labs.

I thank you for this award. I also thank my friends and colleagues, who have made my journey better thanks to your guidance, wisdom, and support. The most important of those persons is my wife, who has stood by my side with unwavering support.

I am humbled by this honor because I know that it really represents a challenge—a challenge to continue to better society in a way that honors the legacy of Art Bueche.

Thank you.

2015 Golden Bridge Society Dinner

On October 4, 2015, NAE president **C. D. Mote, Jr.**, and his wife Patsy hosted an intimate dinner honoring the NAE's most generous members and friends at the historic headquarters of the Organization of American States (OAS), a few blocks from the NAS Building. The OAS, an association of 35 countries from North, South, and Central America and the Caribbean, is one of the world's oldest regional organizations. Its history and significance inspired the evening's South American–themed dinner, held in the elegant Hall of the Americas, where heads of state and other dignitaries have addressed the OAS and where the historic Panama Canal treaties were signed in 1977. To complement this year's theme, two dancers performed the Argentine tango.

The Sunday evening dinner has become an annual tradition to recognize the NAE's best donors and get together with friends in a warm and festive setting. Dr. Mote began by welcoming new donors into the Academy's three lifetime recognition societies—Einstein, Golden Bridge, and Heritage. The Einstein Society celebrates donors who have made commitments of $100,000 or more, the Golden Bridge Society recognizes donors who have given or pledged between $20,000 and $99,999 over their lifetime, and the Heritage Society recognizes members who have included the NAE in their estate plans or made some type of planned gift to the academies.

Three new Einstein Society statuettes were presented to **Gordon England** ('12), **Robert** ('89) and Marilyn **Forney**, and **Ming** ('15) and Eva **Hsieh**. Bob and Marilyn Forney could not attend the dinner; their granddaughter Anne Forney and her husband David Colman accepted the Einstein on their behalf.

Seven new members were welcomed in the Golden Bridge Society, including **Alton** ('03) and Julie **Romig**, who were present at the dinner. New GBS members not in attendance were **Harry** ('90) and Rosemary **Conger**, **Evelyn Hu** ('02) and **David Clarke** ('99), **James Mikulski** ('97), **Ronald Schmidt** ('94), and **Elias Zerhouni** ('13).

Michael ('03) and Diana **King** received the Heritage Society Medal.

The night ended with Dr. Mote announcing the Ming and Eva Hsieh Challenge. Newly inducted member Ming and his wife Eva have agreed to fund a quarter of a million–dollar giving challenge to inspire and encourage others to increase their support of the NAE in 2015. The Hsiehs' own gift will provide resources to programs aligned with the new NAE strategic plan. Gifts or pledges must be received by December 31, 2015, to be eligible for a match.

Dr. Mote expressed his deep appreciation to all our members and friends who support and invest in the NAE and our programs. If you have any questions about the Ming and Eva Hsieh Challenge or would like to make a gift to achieve recognition by the Einstein, Golden Bridge, or Heritage Societies, please contact Radka Nebesky at 202.334.3417 or RNebesky@nae.edu.

2015 US Frontiers of Engineering Held at Beckman Center

On September 9–11, 2015, the NAE held its annual US Frontiers of Engineering symposium at the Beckman Center in Irvine, California. NAE member Robert D. Braun, David and Andrew Lewis Professor of Space Technology, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology, chaired the symposium organizing committee. The session topics were cybersecurity and privacy, engineering the search for Earth-like exoplanets, optical and mechanical metamaterials, and forecasting natural disasters.

The first session, Cybersecurity and Privacy, focused on how to engineer a system that is as secure as possible given practical construction constraints. A well-engineered system incorporates both layered protection and mechanisms for detecting and mitigating the effects of successful attacks. Moreover, the user is just as important to security and privacy as the technology; user-centric designs help the user to make good security and privacy decisions. The first talk described the various security and abstraction levels of modern systems as well as security consequences at the application, operating system, and hardware layers. The next speaker described the user's role and how to

Amy Lo (Northrop Grumman), Jose Blanchet (Columbia University), and David Parkes (Harvard University) chat during a break at the 2015 US FOE meeting.

design interfaces that help her make better security decisions, particularly with regard to mobile platforms. This was followed by a talk on security in medical devices, which have different characteristics and pose different challenges to a security engineer. The session concluded with a talk on the US government's views on challenges and frontiers in engineering cybersecurity.

In the last two decades, astronomers have found thousands of planets orbiting stars other than the Sun. There is particular interest in finding exoplanets, as they are called, that orbit their stars' habitable zones, where it is possible for liquid water, and therefore life, to exist. The session on Engineering the Search for Earth-like Exoplanets focused on the new generation of space-based telescopes necessary to find and study exoplanets. The first speaker described the James Webb Space Telescope (JWST), an international, NASA-led mission to be launched in 2018. JWST has nearly 4 times the collecting area of the Hubble Space Telescope and is cryogenically cooled to mid-infrared wavelengths. The next presentation, on starlight suppression technologies for the direct imaging of exoplanets, covered two main techniques: (1) the internal occulter, or coronagraph, that blocks light inside the telescope and works with wavefront sensing and control to create a stable optical system; and (2) the external occulter, or starshade, a specially shaped screen tens of meters in diameter that flies in formation tens of thousands of kilometers from its telescope to block star light so that only planet light enters the telescope. The third speaker addressed the construction of large structures in space, focusing on large deployables and space-based assembly and construction. The fourth talk reported leading-edge developments in sensing controls for formation flying and satellite proximity operations, with a focus on enabling autonomy for small satellites.

The topic of the third session was optical and mechanical metamaterials—composites whose properties derive from both their structure and composition. Metamaterials have had a large impact on the fields of mechanics and photonics, leading to a reassessment of conventionally accepted boundaries on material performance and the discovery of a great array of surprising and useful properties. The first presenter described research in (1) the design of advanced materials that derive extraordinary strength from three-dimensional architecture and microstructure, and (2) recoverable mechanical deformation in compliant nanomaterials, with impacts on ultralightweight batteries and biomedical devices, among others. This was followed by a talk on the development of engineering materials with remarkably light weight and ultrahigh stiffness. The next speaker focused on metamaterial-based device engineering, in particular the connection between microscopic structural properties (e.g., symmetry and shape) of metamaterials and their macroscopic response. This work enables useful devices that would not be possible with conventional materials, such as one-way antennas, "invisibility cloaks," and acoustic circulators. The session concluded with a talk on optical and infrared metamaterials and their applications in devices that could revolutionize optical technologies in communications, photovoltaics, and thermal radiation management.

The final session, Forecasting Natural Disasters, was about improvements in predicting the track and intensity of natural hazards such as tropical cyclones and flash floods. These improvements are the result of better understanding of atmospheric systems, advances in observational technologies, and greater computational power. The session opened with a talk about a physically based probabilistic tropical cyclone risk assessment and management framework that integrates science, engineering, and economic analysis to support coastal resiliency. The next speaker explained how behavioral research could inform the presentation of scientific information about natural disasters to the public to motivate individuals and organizations to take appropriate actions that reduce risk and economic losses. The session's last presenter described the Google Earth Engine platform (earthengine.google.org), which provides an experimental application programming interface for massively parallel geospatial analysis on global datasets such as Landsat satellite imagery, elevation data, and weather. Applications based on this data can map, measure, and monitor Earth's changes in unprecedented detail for the benefit of people and the environment.

On the first afternoon of the meeting, participants gathered in small groups for "get-acquainted" sessions where they each presented a slide and answered questions about their research or technical work. This event gave them an opportunity to get to know more about each other relatively early in the program. On the second afternoon, attendees met in small groups to discuss topics suggested and led by the attendees themselves. Topics included industry-academic tech transfer, public understanding of artificial intelligence, technology risk management, effective interdisciplinary collaboration, and public advocacy for engineering, among others. Some of the groups have evolved into communities of interest and continued communication after the meeting.

NAE member and vice president **Corale Brierley**, principal of Brierley Consultancy LLC, gave the first evening's dinner speech, titled "The Black Swan." She recounted times in her career when valuable lessons were learned through unexpected experiences. She reminded the group that sometimes the benefit of a new idea is not understood or appreciated until well after the discovery, that life begins at the end of one's comfort zone, and that failure is only a temporary change in direction to set one straight for the next success.

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

Robert Braun will continue as chair for the 2016 US FOE, which will be hosted by Halliburton at its Houston headquarters on September 19–21. The 2016 topics are scalable algorithms and software for high-fidelity graphics, technologies for eradicating cancer, water desalination and purification, and extreme engineering.

Funding for the 2015 US Frontiers of Engineering symposium was provided by The Grainger Foundation, National Science Foundation, Defense Advanced Research Projects Agency, Air Force Office of Scientific Research, DOD ASDR&E STEM Development Office, Microsoft Research, Cummins Inc., and individual donors.

The NAE has been hosting an annual US Frontiers of Engineering meeting since 1995, and also has bilateral programs with Germany, Japan, India, China, and the European Union. The meetings bring together outstanding engineers from industry, academia, and government at a relatively early point in their careers since all participants are 30–45 years old. Frontiers provides an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, something that has become increasingly important as engineering has become more interdisciplinary. The meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series, visit the FOE website at www.naefrontiers.org or contact Janet Hunziker in the NAE Program Office at JHunziker@nae.edu.

Calendar of Meetings and Events

January 1–31	Election of new NAE members and foreign members
January 15	Deadline for submission of petition candidates for NAE officers and councillors
January 25	Symposium: Exploring a New Vision for Center-Based Multidisciplinary Engineering Research
February 4–5	Membership Policy Committee Irvine, California
February 10–11	NAE Council Meeting Irvine, California
February 11	NAE National Meeting Irvine, California
March 1–31	Election of NAE officers and councillors

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

In Memoriam

WM. HOWARD ARNOLD, 84, retired president, Westinghouse Nuclear International, Westinghouse Electric Corporation, died July 16, 2015. Dr. Arnold was elected to the NAE in 1974 for contributions to design of commercial pressurized water reactors for nuclear systems and to systems engineering of light water nuclear power plants.

CHARLES CRUSSARD, 91, retired scientific director, Pechiney (France), died January 14, 2008. Dr. Crussard was elected to the NAE as a foreign member in 1976 for contributions to metallurgical science and technology and its applications.

P. GUNNAR ENGSTRÖM, 92, retired executive vice president, research and development, Asea AB, died July 1, 2015. Mr. Engström was elected to the NAE as a foreign member in 1992 for international leadership in electric power transmission techniques and appreciation of power electronic equipment in electric utility systems.

BRIAN L. EYRE, 80, materials scientist and senior visiting fellow, University of Oxford, died July 28, 2014. Dr. Eyre was elected to the NAE as a foreign member in 2009 for understanding of neutron irradiation–induced damage in materials, and for developing technologies and policies for the UK nuclear industry.

JAMES L. FLANAGAN, 90, retired vice president for research, Rutgers, the State University of New Jersey, and retired director, information principles research, Bell Laboratories, died August 25, 2015. Dr. Flanagan was elected to the NAE in 1978 for contributions to the acoustic theory of speech and hearing processes and engineering applications of this knowledge to voice communication.

RENATO FUCHS, 72, retired senior vice president, manufacturing and operations, Transkaryotic Therapies Inc., died September 7, 2015. Dr. Fuchs was elected to the NAE in 1994 for engineering contributions in the design, construction, and operation for large-scale manufacturing of recombinant DNA proteins.

EDWARD E. HORTON, 87, president, Horton Offshore, died on August 13, 2015. Mr. Horton was elected to the NAE in 2002 for innovative contributions to the development of systems and structures for oil drilling and production in very deep water.

JAMES D. IDOL, 86, professor II, Department of Materials Science and Engineering, Rutgers, the State University of New Jersey, died on July 15, 2015. Dr. Idol was elected to the NAE in 1986 for the invention of ammoxidation processes and catalysts and for major contributions to the plastics industry.

DON R. KOZLOWSKI, 77, former senior vice president, Military Transport Aircraft, the Boeing Company, died June 2, 2015. Mr. Kozlowski was elected to the NAE in 2000 for effective program management in restructuring the C-17 program.

LOUIS C. LUNDSTROM, 100, retired executive director, environmental activities staff, General Motors Corporation, died August 6, 2015. Dr. Lundstrom was elected to the NAE in 1977 for leadership in the development of the systems approach to safe highways and in the development of test technology for improvement in auto safety.

HUDSON MATLOCK, 95, professor emeritus of civil engineering, University of Texas at Austin, died October 8, 2015. Mr. Matlock was elected to the NAE in 1982 for outstanding leadership in research and design related to offshore engineering.

GEORGE E. MUELLER, 97, retired chief executive officer, Kistler Aerospace Corporation, died October 12, 2015. Dr. Mueller was elected to the NAE in 1967 for electronic systems engineering.

HAYDN H. MURRAY, 90, professor emeritus, Indiana University, died February 4, 2015. Dr. Murray was elected to the NAE in 2003 for pioneering work on the mineralogy and industrial applications of clays.

F. ROBERT NAKA, 90, retired president and CEO, CERA Inc., died December 21, 2013. Dr. Naka was elected to the NAE in 1997 for the development of national security systems and for contributions in materials and sensor technologies for advanced military systems.

NORBERT PETERS, 72, professor, Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University, died July 4, 2015. Dr. Peters was elected to the NAE as a foreign member in 2002 for contributions to the field of combustion modelling of turbulent flames and the development of chemical kinetic mechanisms for hydrocarbon oxidation.

VICTOR H. RUMSEY, 95, professor emeritus, University of California, San Diego, died March 11, 2015. Dr. Rumsey was elected to the NAE in 1980 for research in practical applications of electromagnetic theory, especially in design of radio antennas insensitive to frequency and polarization.

WILLIAM H. SILCOX, 93, retired manager, offshore technology development, Chevron Corporation, died August 6, 2015. Mr. Silcox was elected to the NAE in 1986 for the development of original subsea drilling and completion systems, and offshore compliant deepwater structures.

JOSEPH F. TRAUB, 83, Edwin Howard Armstrong Professor, Columbia University, died August 24, 2015. Prof. Traub was elected to the NAE in 1985 for initiating optimal iteration theory, for creating significant new algorithms that solve diverse problems, and for educational leadership in computing.

ROBERT M. WHITE, 92, former president, National Academy of Engineering, died October 14, 2015. Dr. White was elected to the NAE in 1968 for development of methods of weather forecasting and leadership in the evolution of the World Weather Watch System.

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 20001. For more information or to place an order, contact NAP online at <*www.nap.edu*> or by phone at (800) 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, NC, NY, PA, VA, WI, or Canada.)*

Memorial Tributes Volume 19. The Memorial Tributes are compiled by the National Academy of Engineering as a personal remembrance of the lives and outstanding achievements of its members and foreign members. The volumes are intended to stand as an enduring record of the many contributions of engineers and engineering to the benefit of humankind. In most cases, the authors of the tributes are contemporaries or colleagues who had personal knowledge of the interests and the engineering accomplishments of the deceased. The expertise and credibility that the NAE brings to its task of advising the federal government on matters of science and technology stem directly from the abilities, interests, and achievements of our members and foreign members, our colleagues and friends, whose special gifts we remember in this book.

Emerging Workforce Trends in the US Energy and Mining Industries: A Call to Action. Energy and mineral resources are essential for the nation's fundamental functions, economy, and security. Nonfuel minerals are essential for the operations of products that are used by people every day and provided by various sectors of the mining industry. The overall value added to the US gross domestic product in 2011 by major industries that consumed processed nonfuel mineral materials was $2.2 trillion. Recognizing the importance of ensuring a trained and skilled US energy and mining workforce of sufficient size for the future, the Department of Energy's National Energy Technology Laboratory contracted with the National Research Council (NRC) to perform a study of emerging workforce trends in the US energy and mining industries. This report summarizes the study findings.

NAE member **Charles Fairhurst**, senior consulting engineer, Itasca Consulting Group Inc., and professor emeritus, University of Minnesota, cochaired the study committee. Paper, $68.00.

Mesoscale Chemistry: A Workshop Report. In the last few decades great strides have been made in chemistry at the nanoscale, where the atomic granularity of matter and the exact positions of individual atoms are key determinants of structure and dynamics. Less attention, however, has been paid to the mesoscale. It is at this scale, in the range extending from large molecules (10 nm) through viruses to eukaryotic cells (10 microns), that interesting ensemble effects and the functionality that is critical to macroscopic phenomena begin to manifest and cannot be described by laws on the scale of atoms and mole cules alone. A November 2014 workshop explored how knowledge about mesoscale phenomena can impact chemical research and development activities and vice versa. Participants examined opportunities for utilizing those behaviors to develop new catalysts, add functionality to materials, and increase understanding of biological and interfacial systems. The workshop also highlighted challenges for the analysis and description of mesoscale structures. This report summarizes the workshop presentations and discussions.

NAE member **Donna G. Blackmond**, professor of chemistry, the Scripps Research Institute, was a member of the workshop roundtable. Paper, $45.00.

Tying Flood Insurance to Flood Risk for Low-Lying Structures in the Floodplains. Floods take a heavy toll on society, costing lives, damaging buildings and property, disrupting livelihoods, and sometimes necessitating federal disaster relief, which has risen to record levels in recent years. The National Flood Insurance Program (NFIP) was created in 1968 to reduce the flood risk to individuals and their reliance on federal disaster relief by making federal flood insurance available to residents and businesses whose community adopted floodplain management ordinances and minimum standards for new construction in flood-prone areas. Insurance rates for structures built after a floodplain map was adopted were intended to reflect the actual risk of flooding, taking into account the likelihood of inundation, the elevation of the structure, and the relationship of inundation to damage to the structure. Today, rates are subsidized for one-fifth of the NFIP's 5.5 million policies. Most of these structures are negatively elevated (i.e., the elevation of the lowest floor is lower than the NFIP construction standard) and more likely to incur a loss: they are inundated more frequently, and the depths and durations of inundation are greater. This report reviews current NFIP methods and alternative approaches for calculating risk-based premiums for these structures as well as engineering hydrologic and property assessment data needed to implement full risk-based premiums. The report's findings and conclusions will help to improve the accuracy of loss estimates for negatively elevated structures, and in turn increase the credibility, fairness, and transparency of premiums for policyholders.

NAE member **Ross B. Corotis**, Denver Business Challenge Professor, Department of Civil, Environmental, and Architectural Engineering, University of Colorado Boulder, was a member of the study committee. Paper, $43.00.

Innovation, Diversity, and the SBIR/STTR Programs: Summary of a Workshop. The Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs provide federal research and development funding to small businesses. One of the goals of these programs is to foster and encourage participation by minority and disadvantaged persons in technological innovation. A workshop in February 2013 looked at the participation of women, minorities, and both older and younger scientists, engineers, and entrepreneurs in the SBIR and STTR programs, reviewing efforts to expand the pool of SBIR/STTR-funded researchers and identifying mechanisms for improving participation rates. This report is a record of the workshop presentations and discussions.

NAE members on the study committee were **Jacques S. Gansler** (chair), professor and Roger C. Lipitz Chair in Public Policy and Private Enterprise and director, Center for Public Policy and Private Enterprise, University of Maryland, College Park; **Charles E. Kolb**, president and chief executive officer, Aerodyne Research, Inc.; and **Duncan T. Moore**, vice provost for entrepreneurship and Rudolf and Hilda Kingslake Professor of Optical Engineering, the Institute of Optics. Paper, $40.00.

Brazil-US Workshop on Strengthening the Culture of Nuclear Safety and Security: Summary of a Workshop. On August 25–26, 2014, the Instituto de Pesquisas Energéticas e Nucleares (IPEN) and the US National Research Council convened a workshop, on the IPEN campus in São Paulo, to examine how a culture of nuclear safety and security is built and maintained in the nuclear science, technology, and industrial sectors. Participants identified opportunities for cooperation to strengthen that culture and shared research, perspectives, and practices. This report summarizes the workshop presentations and discussions.

NAE members **Michael L. Corradini**, professor, Department of Engineering Physics, University of Wisconsin–Madison, and **James O. Ellis Jr.**, USN (ret.), Annenberg Distinguished Visiting Fellow, Hoover Institution, Stanford University, and retired president and CEO, Institute of Nuclear Power Operations, were members of the workshop planning committee. Paper, $42.00.

Mathematical Sciences Research Challenges for the Next-Generation Electric Grid: Summary of a Workshop. If the United States is to sustain its economic prosperity, quality of life, and global competitiveness, it must maintain an abundance of secure, reliable, and affordable energy resources. Many improvements in the technology and capability of the electric grid over the past several decades depend on complex mathematical algorithms and techniques, and as the complexity of the grid has increased, so have the analytical demands. This report summarizes the presentations and discussions from a workshop convened as part of an ongoing study of the Committee on Analytical Research Foundations for the Next-Generation Electric Grid. The report identifies critical areas of mathematical and computational research that must be addressed for the next-generation electric transmission and distribution system and identifies future needs and ways that current research efforts in these areas could be adjusted or augmented.

NAE members on the study committee were **Thomas J. Overbye** (cochair), Fox Family Professor, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign; **Anjan Bose**, Regents Professor and Distinguished Professor of Electric Power Engineering, Washington State University; **Terry Boston**, PE, president and CEO, PJM Interconnection, LLC; **Frank P. Kelly**, professor of mathematics systems, and master, Christ's College, Statistical Laboratory, University of Cambridge; **Ralph D. Masiello**, senior vice president, Innovation, DNV GL; and **Margaret H. Wright**, Silver Professor of Computer Science, Courant Institute of Mathematical Sciences, New York University. Paper, $54.00.

Cost, Effectiveness, and Deployment of Fuel Economy Technologies for Light-Duty Vehicles. The light-duty vehicle fleet is expected to undergo substantial technological changes over the next several decades as new powertrain designs, alternative fuels, advanced materials, and significant changes to the vehicle body are driven by increasingly stringent fuel economy and greenhouse gas emission standards. By the end of the next decade, cars and light-duty trucks will be more fuel efficient, weigh less, emit less air pollutants, have more safety features, and be more expensive to purchase relative to current vehicles. The gasoline-powered spark ignition engine will remain the dominant powertrain configuration, but by 2030 the deployment of alternative methods to propel and fuel vehicles and alternative modes of transportation, including autonomous vehicles, will be well under way. This report presents a technical evaluation of costs, potential efficiency improvements, and barriers to commercial deployment of fuel reduction technologies for next-generation light-duty vehicles. The report describes promising technologies and makes recommendations for their inclusion on the list of technologies applicable for the 2017–2025 corporate average fuel economy (CAFE) standards.

NAE members on the study committee were **Jared L. Cohon** (chair), president emeritus and University Professor, Department of Civil and Environmental Engineering, Carnegie Mellon University; **Linos J. Jacovides**, professor, Electrical and Computer Engineering Department, Michigan State University, and retired director, Delphi Research Labs; and **Wallace R. Wade**, retired technical fellow and chief engineer, Ford Motor Company. Paper, $124.00.

Funding and Managing the US Inland Waterways System: What Policymakers Need to Know: TRB Special Report 315. This report explores the role and importance of the federally funded inland waterways system, its beneficiaries, priorities for future investment, and sources of funding. The inland waterways system is a small but important component of the national freight system, particularly for bulk commodities; in recent years it has transported 6–7 percent of all domestic ton-miles of cargo. The study committee finds that, to ensure efficient use of limited navigation resources, a sustainable and well-executed plan is critical for maintaining system reliability and performance, both of which require a higher priority on investments in operations and maintenance. Without a funding strategy that prioritizes system preservation, maintenance may continue to be deferred, resulting in further deterioration and a less cost effective and less reliable system. The committee finds that more reliance on a "user pays" funding strategy for the commercial navigation system is feasible, would generate new revenues for maintenance, and would promote economic efficiency. An asset management program focused on economic efficiency, fully implemented and linked to the budgeting process, would help prioritize maintenance spending and determine the funding levels required for reliable freight service.

NAE member **Chris T. Hendrickson**, Hamerschlag University Professor, Departments of Civil and Environmental Engineering and of Engineering and Public Policy, Carnegie Mellon University, chaired the study committee. Free PDF.

Improving the Air Force Scientific Discovery Mission: Leveraging Best Practices in Basic Research Management: A Workshop Report. In 2014 the NRC Air Force Studies Board held two workshops to review current research practices at the Air Force Office of Scientific Research. Speakers and participants explored the unique drivers associated with management of a 6.1 basic research portfolio in the Department of Defense and investigated current and future practices that may further the effective and efficient management of basic research on behalf of the Air Force. This report summarizes the presentations and discussions at the two workshops.

NAE members on the study committee were **Parviz Moin**, Franklin P. and Caroline M. Johnson Professor of Engineering, Stanford University, and **Subhash C. Singhal**, Battelle Fellow Emeritus, Pacific Northwest National Laboratory. Paper, $46.00.

A Strategy for Active Remote Sensing Amid Increased Demand for Radio Spectrum. Active remote sensing is the principal tool used to study and predict short- and long-term changes in the Earth's environment—the atmosphere, oceans, and the land surfaces—as well as its near space environment. Such measurements are essential to understanding terrestrial weather, climate change, space weather hazards, and threats from asteroids. Active remote sensing measurements are of inestimable benefit to society in the face of continued development of a technological civilization that is economically viable and maintains quality of life. This report describes the threats, both current and future, to the effective use of the electromagnetic spectrum required for active remote sensing and offers recommendations for protecting and making effective use of the spectrum required for active remote sensing.

NAE member **Fawwaz Ulaby**, Emmett Leith Distinguished Professor of Electrical Engineering and Computer Science, University of Michigan, chaired the study committee. Paper, $66.00.

The Space Science Decadal Surveys: Lessons Learned and Best Practices. The National Research Council has conducted 11 decadal surveys in the Earth and space sciences since 1964. The surveys are notable for thoroughly sampling the research interests, aspirations, and needs of a scientific community to produce a prioritized program of science goals and objectives and define an executable strategy for achieving them. The reports play a critical role in defining the nation's agenda in that science area for the following 10 years, and often beyond. This report considers lessons learned from the surveys and presents options for changes and improvements to the survey process. It describes the decadal survey prioritization process, including balance in the science program and across the discipline; balance between the needs of current researchers and the development of the future workforce; and balance in mission scale—smaller, competed programs versus large strategic missions.

NAE members on the study committee were **Daniel N. Baker**, director, Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, and **A. Thomas Young**, retired executive vice president, Lockheed Martin Corporation. Paper, $59.00.