Winter 2016

**FRONTIERS OF ENGINEERING**

# The BRIDGE

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# The BRIDGE

## NATIONAL ACADEMY OF ENGINEERING





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## NAE News and Notes

# Editor's Note

Robert D. Braun (NAE) is a professor, Department of Aerospace Engineering Sciences, University of Colorado Boulder.

## Engineering in a Rapidly Advancing World

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 19–21 more than 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: Pixels at Scale, Extreme Engineering, Water Desalination and Purification, and Technologies for the Treatment of Cancer. Seven 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 16 symposium presentations can be viewed at www.naefrontiers.org/symposia/USFOE.aspx.

The first session focused on High-Performance Computer Graphics and Vision. Cochaired by David Luebke of NVIDIA Research and John Owens of the University of California, Davis, the session explored the use of the significantly large number of pixels at our disposal today, including advances in computer vision and image understanding, computer graphics hardware, computational displays, and virtual reality. Four speakers from industry and academia led insightful discussions of these topics. In this issue, papers by Gordon Wetzstein (Stanford University) and Kristen Grauman (University of Texas, Austin) address some of the more compelling computer vision breakthroughs.

The session on Extreme Engineering centered on the use of autonomy in space, air, land and underwater and was cochaired by DeShawn Jackson of Halliburton and Marco Pavone of Stanford University. This session focused on recent breakthroughs in decision making, perception architectures, and mechanical design that have paved the way for autonomous robotic systems to carry out a wide range of tasks of unprecedented complexity. Emphasis was placed on recent algorithmic and mechanical advances that have enabled the design and deployment of robotic systems where autonomy pushed to the extreme has resulted in innovation that borders on science fiction. Each of the four talks in this session engaged large segments of the attendees. In these pages, Lars Blackmore (SpaceX) describes the design considerations, technology challenges, and operational experience of safely returning first-stage launch systems for subsequent reuse.

In the session on Water Desalination and Purification, cochaired by Amy Childress of the University of Southern California and Abhishek Roy of Dow Chemical, four speakers described the global challenge of securing a reliable supply of water among growing human populations, changing climate, and increasing urbanization. The session focused on membrane separation processes to desalinate and purify a range of source waters. Innovations in materials, developments in new processes, and synthesis of novel systems were discussed for applications spanning desalination, wastewater reclamation, and treatment of industrial streams with complex solution chemistries. Papers by Manish Kumar (Pennsylvania State University) and Chris

Stafford (National Institute of Standards and Technology) convey advances achieved to date and those possible in the near future.

The final session focused on Technologies for Understanding and Treating Cancer, with an emphasis on the challenges that engineers from numerous disciplines are working to address. Cochaired by Julie Champion (Georgia Institute of Technology) and Peter Tessier (Rensselaer Polytechnic Institute), the session addressed how cancer cells grow, methods for interfering with this growth, strategies for harnessing the immune system to target and destroy cancer cells, and methods for early detection of cancer. These talks emphasized how advances in materials science, microfluidics, and chemical and biomedical engineering are having a significant impact in fighting cancer. In this issue, Jennifer Cochran (Stanford University) and Darrell Irvine (Massachusetts Institute of Technology) report on such engineering advances.

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. **John Orcutt**, Distinguished Professor of Geophysics at Scripps Institution of Oceanography and the University of California, San Diego. He presented an entertaining and educational perspective on the rapid and fundamental changes occurring in the Arctic and the engineering and societal consequences of these changes.

As chair of the 2016 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. 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 16 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 2017 US FOE Symposium, to be held at United Technologies in East Hartford, Connecticut.

*A personalized VR/AR system that adapts to the user is crucial to deliver the best possible experience.*

# Computational Near-Eye Displays

## Engineering the Interface to the Digital World

Gordon Wetzstein

Gordon Wetzstein is an assistant professor of electrical engineering and, by courtesy, of computer science at Stanford University, and leader of the Stanford Computational Imaging Group.

Immersive virtual reality and augmented reality (VR/AR) systems are entering the consumer market and have the potential to profoundly impact society. Applications of these systems range from communication, entertainment, education, collaborative work, simulation, and training to telesurgery, phobia treatment, and basic vision research. In every immersive experience, the primary interface between the user and the digital world is the near-eye display. Thus, developing near-eye display systems that provide a high-quality user experience is of the utmost importance.

Many characteristics of near-eye displays that define the quality of an experience, such as resolution, refresh rate, contrast, and field of view, have been significantly improved in recent years. However, a significant source of visual discomfort prevails: the vergence-accommodation conflict (VAC), which results from the fact that vergence cues (e.g., the relative rotation of the eyeballs in their sockets), but not focus cues (e.g., deformation of the crystalline lenses in the eyes), are simulated in near-eye display systems. Indeed, natural focus cues are not supported by any existing near-eye display.

Using focus-tunable optics, we explore unprecedented display modes that tackle this issue in multiple ways with the goal of increasing visual comfort and providing more realistic visual experiences.

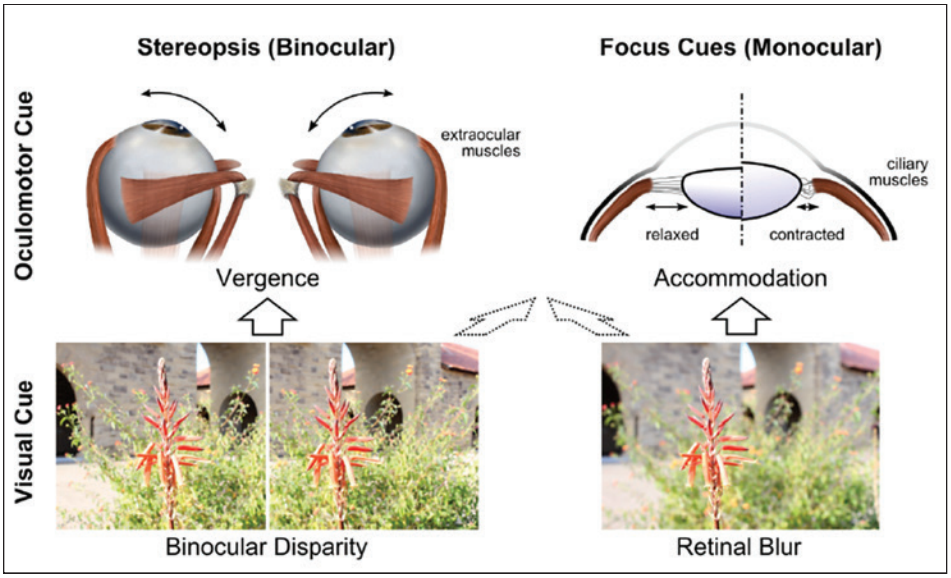


FIGURE 1 Overview of relevant depth cues. Vergence and accommodation are oculomotor cues; binocular disparity and retinal blur are visual cues. In normal viewing conditions, disparity drives vergence and blur drives accommodation. However, these cues are cross-coupled. Near-eye displays support only binocular cues, not focus cues.

## Introduction

In current VR/AR systems, a stereoscopic near-eye display presents two different images to the viewer's left and right eyes. Because each eye sees a slightly different view of the virtual world, binocular disparity cues are created that generate a vivid sense of three-dimensionality. These disparity cues also drive viewers' vergence state as they look around at objects with different depths in the virtual world.

However, in a VR system the accommodation, or focus state, of the viewer's eyes is optically fixed to one specific distance. This is because, despite the simulated disparity cues, the micro display in a VR system is actually at a single, fixed optical distance. The specific distance is defined by the magnified image of the micro display, and the eyes are forced to focus at that distance and only that distance in order for the virtual world to appear sharp. Focusing at other distances (such as those simulated by stereoscopic views) results in a blurred view.

In the physical world, these two properties of the visual response—vergence and accommodation—work in harmony (see figure 1). Thus, the neural systems that drive the vergence and accommodative states of the eye are neurally coupled.

VR/AR displays artificially decouple vergence and focus cues because their image formation keeps the focus at a fixed optical distance but drives vergences to arbitrary distances via computer-generated stereoscopic imagery. The resulting discrepancy—the vergence-accommodation conflict—between natural depth cues and those produced by VR/AR displays may lead to visual discomfort and fatigue, eyestrain, double vision, headaches, nausea, compromised image quality, and even pathologies in the developing visual system of children.

The benefits of providing correct or nearly correct focus cues include not only increased visual comfort but also improvements in 3D shape perception, stereoscopic correspondence matching, and discrimination of larger depth intervals. Significant efforts have therefore been made to engineer focus-supporting displays.

But all technologies that might support focus cues suffer from undesirable tradeoffs in compromised image resolution, device form factor or size, and brightness, contrast, or other important display characteristics. These tradeoffs pose substantial challenges for high-quality AR/VR visual imagery with practical, wearable displays.

## Background

In recent years a number of near-eye displays have been proposed that support focus cues. Generally, these displays can be divided into the following classes: adaptive focus, volumetric, light field, and holographic displays.

*Two-dimensional adaptive focus displays* do not produce correct focus cues: the virtual image of a single display plane is presented to each eye, just as in conventional near-eye displays. However, the system is capable of dynamically adjusting the distance of the observed image, either by actuating (physically moving) the screen (Sugihara and Miyasoto 1998) or using focus-tunable optics (programmable liquid lenses). Because this technology only enables the distance of the entire virtual image to be adjusted at once, the correct focal distance at which to place the display will depend on where in the simulated 3D scene the user is looking.

Peli (1999) reviews several studies that proposed the idea of gaze-contingent focus, but I am not aware of anyone having built a practical gaze-contingent, focus-tunable display prototype. The challenge for this technology is to engineer a robust gaze and vergence tracking system in a head-mounted display with custom optics.

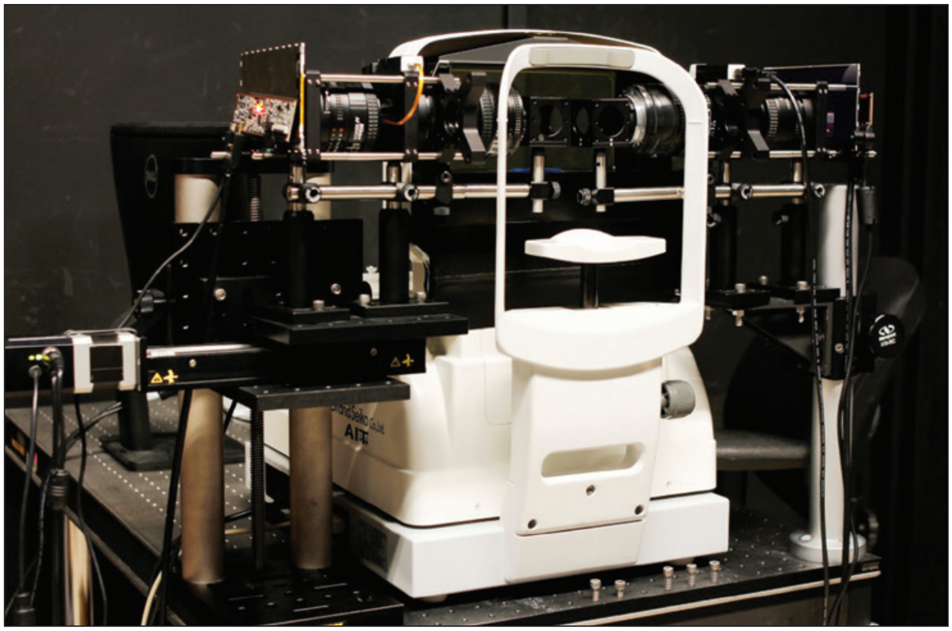

FIGURE 2 Prototype focus-tunable stereoscopic display. This setup allows for a range of focus-tunable and monovision display modes to be tested in user studies. An autorefractor is integrated in the setup to measure where a user accommodates for a displayed stimulus. The outcome of these studies will inform the design of future near-eye displays.

A software-only alternative to gaze-contingent focus is gaze-contingent blur rendering (Mauderer et al. 2014), but because the distance to the display is still fixed in this technique it does not affect the VAC. Konrad and colleagues (2016) recently evaluated several focus-tunable display modes in near-eye displays and proposed monovision as a practical alternative to gaze-contingent focus, where each eye is optically accommodated at a different depth.

*Three-dimensional volumetric* and *multiplane displays* represent the most common approach to focus-supporting near-eye displays. Instead of using 2D display primitives at a fixed or adaptive distance to the eye, volumetric displays either mechanically or optically scan the 3D space of possible light-emitting display primitives (i.e., pixels) in front of each eye (Schowengerdt and Seibel 2006).

Multiplane displays approximate this volume using a few virtual planes generated by beam splitters (Akeley et al. 2004; Dolgoff 1997) or time-multiplexed focus-tunable optics (Liu et al. 2008; Llull et al. 2015; Love et al. 2009; Rolland et al. 2000; von Waldkirch et al. 2004). Whereas implementations with beam splitters compromise the form factor of a near-eye display, temporal multiplexing introduces perceived flicker and requires display refresh rates beyond those offered by current-generation microdisplays.

*Four-dimensional light field* and *holographic displays* aim to synthesize the full 4D light field in front of each eye. Conceptually, this approach allows for parallax over the entire eyebox to be accurately reproduced, including monocular occlusions, specular highlights, and other effects that cannot be reproduced by volumetric displays. Current-generation light field displays provide limited resolution (Hua and Javidi 2014; Huang et al. 2015; Lanman and Luebke 2013), whereas holographic displays suffer from speckle and require display pixel sizes to be in the order of the wavelength of light, which currently cannot be achieved at high resolution for near-eye displays, where the screen is magnified to provide a large field of view.

## Emerging Computational Near-Eye Display Systems

In our work, we ask whether it is possible to provide natural focus cues and to mitigate visual discomfort using focus-tunable optics, i.e., programmable liquid lenses. For this purpose, we demonstrate a prototype focus-tunable near-eye display system (figure 2) that allows us to evaluate several advanced display modes via user studies.

*Conventional near-eye displays* are simple magnifiers that enlarge the image of a microdisplay and create a virtual image at some fixed distance to the viewer.

*Adaptive depth of field rendering* is a software-only approach that renders the fixated object sharply while blurring other objects according to their relative distance. When combined with eye tracking, this mode is known as gaze-contingent retinal blur (Mauderer et al.

2014). Because the human accommodation system may be driven by the accommodation-dependent blur gradient, this display mode does not reproduce a physically correct stimulus.

*Adaptive focus display* is a software/hardware approach that either changes the focal length of the lenses or the distance between the micro display and the lenses (Konrad et al. 2016). When combined with eye tracking, this mode is known as gaze-contingent focus. In this mode, the magnified virtual image observed by the viewer can be dynamically placed at arbitrary distances, for example at the distance where the viewer is verged (requires vergence tracking) or at the depth corresponding to their gaze direction (requires gaze tracking). No eye tracking is necessary to evaluate this mode when the viewer is asked to fixate on a specific object, for example one that moves.

*Monovision* is a common treatment for presbyopia, a condition that often occurs with age in which people lose the ability to focus their eyes on nearby objects. It entails placing lenses with different prescription values for each eye such that one eye dominates for distance vision and the other for near vision. Monovision was recently proposed and evaluated for emmetropic viewers (those with normal or corrected vision) in VR/AR applications (Konrad et al. 2016).

## How Our Research Informs Next-Generation VR/AR Displays

Preliminary data recorded for our study suggest that both the focus-tunable mode and the monovision mode could improve conventional displays, but both require optical changes to existing VR/AR displays. A software-only solution (i.e., depth of field rendering) proved ineffective. The focus-tunable mode provided the best gain over conventional VR/AR displays. We implemented this display mode with focus-tunable optics, but it could also be implemented by actuating the microdisplay in the VR/AR headset.

Based on our study, we conclude that the adaptive focus display mode seems to be the most promising direction for future display designs. Dynamically changing the accommodation plane depending on the user's gaze direction could improve visual comfort and realism in immersive VR/AR applications in a significant way.

Eye conditions, including myopia (near-sightedness) and hyperopia (far-sightedness), have to be corrected adequately with the near-eye display, so the user's prescription must be known or measured. Presbyopic users cannot accommodate, so dynamically changing the accommodation plane would almost certainly always create a worse experience than the conventional display mode. For them it is crucial for the display to present a sharp image within the user's accommodation range.

In summary, a personalized VR/AR experience that adapts to the user, whether emmetropic, myopic, hyperopic, or presbyopic, is crucial to deliver the best possible experience.

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*Advances in "first-person" computational vision are poised to transform how intelligent machines learn visual representations and automatically summarize long videos.*

# First-Person Computational Vision


Kristen Grauman is associate professor, Department of Computer Science, University of Texas at Austin.

## Kristen Grauman


Recent advances in sensor miniaturization, low-power computing, and battery life have carved the path for the first generation of mainstream wearable cameras. Images and video captured by a first-person (wearable) camera differ in important ways from third-person visual data. A traditional third-person camera passively watches the world, typically from a stationary position. In contrast, a first-person camera is inherently linked to the ongoing experiences of its wearer—it encounters the visual world in the context of the wearer's physical activity, behavior, and goals.

To grasp this difference concretely, imagine two ways you could observe a scene in a shopping mall. In the first, you watch a surveillance camera video and see shoppers occasionally pass by the field of view of the camera. In the second, you watch the video captured by a shopper's head-mounted camera as he actively navigates the mall—going in and out of stores, touching certain objects, moving his head to read signs or look for a friend. While both cases represent similar situations—and indeed the same physical environment—the latter highlights the striking difference in capturing the visual experience from the point of view of the camera wearer.

This distinction has intriguing implications for computer vision research—the realm of artificial intelligence and machine learning that aims to automate *visual intelligence* so that computers can "understand" the semantics and geometry embedded in images and video.

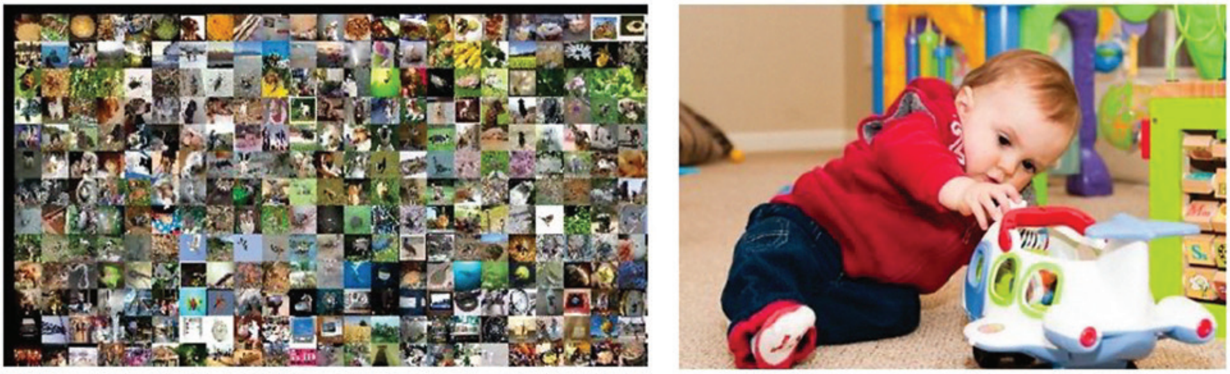


FIGURE 1 (a) The status quo in computer vision is to learn object categories from massive collections of "disembodied" Web photos that have been labeled by human supervisors as to their contents. (b) In first-person vision, it is possible to learn from embodied spatiotemporal observations, capturing not only what is seen but also how it relates to the movement and actions of the self (i.e., the egocentric camera) in the world. Left image is from the ImageNet dataset (Deng et al. 2009); right image is shared by user Daniel under the Creative Commons license.

## Emerging Applications for First-Person Computational Vision

First-person computational vision is poised to enable a class of new applications in domains ranging well beyond augmented reality to behavior assessment, perceptual mobile robotics, video indexing for life-loggers or law enforcement, and even the quantitative study of infant motor and linguistic development.

What's more, the first-person perspective in computational vision has the potential to transform the basic research agenda of computer vision as a field: from one focused on "disembodied" static images, heavily supervised machine learning for closed-world tasks, and stationary testbeds—to one that instead encompasses embodied learning procedures, unsupervised learning and open-world tasks, and dynamic testbeds that change as a function of the system's own actions and decisions.

My group's recent work explores first-person computational vision on two main fronts:

- **Embodied visual representation learning.** How do visual observations from a first-person camera relate to its 3D ego-motion? What can a vision system learn simply by moving around and looking, if it is cognizant of its own ego-motion? How should an agent—whether a human wearer, an autonomous vehicle, or a robot—choose to move, so as to most efficiently resolve ambiguity about a recognition task? These questions have interesting implications for modern visual recognition problems and representation learning challenges underlying many tasks in computer vision.
- **Egocentric summarization.** An always-on first-person camera is a double-edged sword: the entire visual experience is retained without any active control by the wearer, but the entire visual experience is not substantive. How can a system automatically summarize a long egocentric video, pulling out the most important parts to construct a visual index of all significant events? What attention cues does a first-person video reveal, and when was the camera wearer engaged with the environment? Could an intelligent first-person camera predict when it is even a good moment to take photos or video? These questions lead to applications in personal video summarization, sharing first-person experiences, and in situ attention analysis.

Throughout these two research threads, our work is driven by the notion that the camera wearer is an active participant in the visual observations received. We consider egocentric or first-person cameras of varying sources—those worn by people as well as autonomous vehicles and mobile robots.

## Embodied Visual Learning: How Does Ego-Motion Shape Visual Learning and Action?

Cognitive science indicates that proper development of visual perception requires internalizing the link between "how I move" and "what I see." For example, in their famous "kitten carousel" experiment, Held and

Hein (1963) examined how the visual development of kittens is shaped by their self-awareness and control (or lack thereof) of their own physical motion.

However, today's best computer vision algorithms, particularly those tackling recognition tasks, are deprived of this link, learning solely from batches of images downloaded from the Web and labeled by human annotators. We argue that such "disembodied" image collections, though clearly valuable when collected at scale, deprive feature learning methods from the informative physical context of the original visual experience (figure 1).

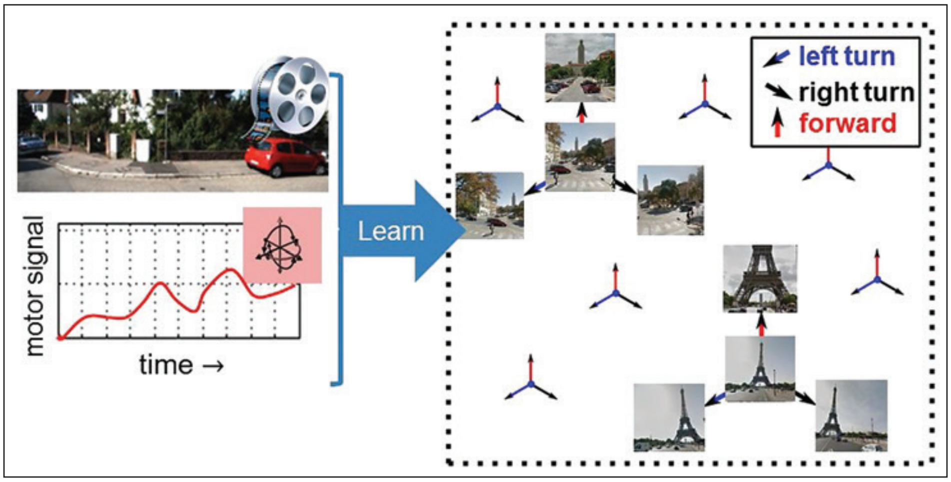


FIGURE 2 Overview of idea to learn visual representations that are equivariant with respect to the camera's ego-motion. Given an unlabeled video accompanied by external measurements of the camera's motion (left), the approach optimizes an embedding that keeps pairs of views organized according to the ego-motion that separates them (right). In other words, the embedding requires that pairs of frames that share an ego-motion be related by the same transformation in the learned feature space. Such a learned representation injects the embodied knowledge of self-motion into the description of what is seen.

We propose to develop *embodied visual representations* that explicitly link what is seen to how the sensor is moving. To this end, we present a deep feature learning approach that embeds information not only from the video stream the observer sees but also from the motor actions he simultaneously makes (Jayaraman and Grauman 2015). Specifically, we require that the features learned in a convolutional neural network exhibit *equivariance*, i.e., respond predictably to transformations associated with distinct ego-motions.

During training, the input image sequences are accompanied by a synchronized stream of ego-motor sensor readings. However, they need not possess any semantic labels. The ego-motor signal could correspond, for example, to the inertial sensor measurements received alongside video on a wearable or car-mounted camera.

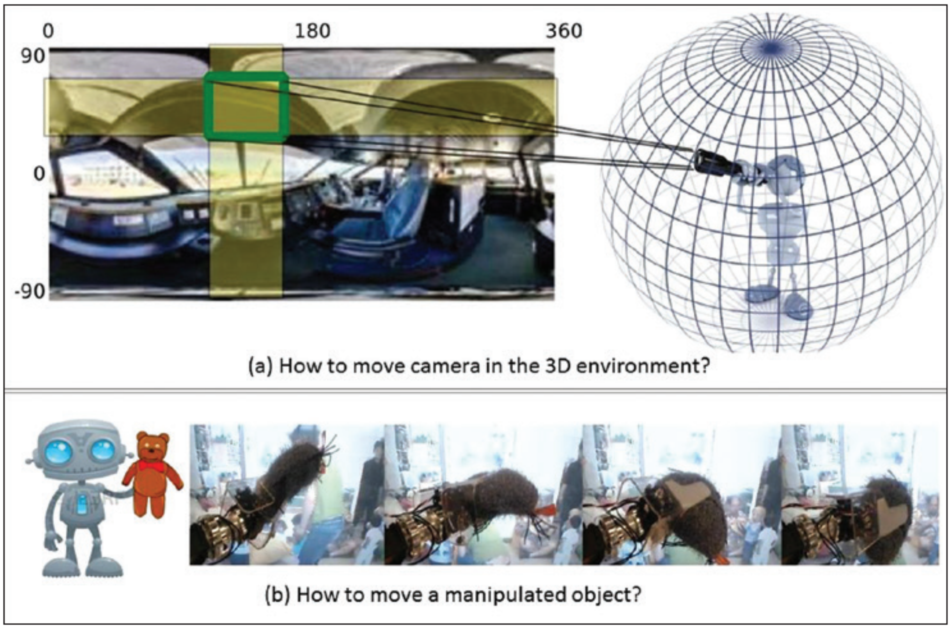


FIGURE 3 Active visual recognition requires learning how to move to reduce ambiguity in a task. A first-person vision system must learn (a) how to move its camera within the scene or (b) how to manipulate an object with respect to itself, in order to produce more accurate recognition predictions more rapidly. In (a), a robot standing in a 3D scene actively determines where to look next to categorize its environment. In (b), a robot holding an object actively decides how to rotate the object in its grasp so as to recognize it most quickly. Reprinted with permission from Jayaraman and Grauman (2016).

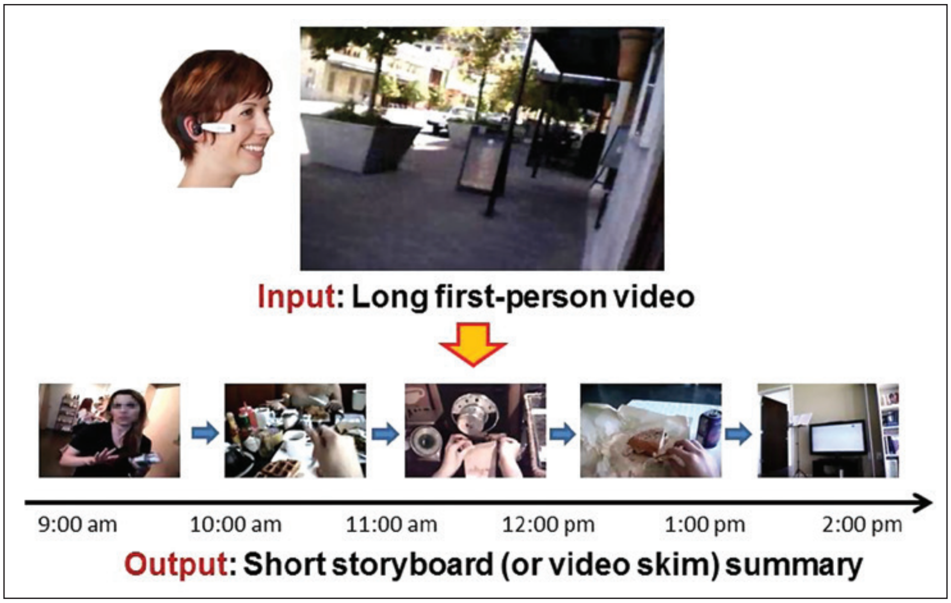


FIGURE 4 The goal in egocentric video summarization is to compress a long input video (here, depicting daily life activity) into a short human-watchable output that conveys all essential events, objects, and people to reconstruct the full story.

The objective is to learn a function mapping from pixels in a video frame to a space that is equivariant to various motion classes. In other words, the resulting learned features should change in predictable and systematic ways as a function of the transformation applied to the original input (figure 2).

To exploit the features for recognition, we augment the neural network with a classification loss when class-labeled images are available, driving the system to discover a representation that is also suited for the recognition task at hand. In this way, ego-motion serves as side information to regularize the features learned, which we show facilitates category learning when labeled examples are scarce. We demonstrate the impact for recognition, including a scenario where features learned from "ego-video" on an autonomous car substantially improve large-scale scene recognition.

Building on this concept, we further explore how the system can actively choose *how to move* about a scene, or *how to manipulate* an object, so as to recognize its surroundings using the fewest possible observations (Jayaraman and Grauman 2016). The goal is to learn how the system should move to improve its sequence of observations, and how a sequence of future observations is likely to change conditioned on its possible actions.

We show how a recurrent neural network–based system may perform end-to-end learning of motion policies suited for this "active recognition" setting. In particular, the three functions of control, per-view recognition, and evidence fusion are simultaneously addressed in a single learning objective. Results so far show that this significantly improves the capacity to recognize a scene by instructing the egocentric camera where to point next, and to recognize an object manipulated by a robot arm by determining how to turn the object in its grasp to get the sequence of most informative views (figure 3).

### Egocentric Summarization: What Is Important in a Long First-Person Video?

A second major thrust of our research explores *video summarization* from the first-person perspective. Given hours of first-person video, the goal is to produce a compact storyboard or a condensed video that retains all the important people, objects, and events from the source video (figure 4). In other words, long video in, short video out. If the summary is done well, it can serve as a good proxy for the original in the eyes of a human viewer.

While summarization is valuable in many domains where video must be more accessible for searching and browsing, it is particularly compelling in the first-person setting because of (1) the long-running nature of video generated from an always-on egocentric camera, and (2) the *storyline* embedded in the unedited video captured from a first-person perspective.

Our work is inspired by the potential application of aiding a person with memory loss, who by reviewing their visual experience in brief could improve their recall (Hodges et al. 2011). Other applications include facilitating transparency and memory for law enforcement officers wearing bodycams, or allowing a robot exploring uncharted territory to return with an executive visual summary of everything it saw.

We are developing methods to generate visual synopses from egocentric video. Leveraging cues about ego attention and interactions to infer a storyline, the proposed methods automatically detect the highlights in long source videos. Our main contributions so far entail

- learning to predict when an observed object/person is important given the context of the video (Lee and Grauman 2015),
- inferring the influence between subevents in order to produce smooth, coherent summaries (Lu and Grauman 2013),
- identifying which egocentric video frames passively captured with the wearable camera look as if they could be intentionally taken photographs (i.e., if the camera wearer were instead actively controlling a camera) (Xiong and Grauman 2015), and
- detecting temporal intervals where the camera wearer's engagement with the environment is heightened (Su and Grauman 2016).

With experiments processing dozens of hours of unconstrained video of daily life activity, we show that long first-person videos can be distilled to succinct visual storyboards that are understandable in just moments.

## Conclusion

The first-person setting offers exciting new opportunities for large-scale visual learning. The work described above offers a starting point toward the greater goals of embodied representation learning, first-person recognition, and storylines in first-person observations.

Future directions for research in this area include expanding sensing to multiple modalities (audio, three-dimensional depth), giving an agent volition about its motions during training as well as at the time of inference, investigating the most effective means to convey a visual or visual-linguistic summary, and scaling algorithms to cope with large-scale streaming video while making such complex decisions.

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*Precision landing can enhance exploration of the solar system and enable rockets that can be refueled and reused.*

# Autonomous Precision Landing of Space Rockets


Lars Blackmore is principal rocket landing engineer at SpaceX.

## Lars Blackmore


Landing an autonomous spacecraft or rocket is very challenging, and landing one with precision close to a prescribed target even more so. Precision landing has the potential to improve exploration of the solar system and to enable rockets that can be refueled and reused like an airplane.

This paper reviews the challenges of precision landing, recent advances that have enabled precision landing on Earth for commercial reusable rockets, and what is required to extend this to landing on planets such as Mars.

### Brief History of Autonomous Space Landings

In the past 50 years autonomous spacecraft have brought humans back from space, landed several rovers on the surface of Mars (Bonfiglio et al. 2011; Golombek et al. 1997; Soffen and Snyder 1976; Squyres 2005; Way et al. 2006), got a probe onto Saturn's moon Titan (Tomasko et al. 2002), landed on an asteroid (Bibring et al. 2007), and more. Because of these missions, it is now known that Mars was once warm with plenty of water and could likely have supported life, and that Titan has lakes of methane, an organic compound. Steady progress has enabled heavier payloads to be landed in more exotic locations, and recent improvements, such as advanced decelerator technologies (Tibbits and Ivanov 2015), will further expand explorers' reach in the solar system.

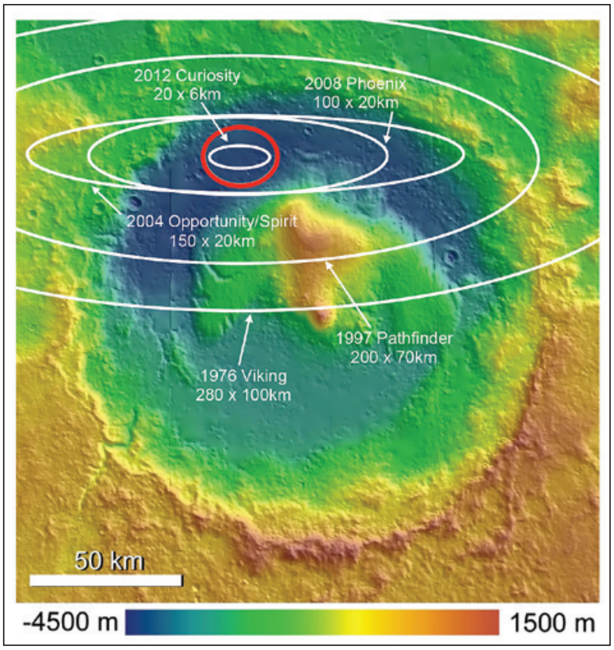


FIGURE 1 Landing ellipses for successful Mars landings to date, shown on elevation map of Gale Crater. Highlighted in red is Curiosity's landing target, known as Aeolis Palus. Image credit: Ryan Anderson, USGS Astrogeology Science Center.

Although these missions have aimed for a particular location on the surface of a target planet, the precision has varied. Precision is quantified using a *landing ellipse*, the region where it is 99 percent likely that the vehicle will land. Before flight, mission planners must choose a landing site such that everywhere in the landing ellipse is safe for touchdown. Figure 1 shows that the landing ellipse for Mars missions has steadily improved, but is still measured in kilometers rather than meters.

## The Need for Precision

When precision is measured in kilometers, missions must land in a desert (in the case of Mars) or in the ocean or on plains (in the case of Earth). If landing precision could be measured in meters instead of kilometers, a world of new opportunities would open up: it would be possible to

- explore Martian caves and valleys,
- return samples from other planets,
- set up permanent outposts throughout the solar system, and
- make rockets that, after putting a payload into orbit, can be refueled and reused like an airplane, instead of being thrown away after a single flight, thus dramatically decreasing the cost of space travel.

## Challenges

There are some important challenges to precision landing on a planet.

### *Extreme Environment*

A vehicle entering an atmosphere from space goes through extreme conditions.

- The majority of the entry energy is dissipated through friction with the atmosphere, resulting in extreme heating that must be dissipated; for example, the leading edge of the Apollo heatshield reached over 2500 degrees Celsius (Launius and Jenkins 2012).
- Drag causes enormous forces on the reentry vehicle; for example, SpaceX's Falcon 9 Reusable (F9R) weighs about 35 metric tons and has a peak deceleration of six times Earth gravity on reentry.
- Winds push around the reentry vehicle, with high-altitude winds at Earth regularly exceeding 100 miles per hour.
- Communication may be denied for all or part of reentry as ionized air around the spacecraft interferes with radio communications; for example, the Apollo 13 return capsule endured a 6-minute blackout.
- And finally, a spacecraft operating outside of Earth orbit is subject to high radiation, which can be fatal for electronics. This is especially true of missions operating near Jupiter, where the radiation environment is particularly intense.

### *Small Margin for Error*

With most landings, the first attempt must be a success or the vehicle will be destroyed on impact. Moreover, additional propellant is rarely available for a second landing attempt. For large rocket engines, throttling down to a hover is technically challenging and inefficient—every second spent hovering is wasted propellant.

For F9R, the rocket has to hit zero velocity at exactly zero altitude. If it reaches zero velocity too low, it will crash; if it reaches zero too high, it will start going back up, at which point cutting the engines and falling is the only option. This requires precise knowledge and control of vertical position and velocity.

### *Touchdown Challenges*

A dedicated system, such as landing legs, is usually used to attenuate the loads of landing, keep the rocket safe from rocks, and prevent it from tipping over after landing. Being able to design legs that can do this as mass- and space-efficiently as possible is a challenge, as is delivering the rocket to the upright and stationary position required to avoid overloading the legs' capabilities. For the *Curiosity* rover, the SkyCrane system enabled the dual use of the rover suspension as the landing attenuation system (Prakash et al. 2008).

In addition, the landing environment may be hazardous. For the Mars Exploration rovers, the combination of rocks and high winds threatened to burst the landing airbags, so an autonomous vision and rocket system was added to detect and reduce lateral velocity (Johnson et al. 2007).

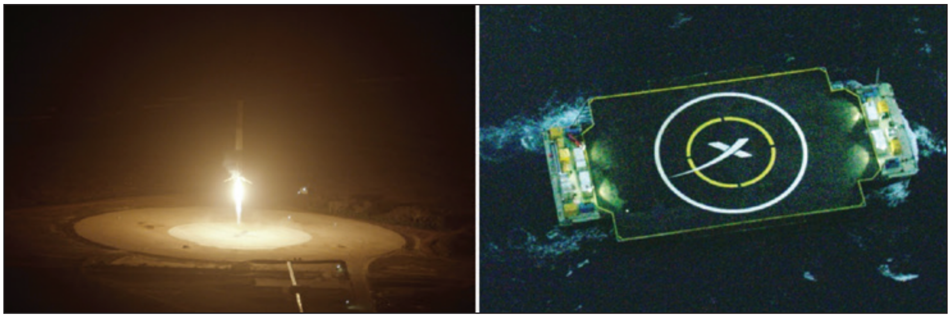

FIGURE 2 Left: SpaceX's Landing Zone 1 at Cape Canaveral. Right: The SpaceX autonomous spaceport drone ship.

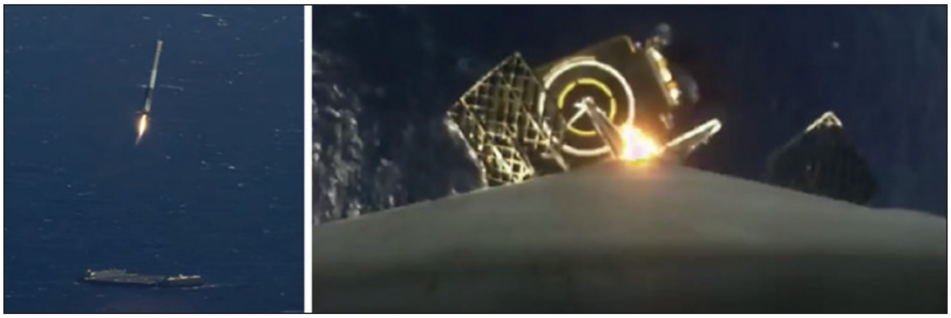

FIGURE 3 SpaceX F9R approaching the drone ship for landing.

### *Need to Hit the Target*

Achieving precision landing requires the vehicle to hit the target despite being pushed around by disturbances such as winds. For a space reentry vehicle, this is a unique problem, since it is neither a ballistic missile nor an airplane. A ballistic missile tries to hit its target at high speed, so (like a bullet) it uses a high ballistic coefficient and high velocity to avoid being affected by disturbances. An airplane does get pushed around by disturbances, but its wings give it the control authority to correct for those disturbances with ease. A rocket landing vertically has neither of these advantages, making precision landing highly challenging.

## Recent Advances

In the past two years, two commercial companies, SpaceX and Blue Origin, have sent rockets into space and landed them back on Earth within meters of their targets. Blue Origin's *New Shepard* rocket has landed several times at the company's West Texas test site. SpaceX's *Falcon* 9 first stage has landed both on land at Cape Canaveral and on a floating landing platform known as the autonomous spaceport drone ship (ASDS), shown in figure 2. Images from recent SpaceX landings are shown in figure 3.

Central to achieving precision landing is the ability to control dispersions, which are variations in the trajectory caused by environmental uncertainty. To illustrate this, consider the example of *Falcon* 9's first stage returning from space. To achieve precision landing, dispersions must be controlled so that, at touchdown, at least 99 percent of them fit within the designated landing zone. For F9R, this means achieving dispersions in the landing location of 10 meters or better for a drone ship touchdown and 30 meters or better for a landing at Cape Canaveral.

Figure 4 shows the various phases of F9R's mission. On ascent, winds push the rocket around so that dispersions grow. The first opportunity to shrink dispersions is the boostback burn, which sends the rocket shooting back toward the launch pad. During atmospheric entry, winds and atmospheric uncertainties again act to increase dispersions. The landing burn is the last opportunity to reduce the dispersions, and requires the ability to *divert*, or move sideways.

For F9R, controlling dispersions requires precision boostback burn targeting, endoatmospheric control with fins (shown in figure 5), and a landing burn with a divert maneuver. The latter is one of the most challenging

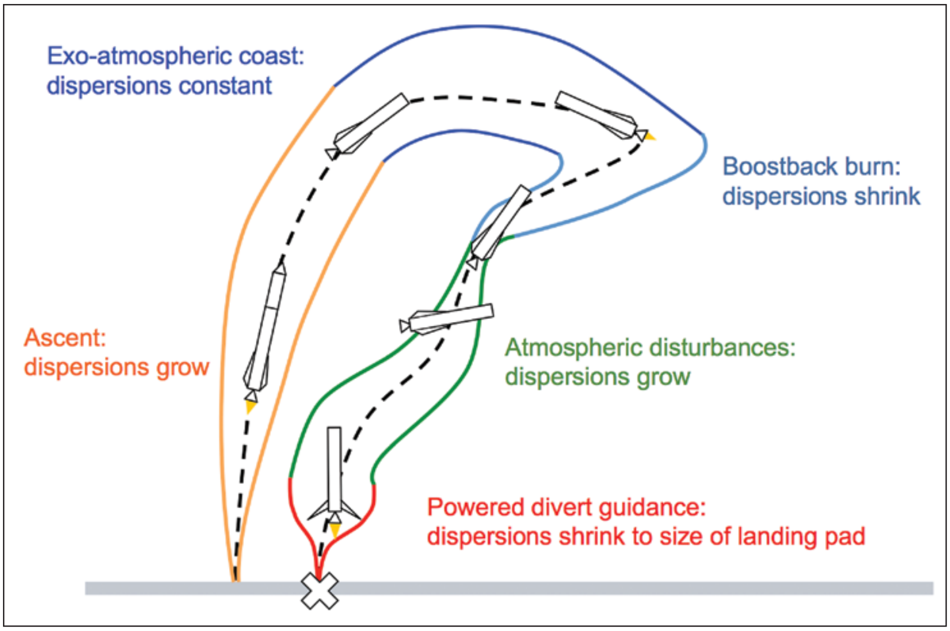


FIGURE 4 Phases of an F9R return-to-launch-site mission. The colored lines represent the largest possible variations in the trajectory, known as dispersions.

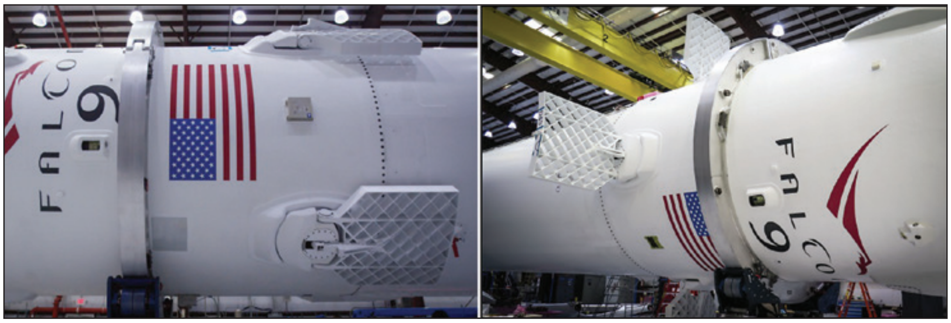

FIGURE 5 F9R's grid fins, stowed for launch (left) and deployed for entry (right).

aspects, and is also required for proposed precision landings on Mars (Wolf et al. 2011). The vehicle must compute a divert trajectory from its current location to the target, ending at rest and in a good orientation for landing without exceeding the capabilities of the hardware.

The computation must be done autonomously, in a fraction of a second. Failure to find a feasible solution in time will crash the spacecraft into the ground. Failure to find the optimal solution may use up the available propellant, with the same result. Finally, a hardware failure may require replanning the trajectory multiple times.

A general solution to such problems has existed in one dimension since the 1960s (Meditch 1964), but not in three dimensions. Over the past decade, research has shown how to use modern mathematical optimization techniques to solve this problem for a Mars landing, with guarantees that the best solution can be found in time (Açikmeşe and Ploen 2007; Blackmore et al. 2010).

Because Earth's atmosphere is 100 times as dense as that of Mars, aerodynamic forces become the primary concern rather than a disturbance so small that it can be neglected in the trajectory planning phase. As a result, Earth landing is a very different problem, but SpaceX and Blue Origin have shown that this too can be solved. SpaceX uses CVXGEN (Mattingley and Boyd 2012) to generate customized flight code, which enables very high-speed onboard convex optimization.

## Next Steps

Although high-precision landings from space have happened on Earth, challenges stand in the way of transferring this technology to landing on other bodies in the solar system.

One problem is navigation: precision landing requires that the rocket know precisely where it is and how fast it's moving. While GPS is a great asset for Earth landing, everywhere else in the universe is a GPS-denied environment. Almost all planetary missions have relied on Earth-based navigation: enormous radio antennas track the vehicle, compute its position and velocity, and uplink that information to the vehicle's flight computer. This is sufficient for landings that only need to be precise to many kilometers, but not for landings that need to be precise to many meters.

Analogous to driving while looking in the rearview mirror, Earth-based tracking gets less and less accurate at greater distances from the starting point. Instead, the focus needs to be on the destination planet in order to be able to land precisely on it. *Deep Impact* is an example of a mission that used its target to navigate (Henderson and Blume 2015), but (as its name implies) it was an impactor mission, not a landing.

Recent research has achieved navigation accuracy on the order of tens of meters (Johnson et al. 2015; Wolf et al. 2011) using terrain relative navigation, where the lander images the surface of the planet during landing and matches features with an onboard map to determine its location. This can be tested on Earth, at least in part, without the need to perform the entire reentry from space.

Several companies have used experimental vehicles, some of which are shown in figure 6, to demonstrate powered descent technology with low-altitude hops. Using these vehicles, terrain relative navigation has been tested on Earth (Johnson et al. 2015), and a demonstration on Mars is being considered for the Mars 2020 rover mission. If this is successful, combining terrain relative navigation with demonstrated precision guidance and control could finally make precision landings on Mars, Europa, and other bodies in this solar system a reality.

FIGURE 6 Various experimental vertical takeoff and landing testbeds. Clockwise from top left: NASA's *Morpheus* (left) and *Mighty Eagle* (right), Masten Aerospace's *Xoie*, SpaceX's *Grasshopper*, McDonnell Douglas' *DC-X*, and Armadillo Aerospace's *Mod*. Image credits: NASA/Dimitri Gerondidakis (*Morpheus*); NASA/MSFC/Todd Freestone (*Mighty Eagle*); Ian Kluft (*Xoie*); NASA (*DC-X*); Armadillo Aerospace/Matthew C. Ross (*Mod*).

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*Desalination technology is becoming more sustainable, accessible, energy efficient, and versatile.*

# Water Desalination
## History, Advances, and Challenges

Manish Kumar, Tyler Culp, and Yuexiao Shen


Manish Kumar


Tyler Culp


Yuexiao Shen

Desalination is the removal of salt and contaminants from water. It involves a broad range of technologies that yield access to marginal sources of water such as seawater, brackish ground- and surface water, and wastewater. Given the reduction in access to fresh water in recent decades and the uncertainty in availability effected by climate change, desalination is critical for ensuring the future of humanity.

This paper describes advances toward more sustainable desalination and exciting directions that could make this technology more accessible, energy efficient, and versatile. It reviews the emergence of membranes as the preferred technology for desalination, recent advances, challenges to its sustainable implementation, and needs for further research.

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Manish Kumar is an assistant professor, Tyler Culp is a doctoral candidate, and Yuexiao Shen is a postdoctoral scientist, all in chemical engineering at Pennsylvania State University.

## Introduction

Desalination represents a promise of near unlimited water supply and is an attractive potential solution to the age-old conundrum of seawater abundance and practical inaccessibility for potable use. It now encompasses the removal of both salts and dissolved contaminants from various sources such as seawater, brackish surface and groundwater, and industrial and municipal wastewaters.

The primary descriptor of importance for desalination processes is the amount of dissolved solids (primarily inorganic salts) represented by the total dissolved solids (TDS; the solids left over after water is evaporated from particle-free water). Table 1 lists the typical range of TDS levels in waters subjected to desalination-based water treatment processes (Australian NWC 2008).

In addition to being a measure of usability (such as for consumption), TDS levels determine the bounds for the minimum energy needed to remove these solutes from water (or to move water away from these solutes). Just as energy is released when a solute is dissolved in a compatible solvent, energy is needed to separate the solute from the solvent and is dependent on the concentration of the solute. Table 1 shows that higher-salinity water (such as seawater) requires larger amounts of energy for desalination, whereas water from low-salinity streams (such as those from wastewater reuse) could be much lower.

The growing pressure on limited freshwater sources has focused the world's attention on seawater and the recovery of water from marginal sources such as brackish ground- and surface water as well as recycled wastewater. It has also raised awareness and catalyzed the implementation of wastewater reuse, where wastewater is treated to a high quality and in some cases used for direct or indirect potable reuse. Desalination is thus a critical technology for humanity to allow for sustainable development.

## Background and History

Desalination has a long history in both mythology and practice. An early and illustrative reference appears in the Bible (Exodus 15:22–26) and is widely considered to be about desalination.

> When they came to Marah, they could not drink the water of Marah because it was bitter; therefore it was named Marah. And the people grumbled against Moses, saying, "What shall we drink?" And he cried to the LORD, and the LORD showed him a log, and he threw it into the water, and the water became sweet.

### *Distillation-Based Technologies*

Early scientific descriptions of desalination centered around the application of distillation. In his *Meteorologica*, Aristotle wrote that "Salt water when it turns into vapour becomes sweet and the vapour does not form salt water again when it condenses" (Forbes 1948, p. 383). This is the definition of distillation, a process used to create fresh water from seawater at larger scales starting in the 1930s (NRC 2008). Distillation-based technologies remained a major approach to water desalination until the development of membranes.

The most common distillation-based desalination methods are thermally driven technologies, including multistage flash distillation, multiple-effect distillation, and mechanical vapor compression processes. In these processes water is evaporated by the addition of heat and in many cases assisted by the use of vacuum. The evaporated water is then condensed to recover desalinated water. Several large plants, primarily in the Middle East, have used thermal distillation since the 1930s (NRC 2008).

**TABLE 1 Typical water sources for desalination and their total dissolved solids (TDS) ranges as well as the calculated minimum energy for separation per unit volume (specific energy consumption).**

| Water Source* | Total dissolved solids (mg/L) | Minimum energy for separation (kwh/m3)** |
|---|---|---|
| Seawater | 15,000 – 50,000 | 0.67 |
| Brackish water | 1,500 –15,000 | 0.17 |
| River water | 500 – 3,000 | 0.04 |
| Pure water | < 500 | < 0.01 |
| Wastewater (untreated domestic) | 250 – 1,000 | 0.01 |
| Wastewater (treated domestic) | 500 – 700 | 0.01 |

* Data from Australian NWC (2008).
** Calculated based on average TDS of the range.

But thermal desalination has very high energy consumption and is increasingly being replaced by the use of membranes, specifically reverse osmosis (RO) membranes. Figure 1 shows the energy consumption per unit volume of water for several commonly used water desalination techniques (Al-Karaghouli and Kazmerski 2013). As is evident from this figure, RO is a substantially more energy efficient technology for water desalination.

### *Emergence of Membrane Technology*

Membrane technologies arose as a result of a breakthrough in the use of polymer films for separating salt from water in the late 1950s/early 1960s. A brief history of the development of RO membranes is shown in figure 2, based on Baker (2004).

Reid and Breton (1959) first demonstrated the possibility of desalination using polymeric cellulose films and thus the first polymeric RO membranes were created. Loeb and Sourirajan (1963) then showed that an asymmetric cellulose acetate membrane can be used for desalination. The permeabilities of these early membranes were low and RO membranes were considered a novelty separation technique rather than a solution to desalination.

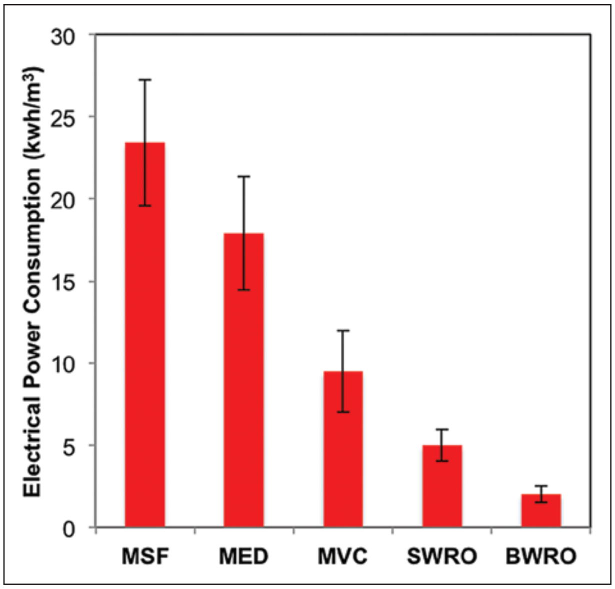


FIGURE 1 Typical equivalent (specific) electrical power consumption for thermal and membrane distillation strategies (based on data from Al-Karaghouli and Kazmerski 2013). BWRO = brackish water reverse osmosis; MED = multiple-effect distillation; MSF = multistage flash distillation; MVC = mechanical vapor compression; SWRO = seawater reverse osmosis.

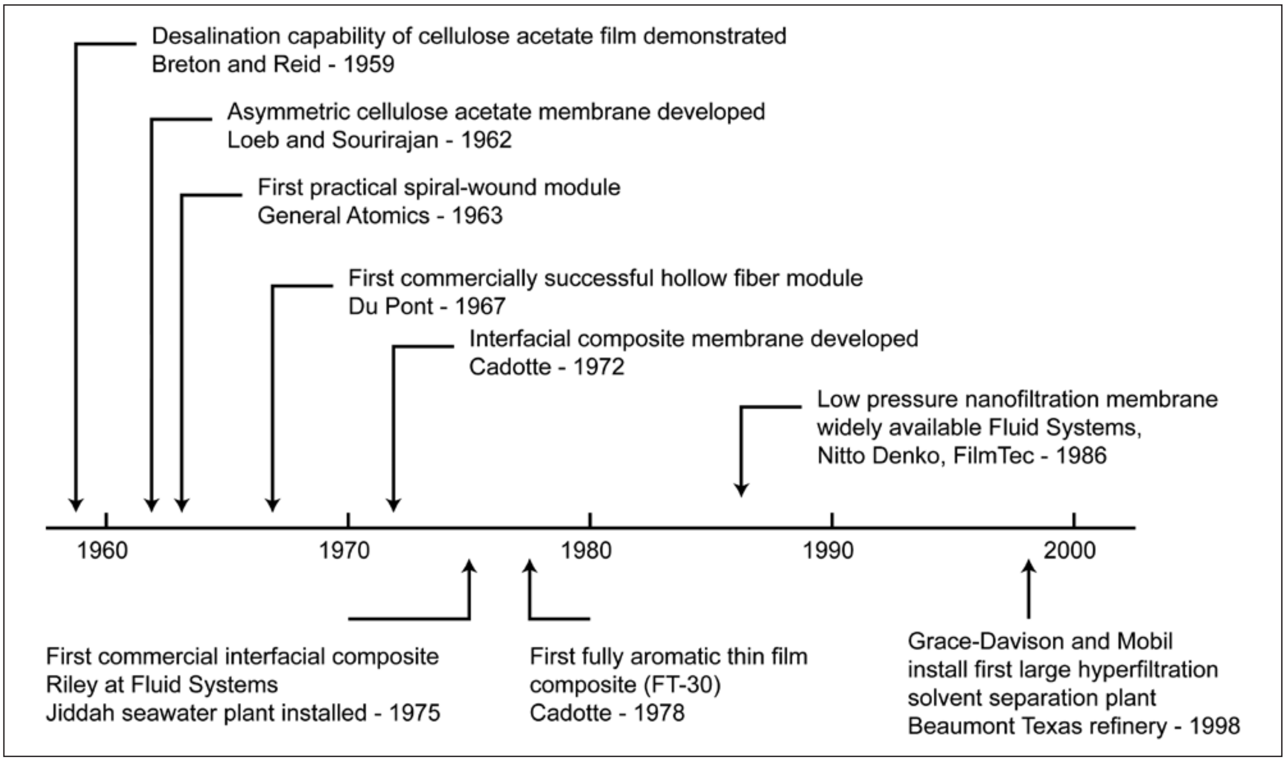


FIGURE 2 Brief timeline of the development of reverse osmosis membranes. Reproduced with permission from Baker (2004). © 2004 Wiley.

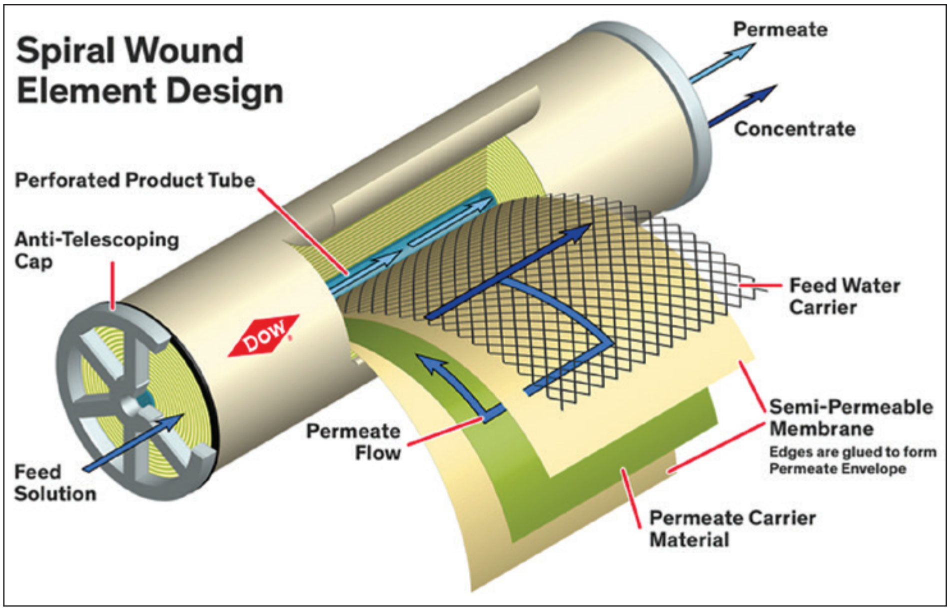


FIGURE 3 Typical spiral wound module design (used with permission from Dow Chemical).

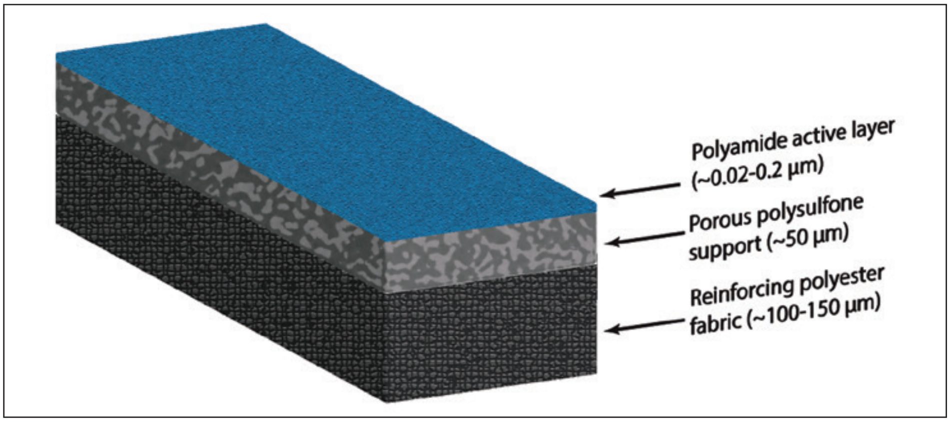


FIGURE 4 Architecture of a thin film composite (TFC) reverse osmosis (RO) membrane. A crosslinked polyamide nonporous active layer is supported on a microporous polysulfone membrane cast on a polyester fabric.

An innovation in the packaging of large membrane areas into small volumes was the development of the spiral wound module (figure 3) by General Atomics in 1963. The spiral wound configuration is now common in RO applications (Cadotte 1981; Westmoreland 1968). In this module, "leaves" of membranes, with feed and permeate spacers, are connected to a perforated permeate tube and rolled up in a "jelly roll" configuration. Hollow-fiber modules containing thin fibers were developed a few years later by DuPont, but this configuration is less commonly used for RO.

A major advance in membrane chemistry that has made possible the application of RO membranes is the development of the thin film composite (TFC) architecture. Previously, membranes were either several-micron-thick polymer layers with a uniform architecture or similar-size polymer layers with an "asymmetric" structure with a nonporous salt-rejecting top surface opening up to a more porous support.

Cadotte (1981) patented the design for the three-layer TFC membrane that is now the industry standard. It provides high permeability while maintaining selectivity for water (vs. salt or other solutes). His major innovation was to make the crosslinked "active layer" of the membrane of nanoscale thickness and support it on a microporous membrane (figure 4). A 20–200 nm thin crosslinked polyamide layer is supported on (or indeed grown from) a microporous polysulfone layer that is in turn supported on a polyester fabric.

The most common chemistry for modern RO membranes is interfacial polymerization, another major advance in RO membrane manufacturing. The procedure, described in figure 5, has been the standard for making RO membranes for the past 5 decades.

The energy consumption of RO technology has dramatically declined (figure 6, based on data from Gude 2011 and Elimelech and Phillip 2011) thanks to improvements in formulation, manufacturing procedures, and processes, such as energy recovery from pressurized brine. These advances rapidly enhanced sustainability and exponentially increased the implementation of these membranes for seawater and brackish water desalination as well as wastewater reuse.

For some cases, such as seawater reverse osmosis, it is argued that current membranes have reached very close

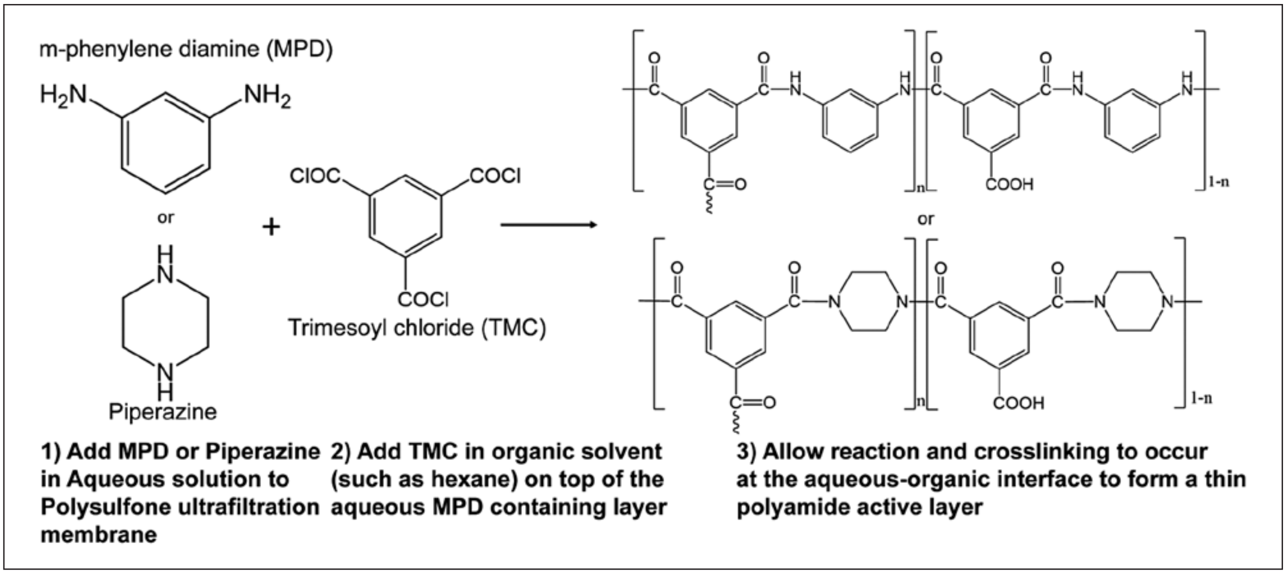


FIGURE 5 The reaction scheme and procedure most commonly used for synthesizing thin film composite (TFC) reverse osmosis (RO) and nanofiltration membranes (NF). RO membranes are typically synthesized using the MPD aqueous monomer while NF membranes are more commonly synthesized using the piperazine monomer. TMC is used for both types of membranes.

to the thermodynamic limit of ~1 kWh/m$^3$ and that further improvement in materials may not yield additional energy sustainability (Elimelech and Phillip 2011). On the other hand, advances in permeability and selectivity can still yield major gains in brackish water treatment and wastewater reuse.

Ultrapermeable membranes with very high salt rejection appropriate for reverse osmosis may substantially reduce the necessary energy (~45 percent) or plant infrastructure (pressure vessels, up to 65 percent) in low-salinity sources (Cohen-Tanugi et al. 2014) such as brackish water desalination and water reuse. The energy advantage is significantly lower for high-salinity seawater applications (15 percent less energy) but the plant size can be reduced by 44 percent (Cohen-Tanugi et al. 2014).

A focus on increasing selectivity rather than simply increasing membrane permeability has been proposed in recent work as a sustainable approach to improve membrane materials (Werber et al. 2016a).

## Advances in RO Desalination

Recent advances in desalination membranes promise a path to higher sustainability. Some of these advances are described below.

### *Channel-Based Membranes as an Alternative to Solution-Diffusion RO Membranes*

RO membranes currently rely on the solution-diffusion mechanism to separate solutes from water, a transport method in which components of the solution first dissolve into the membrane matrix and then diffuse across the membrane by "jumping" between transiently connected pores. In contrast, biological membranes conduct efficient and selective channel-based transport, in which water or selected solutes are transported "straight through" protein channels (membrane proteins, MPs). MP channels are approximately 4 nm in length in comparison to the tortuous unconnected pores in the 20–200 nm thick RO membrane active layers.

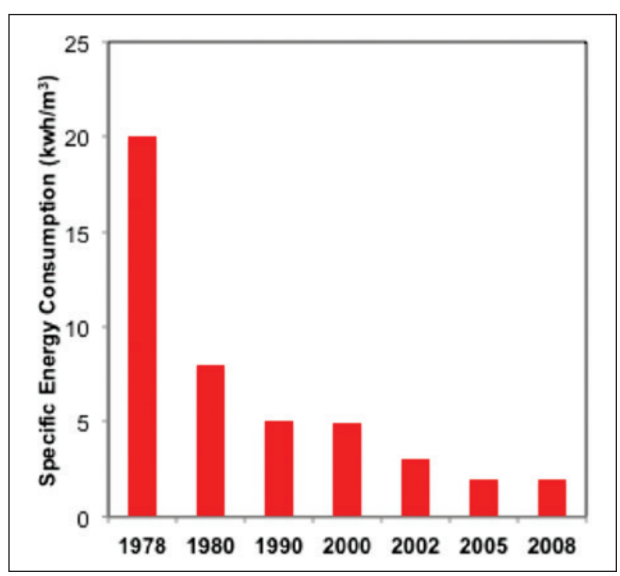


FIGURE 6 Decline in specific energy consumption of reverse osmosis membranes, 1978–2008.

Attention has recently been focused on water channel proteins called aquaporins (AQPs) and their synthetic analogs, carbon nanotubes (CNTs). AQPs selectively transport water across cell membranes in many forms of life (including in humans) (Agre 2004).

Both AQPs and CNTs efficiently transport water at the rate of several billions of molecules per second. They consist of narrow pores lined with hydrophobic surfaces, resulting in single-file water transport (de Groot and Grubmuller 2001; Hinds 2007). While CNTs cannot be made at dimensions that are substantially less than 10 Å in diameter and thus cannot reject salt (hydrated sodium and chloride ions are about 7.2 and 6.6 Å in diameter respectively; Israelachvili 2011), AQPs are highly water selective due to their small pore size (~3 Å) and the presence of amino acid residues that reject charged ions (Agre et al. 2002). The exceptional permeability and selectivity of AQPs has led to research on their incorporation in water purification membranes (Shen et al. 2014) and AQP-based biomimetic membranes were proposed in the mid- to late 2000s in several patents and papers.

There have been many advances since, including methods to incorporate AQPs in stable lipids and lipid-like block copolymers, their packing at high density into membranes, the integration of such layers into various membrane architectures, and finally the development of a scalable membrane where AQPs are inserted into the active layer of RO membranes (Zhao et al. 2012). The latter has resulted in commercially available membranes at small scale, but they face significant challenges to scaleup because of concerns about stability and cost.

Another advance inspired by biological channels and arguably more scalable is the development of artificial water channels and proposals to develop membranes around them (Barboiu 2012). These bioinspired channels are made synthetically using organic synthesis but have until recently been a less studied area with only a few architectures reported (Shen et al. 2014). We recently demonstrated for the first time that such channels can approach the permeabilities of AQPs and CNTs while providing several advantages (figure 7) (Licsandru et al. 2016; Shen et al. 2015). The channels tested were peptide-appended pillar[5] arene channels and imidazole-quartet artificial proton channels.

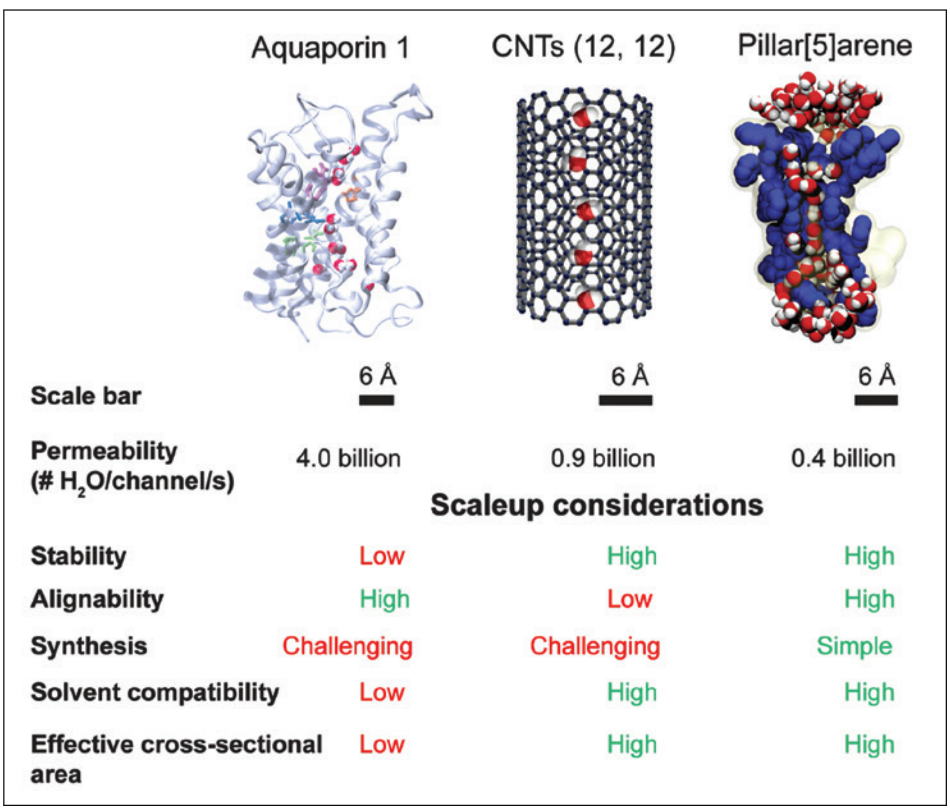


FIGURE 7 Biological water channels, aquaporins (AQPs), and their synthetic analogs, carbon nanotubes (CNTs), have high water permeabilities of ~1–10 billion water molecules per second. They have been integrated into membranes but these membranes face scaleup challenges. We have recently shown that specific artificial water channels, peptide-appended pillar[5]arenes, have transport rates similar to those of AQPs and CNTs. PAPs also have several advantages for scaleup, including high usable cross section, simple synthesis, organic solvent compatibility, and stability (both chemical and biological).

Artificial channels provide distinct advantages for scaleup when compared to CNTs and AQPs because of their compatibility with organic solvents and chemical and biological stability. They could thus be suitable for incorporation in selective high-permeability membranes.

Graphene-based membranes can also be considered as an example of channel-based membranes and may be promising as next-generation RO membranes (Cohen-Tanugi and Grossman 2012; Mi 2014; Werber et al. 2016b). Graphene is a single thin layer of sp2 hybridized carbon that has unusual mechanical, thermal, and electrical properties and may lend itself to a variety of applications.

Pores drilled into graphene may be an option for filtration membranes but currently the pores cannot be made small enough to reject salt (Wang and Karnik 2012). More practical for desalination is the use of oxidized graphene or graphene oxide sheets stacked together so that the distance between the layers can be small enough to reject solutes (Mi 2014). This work is rapidly progressing and could be a new material for sustainable desalination.

### *Fouling-Resistant Membranes*

A major challenge during operation of RO membranes is the deposition of colloidal materials and organic macromolecules on the membrane surface and the growth of microbes. This deposition leads to cake formation, irreversible adsorption, and growth of persistent biofilms, collectively referred to as fouling.

Fouling can cause a substantial increase in power consumption due to additional resistance to flow. In addition, salt accumulates in fouling cake layers. The cake-enhanced concentration polarization and, for biofilms, biofilm-enhanced osmotic pressure (Herzberg and Elimelech 2007; Hoek and Elimelech 2003) increase the effective osmotic pressure to be overcome, thus decreasing the driving force for membrane filtration and increasing power consumption.

Several membrane modification strategies are under consideration to reduce membrane fouling in RO systems. These include the grafting of superhydrophilic or amphiphilic molecules that can prevent adsorption of macromolecules and biological cells; use of nanoparticles, carbon-based materials such as CNTs, and graphene oxide flakes to impart biocidal properties to the RO membrane surface; and use of electroactive or magnetically actuated surfaces to prevent deposition or cause cell death. Methods that interrupt or manipulate cell-to-cell communication are also being explored for biofouling control.

### *Desalination Powered by Renewable Energy*

Desalination has always been considered incompatible with renewable energy infrastructure because of its energy-intensive processes (Charcosset 2009). But with the rapid improvement in RO membranes and systems and concomitant decrease in energy use, more attention is being paid to the coupling of desalination units to solar (using photovoltaics) or wind energy sources. The applications are so far limited to small plants and used for "off-the-grid" applications.

## Critical Challenges in Desalination

Notwithstanding rapid progress in the development and deployment of membrane desalination in recent years, there are still persistent fundamental and practical challenges to its sustainable implementation.

**Inscrutability of desalination membranes.** Although crosslinked TFC RO membranes have been used for a few decades now, the microstructural details of these membranes remain unknown. This lack of knowledge prevents the establishment of a direct link between modifications in the chemistry and microstructure that drive transport properties. Efforts are ongoing to develop tools to enhance understanding of RO membrane structure.

**Concentration polarization.** When salt is rejected from the surface of RO membranes it forms a concentrated layer adjacent to the membrane, reducing the driving force for transport across the membrane. The thickness of this concentration polarization layer can be reduced by enhancing the back transport of solutes. Several ideas have been tested at various scales but their implementation in a sustainable manner has been challenging.

**Seawater intakes and discharges.** A particular challenge to the development of seawater desalination plants (including RO plants) is the impingement and entrainment of marine microorganisms during intake to the plant. Impingement is the collision and trapping of marine organisms that are larger than intake screens; entrainment is the passage of small organisms through these screens and the subsequent destruction of these marine organisms. Also, when dense brine is discharged back to the ocean, it can have detrimental effects on the marine environment if proper mixing does not occur. Efforts are needed to better understand these challenges as well as the effect of intake designs and discharge diffusers on the marine environment (Szeptycki et al. 2016).

**Inland desalination brine disposal.** Whereas coastal plants can discharge concentrated brine to the ocean, inland RO plants need to find a sustainable avenue to manage their brine, which could be as high as 20 percent of the feed flow. Brine minimization and beneficial reuse of brine components as sustainable alternatives to deep well disposal, disposal for municipal sewers, and use of evaporation ponds need to be evaluated carefully.

**Lack of chlorine resistance in polyamide membranes.** Sodium hypochlorite (i.e., bleach) is ubiquitous in water treatment plants for preventing growth of biofilms on surfaces in contact with water, including types of water treatment membranes. But this is not an option for polyamide membranes commonly used for desalination because of their high susceptibility to damage from chlorine. Development of chlorine-resistant membranes is an important practical need.

**Translation of new materials.** Many new materials have been developed for RO desalination, but their translation to products and use at larger scales is limited. Efforts are needed to translate innovations in materials and process design to actual products and plants.

**High-salinity streams.** High-salinity streams emerge from energy operations such as hydraulic fracturing (fracking), proposed underground $CO_2$ storage, unconventional oil development, and flue gas desulfurization applications that frequently have TDS values in excess of 100,000 ppm. These pose unique challenges to RO materials, RO process components, and operating strategies.

## Outlook

Membrane desalination technology is growing rapidly and becoming a critical tool for ensuring long-term water sustainability around the world. There is intense scientific interest in improving the sustainability of this technology, and several innovations are looking to further reduce the technique's power consumption and barriers to widespread use and sustainability. The future of this technology is bright and it is expected to play a major role in the resource-limited future facing the world.

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*A paradigm shift in manufacturing may yield more energy efficient membranes, offering a solution to the challenge of water security.*

# Scalable Manufacturing of Layer-by-Layer Membranes for Water Purification

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Christopher M. Stafford

"When the well is dry, we know the worth of water."
– Benjamin Franklin

Water is critical to world health, economic development, and security. This was highlighted recently when the Obama administration hosted the White House Water Summit to raise awareness of water availability concerns across the United States and to engage stakeholders in identifying long-term solutions for water production and management suitable for investment.

## Background

Water availability is not a new issue. The demand for clean water has risen dramatically since the Industrial Revolution and will continue through the Information Age and beyond. The world's population has climbed to 7 billion, and as it expands further and water scarcity becomes a more widespread reality, it is imperative to think creatively about ways to safeguard access to clean water.

The obvious and most fundamental purpose of clean water is as a source of sustenance, to produce the food and water that every society needs to survive. Clean water is also vital to many of the complex processes that produce the technology that modern society demands and consumes. Many of those processes, however, introduce contaminants, such as heavy metals and other chemicals, into local water supplies.

For all these reasons there is a clear and growing need for technologies and processes that ensure water is clean, safe, and accessible (Shannon et al. 2008).

## Membrane Technology

Membranes and membrane technology, in particular polymer-based membranes, are key to the world's water future (Geise et al. 2010). Membranes are capable of separating a wide range of contaminants from impaired water sources, from viruses and bacteria to heavy metals to dissolved salts.

Given that water covers 71 percent of the Earth's surface and 97 percent of that water is in the world's oceans, an obvious focal point of research is desalination, the recovery of water from high-salinity water sources. This can be an energy-intensive process because of the high osmotic pressure of seawater: the average sea surface salinity is 35,000 g/L (for simplicity, let's assume it is all sodium chloride), which generates an osmotic pressure ($\Delta\pi$) of nearly 400 psi or 27.4 bar. Desalination is nonetheless highly attractive because of the volume of water available for recovery.

This paper focuses on membrane desalination via reverse osmosis, so a short introduction to reverse osmosis is warranted.

## Reverse Osmosis

In traditional osmosis, water flows across a semipermeable membrane from regions of low solute concentrations (in this example, pure water) to regions of high solute concentration (a concentrated salt solution), in effect diluting the solute and lowering the overall free energy of the system. The driving force for the flow of water is the osmotic pressure and is dependent on the concentration of solute molecules in the concentrated solution.

In reverse osmosis, pressure is applied to the high concentration region, which has to be greater than the osmotic pressure of the solution to drive water from regions of high concentration to those of low concentration (see figure 1), again with the aid of a semipermeable membrane. This process generates purified water on one side of the membrane and a more concentrated salt solution on the other side.

The water flux ($J_w$) through the semipermeable membrane can be defined as:

$$J_w = A\frac{K_w}{h}(\Delta P - \Delta\pi)$$

where $A$ is the membrane area, $K_w$ is the permeability of the membrane, $h$ is the membrane thickness, and $(\Delta P - \Delta\pi)$ is the difference between the applied pressure and the osmotic pressure. From this equation, one can see that there is an inverse relationship between the applied pressure and the membrane thickness. Thus, a thinner membrane would be ideal as it would require less energy (pressure) to generate a given amount of water from an impaired water source of a given concentration of dissolved solutes (i.e., osmotic pressure).

## Paradigm Shift in Membrane Technology

The manufacture of today's state-of-the-art reverse osmosis membranes is based on 1970s technology of interfacial polymerization of a selective layer directly on a porous support (Cadotte 1977, 1979).

In this process, polymerization of an aromatic triacid chloride (A) and an aromatic diamine (B) occurs at the interface of two immiscible liquids, where one liquid (typically the aqueous amine solution) is wicked into the porous support. The result is a highly crosslinked, aromatic polyamide (think crosslinked Kevlar or Nomex) membrane that selectively allows the passage of water and rejects salt. The chemistry easily lends itself to roll-to-roll (R2R) or web processing, can be performed over large widths of substrates, and produces a relatively low number of defects across the membrane surface.

Over the past 40 years, this membrane technology has slowly evolved through an Edisonian, trial-and-error approach. The process makes extremely thin (100s nm) selective membranes, but they are difficult to character-

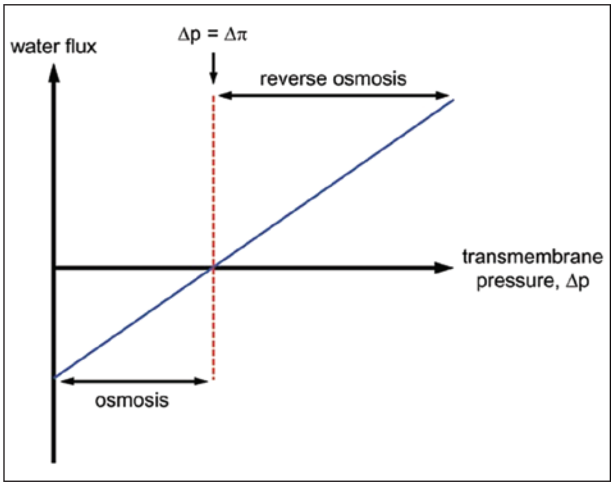


FIGURE 1 Schematic diagram of water flux as a function of applied pressure, indicating the regimes for traditional osmosis ($\Delta P < \Delta\pi$) and reverse osmosis ($\Delta P > \Delta\pi$).

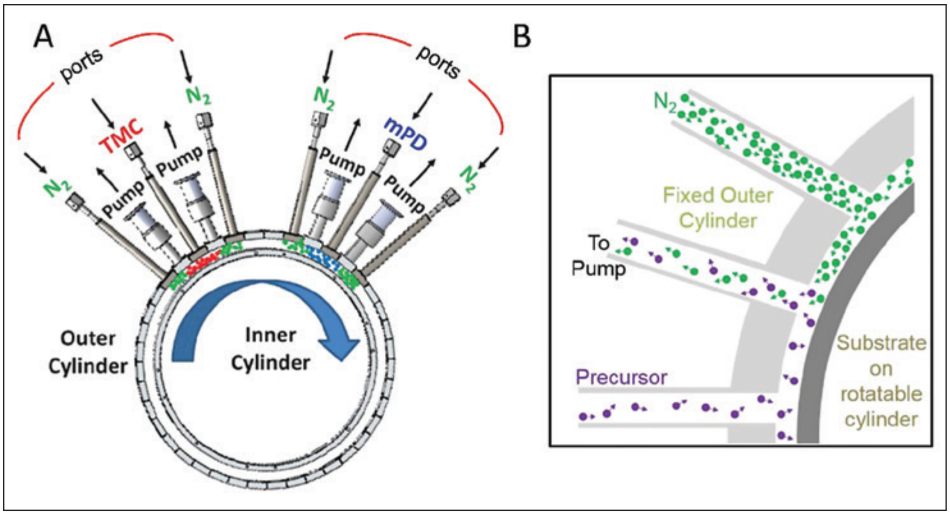


FIGURE 2 (A) Schematic of a spatial molecular layer deposition reactor for the alternating deposition of reactive monomers/precursors to form polyamide membranes. mPD = *m*-phenylenediamine; $N_2$ = nitrogen; TMC = trimesoyl chloride. (B) Zoomed-in view of monomer/precursor arrival to the rotating/moving substrate and removal of unreacted monomer/precursor by the sweep gas and pumping. Adapted from Sharma et al. (2015).

ize because of high roughness and large heterogeneity. Thus, understanding of how these membranes work is insufficient to allow the rational design of next-generation membranes.

In 2011 my research team at NIST proposed a paradigm shift in how these types of membranes are fabricated, in which the selective layer is created layer by layer through a reactive deposition process. We anticipated the resulting membranes to be smooth, tailorable, and exceptionally thin (10s of nm). The ability to tune the membrane thickness makes this process attractive due to potential energy savings from reduced pressure requirements.

In our original demonstration (Johnson et al. 2012), we used a solution-based deposition process in which we sequentially and repeatedly layered each reactive monomer (A + B) onto a solid substrate through an automated spin coating process. We observed growth rates of approximately 0.34 nm/cycle, where one cycle represents a single (A + B) deposition sequence.

The growth rate was shown to be dependent on monomer chemistry, spin conditions, and rinse solvents (Chan et al. 2012). Additionally, the layer-by-layer films are quite smooth, exhibiting a remarkably low root mean square (RMS) roughness of 2 nm compared to commercial interfacial polymerized membranes that exhibit an RMS roughness of 100 nm or more.

The fact that the films are relatively smooth and homogeneous has two compelling advantages: (1) it enables advanced measurements of the film structure via scattering- or reflectivity-based techniques, among others, and (2) it allows *quantitative* structure-property relationships to be developed as the film thickness is well defined. X-ray photoelectron spectroscopy and swelling measurements indicate that the crosslink density of the layer-by-layer membranes is comparable to that of their commercial counterparts, even though the layer-by-layer films are considerably thinner (Chan et al. 2013).

Other researchers have adopted this approach and verified that membranes produced using this layer-by-layer process indeed have viable water flux and salt rejection (Gu et al. 2013).

## Technological Challenges

One major drawback to the solution-based layer-by-layer approach is throughput: spin-assisted assembly is a relatively slow process and not easily scalable.

We have started to explore the use of a vapor-based approach, in which each monomer is deposited in the gas phase, similar to atomic layer deposition of metals and oxides (Sharma et al. 2015). Each monomer/precursor is (1) heated in order to build up sufficient vapor pressure of the precursor and then (2) metered into a rotating drum reactor through dosing ports with differential pumping and purge ports on either side (see figure 2). Again, the number of cycles (or number of consecutive ports) determines the thickness of the resulting membrane.

This approach has many advantages—such as speed, safety, and scalability—over the solution-based approach. We have shown that we can deposit 20 layers of (A + B) per minute (3 s/cycle), compared to 1 layer of (A + B) every 2 minutes using the solution-based approach (2 min/cycle). The growth rate using the vapor-based approach (0.36 nm/cycle) is nearly identical to the solution-based approach, ensuring that the processes are similar. One key advantage of the vapor-based approach is the potential for scale-up via continuous, roll-to-roll, or web processing.

But there are still many challenges yet to overcome, from membrane support design to membrane characterization. For example, the active layer must be coated onto a microporous support layer; thus a method for adequately preventing intrusion of the reactants into the underlying support must be devised. Also, the polyamide network topology needs to be optimized to allow the highest flux of water while maintaining adequate rejection of salt. This can be achieved through judicious monomer selection and deposition conditions.

A paradigm shift in manufacturing may lead to membranes and processes that are more energy efficient, offering one solution to the grand challenge of water security.

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*In my research lab we use protein engineering to create novel cancer diagnostics and therapeutics.*

# Engineered Proteins for Visualizing and Treating Cancer

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Jennifer R. Cochran

Cancer is complex and its diagnosis and treatment can more effectively be tackled by teams of scientists, engineers, and clinicians whose expertise spans bench-to-bedside approaches.

An emerging core philosophy applies understanding of molecular mechanisms underlying disease pathophysiology as design criteria toward the development of safer and more efficacious tumor targeting agents (Kariolis et al. 2013). Armed with this knowledge, academic and industrial researchers are using a variety of approaches to create tailor-made proteins for application in cancer imaging and therapy. These efforts leverage enabling tools and technologies, including methods for (1) protein design and engineering, (2) biochemical and biophysical analyses, and (3) preclinical evaluation in animal models.

Important deliverables of this work include insight into ligand-mediated cell surface receptor interactions that drive disease, and the development of new protein-based drugs and imaging agents for translation to the clinic.

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Dr. Cochran is an inventor on intellectual property related to these technologies that is owned and managed by Stanford University. She is a cofounder, shareholder, and director of Nodus Therapeutics, which is commercializing engineered proteins for applications in cancer therapy.

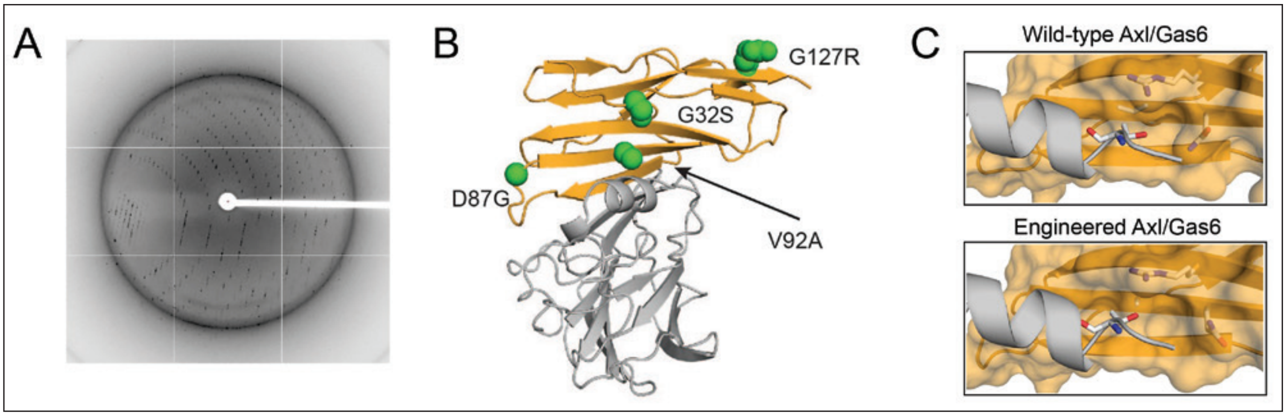


FIGURE 1 Structural analysis of an engineered protein therapeutic elucidates how it binds its target. (A) Protein crystal mounted in an x-ray beam line. Black spots represent data showing the organization of atoms in the crystal. Data from I. Mathews, SLAC National Accelerator Laboratory. (B) Structure of the engineered Axl receptor decoy in complex with Gas6 ligand: Gas6 LG1 domain (grey) and engineered Axl Ig1 domain (orange). Green spheres indicate locations of Axl mutations identified from protein engineering screen. (C) Close-up images of the wild-type Axl/Gas6 and engineered Axl/Gas6 interfaces. In the engineered version, the mutation of valine at position 92 of Axl to alanine creates a larger pocket that reinforces the structure of a key helix on Gas6. These high-resolution images provide a molecular snapshot of structural alterations in the engineered Axl/Gas6 interface that confer high affinity binding. Images B and C reprinted with permission from Kariolis et al. (2014).

## Background

As the field of protein engineering evolved during the 1980s, modified proteins soon joined recombinant versions of natural proteins as a major class of new therapeutics. The ability to customize the biochemical and biophysical properties of proteins to augment their clinical potential has presented many exciting new opportunities for the pharmaceutical industry.

The market value of such biopharmaceuticals is currently over $140 billion, exceeding the GDP of three-quarters of the economies in the World Bank rankings (Walsh 2014). Monoclonal antibodies used to treat cancer, rheumatoid arthritis, and cardiovascular and other diseases account for a large share of these efforts (Drewe and Powell 2002). In 2014 the US and European markets included close to 50 monoclonal antibody drugs, a $75 billion market (Ecker et al. 2015). In 2015, the top three revenue-generating cancer drugs were monoclonal antibodies: rituximab (Rituxan®), bevacizumab (Avastin®), and trastuzumab (Herceptin®), all produced by Genentech/Roche. The size of this market underscores both the clinical and economic importance of protein therapeutics in translational medicine.

## Current Challenges

Challenges for cancer therapeutics include the need for more selective localization to tumors versus healthy tissue, and improved tissue penetration and delivery to brain tumors, which are protected by the restrictive blood-brain barrier. Other therapeutic challenges are tumor heterogeneity that makes cancers difficult to treat, acquired drug resistance that cannot be overcome because of dose limiting drug toxicity, and lack of effective drugs to treat cancer once it has spread.

Limitations of monoclonal antibodies in addressing these and other challenges have motivated the development of alternative tumor targeting proteins with different molecular sizes and biophysical attributes, conferring altered pharmacological properties (Weidle et al. 2013). In the following sections I describe some examples of engineered protein therapeutics developed by our research team that have opportunities to affect cancer in new and impactful ways.

## An Ultra-High Affinity Engineered Protein Therapeutic for Treating Metastatic Disease

Despite advances over the past few decades in the development of targeted therapeutics, there is a lack of effective drugs to treat cancers once they have spread (called metastasis), and 90 percent of patients succumb to metastatic disease. We teamed up with cancer biologist Amato Giaccia (Stanford Radiation Oncology) to address this challenge.

In a number of human cancers, aberrant signaling through the Axl receptor tyrosine kinase has been demonstrated to drive metastasis (Li et al. 2009), confer therapeutic resistance (Hong et al. 2013), and promote disease progression (Vajkoczy et al. 2006). Additionally,

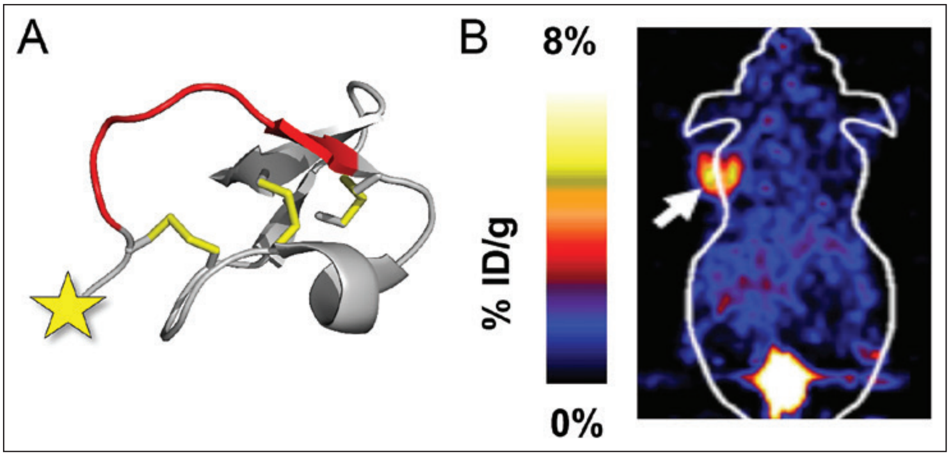


FIGURE 2 (A) 3D structural representation of a trypsin inhibitor peptide from Ecballium elaterium II (EETI-II), which was used as a starting point for engineering a tumor-targeting agent. Gold star indicates attachment site for molecular imaging probe. Protein Data Bank ID: 2IT7. (B) Positron emission tomography (PET) image after injection of a radiolabeled engineered knottin peptide in a mouse model of cancer. Image was acquired 1 hr postinjection. White arrow designates tumor. Color scale represents percent injected dose per gram (%ID/g) and is a quantitative measure of imaging signal.

Axl overexpression has been observed in multiple solid and hematological malignancies (Linger et al. 2008), with expression levels often correlating with disease stage and poor clinical prognosis (Gustafsson et al. 2009; Hong et al. 2013; Rankin et al. 2010). Ambiguity surrounding the fundamental characteristics of Axl's interaction with its ligand, growth arrest-specific 6 (Gas6), including its affinity and the mechanism of receptor activation, have hindered the development of effective Axl antagonists.

We used rational and combinatorial approaches to engineer an Axl "decoy receptor" that binds to the Gas6 ligand with ultra-high affinity and inhibits its function (Kariolis et al. 2014). Upon fusion to an antibody fragment crystallizable (Fc) domain, the engineered Axl decoy receptor binds Gas6 with an affinity of ~400 femtomolar, placing it among the tightest protein-protein interactions found in nature. Crystallographic analysis of the ligand/receptor interaction, carried out in collaboration with Irimpan Mathews (SLAC National Accelerator Laboratory), showed that mutations in Axl induced structural alterations that resulted in increased Gas6/Axl binding (figure 1).

The engineered Axl decoy receptor effectively sequestered Gas6, allowing complete abrogation of Axl signaling. Moreover, Gas6 binding affinity was critical and correlative with the ability of decoy receptors to effectively inhibit metastasis and disease progression. The engineered Axl decoy receptor inhibited up to 90 percent of metastatic nodules in two murine models of ovarian cancer compared to wild-type Axl (~50 percent inhibition), with virtually no toxic side effects (Kariolis et al. 2014).

## Inspiration from Nature to Develop a Novel Class of Tumor Targeting Agents

A major obstacle to the development of therapeutics that target the brain is the presence of the blood-brain barrier, which prevents foreign particles and molecules from entering the central nervous system. We recently demonstrated the promise of using engineered peptides, known as knottins, to target brain tumors for applications such as image-guided resection and targeted drug delivery (Ackerman et al. 2014a; Kintzing and Cochran 2016).

Knottins are unique peptides (30–50 amino acids) containing a disulfide-bonded core that confers outstanding proteolytic resistance and thermal stability (Kolmar 2009). They are found in a wide variety of plants, animals, insects, and fungi, and carry out diverse functions such as ion channel inhibition, enzyme inactivation, and antimicrobial activity (Zhu et al. 2003).

We used molecular engineering approaches to redirect a knottin found in squash seeds that normally functions as an enzyme inhibitor, to create an engineered knottin that binds tumor-associated receptors with high affinity (Kimura et al. 2009). In collaboration with Zheng Cheng and Sanjiv Sam Gambhir (Stanford Radiology) we established these engineered peptides as a new class of molecular imaging agents for cancer (Kimura et al. 2009b) (figure 2). We then showed that intravenous injection of an engineered knottin, conjugated to a near-infrared fluorescent dye molecule, targeted and illuminated intracranial brain tumors in animal models of medulloblastoma (collaborations with Matthew Scott, Stanford Developmental Biology, and Samuel Cheshier and Gerald Grant, Stanford Neurosurgery) (Ackerman et al. 2014b; Moore et al. 2013).

Disulfide-rich peptides, including knottins, have generated great interest as potential drug candidates as they offer the pharmacological benefits of small molecule drugs along with the target-binding affinity and specificity of protein biologics. We postulated that if we could use an engineered knottin peptide to visualize tumors, then we could also use it as a vehicle to deliver drugs to tumors, with a goal of minimizing toxic side effects of systemic chemotherapy.

In one study, carried out in collaboration with the Stanford ChEM-H Medicinal Chemistry Knowledge Center, the engineered knottin peptide was conjugated to the nucleoside analogue gemcitabine, using a variety of linker strategies, and an optimal candidate was shown to inhibit proliferation of breast, ovarian, pancreatic, and brain tumor cells in vitro (Cox et al. 2016). Notably, this peptide-drug conjugate was shown to kill cells via receptor-mediated internalization, and thus exhibited increased potency against pancreatic cells that acquired some resistance to treatment with gemcitabine alone.

In a second study, carried out in collaboration with Sutro Biopharma, Inc., the engineered peptide was fused to an antibody Fc domain and conjugated to the tubulin inhibitor monomethyl-auristatin-F. This knottin-Fc-drug conjugate was capable of inducing regression and prolonged survival in a flank glioblastoma model (Currier et al. 2016), highlighting promise for further clinical development.

## Conclusions

Research and development efforts over the past few decades have culminated in a growing number of FDA-approved protein therapeutics that enable targeted treatment of cancer. In parallel, continued efforts to develop safer and more effective cancer therapeutics are being fueled by expanding knowledge of mechanisms underlying disease pathophysiology and the ability to customize proteins using a variety of engineering methods.

The case studies presented above provide examples of how our research team is using protein design and engineering to generate next-generation cancer therapeutics. Protein engineers are also using these powerful technologies to create molecular toolkits for answering a wide range of research questions in basic science, biotechnology, and biomedicine.

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*Engineering approaches offer new ideas for ways to create more potent and effective cancer immunotherapies.*

# Engineering Immunotherapy


Darrell J. Irvine



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Immunotherapy aims to promote an immune response to disease. Pursued for more than 30 years as a potential treatment for cancer, it is based on the capacity of the immune system to safely distinguish healthy cells from tumor cells and to be resistant to mutational escape by tumors, and on the possibility of establishing immune memory to prevent recurrence.

### The New Age of Immunotherapy

For many years treatments targeting the immune system showed only anecdotal efficacy in clinical trials, leading many researchers to become disillusioned with the field by the late 1990s. Yet the 1990s were a period when many critical elements of fundamental biology regulating the immune response were identified or characterized: the first tumor antigens, Toll-like receptors and related signaling pathways that govern inflammation and the immune system's ability to identify "danger," regulatory receptors that promote or block T cell activation, and specific mechanisms used by tumor cells to avoid immune destruction.

These discoveries led to a transformation in the field of immuno-oncology, which was most prominently impacted by clinical studies, in the early 2000s, of an antibody that blocks a key negative regulatory receptor on T cells, cytotoxic T lymphocyte antigen-4 (CTLA-4). Treatment of melanoma patients with this antibody enabled endogenous antitumor immune responses that led to tumor regressions in a small proportion of heavily pretreated patients with metastatic disease. About 20 percent of the patients survived more than 5 years, well beyond the expected lifespan for advanced disease (Hodi et al. 2010; Lebbé et al. 2014). This "tail of the curve" effect in overall survival reflects a dramatic change in outcome from the best modern "targeted" therapies, where early tumor regression is generally followed by drug resistance, relapse, and death.

Following these early findings, a second class of antibodies blocking another negative regulator axis in T cells, antibodies to PD-1 on T cells (or to its ligand, PD-L1 expressed on tumor cells), showed even more dramatic effects in large clinical trials. Among patients with melanoma, renal cell carcinoma, and lung cancer, 30–50 percent showed tumor regressions (Topalian et al. 2012). These drugs, although acting by distinct mechanisms, are collectively referred to as "checkpoint blockade" therapies, as they disrupt regulatory checkpoints that restrain the immune response to cancer.

*The creation of an army of tumor-specific T cells elicits tumor regressions when combined with appropriate adjuvant treatments.*

In parallel to these advances, a second type of immunotherapy approach has been developed: adoptive cell therapy (ACT), based on the transfer of autologous tumor-specific T cells into patients. In ACT, T cells are isolated from the peripheral blood or from tumor biopsies, cultured with the patient's own tumor cells to identify tumor-reactive clones, and then expanded to large numbers for reinfusion into the patient (Rosenberg and Restifo 2015). The creation ex vivo of an army of tumor-specific T cells has been shown to elicit objective tumor regressions when combined with appropriate adjuvant treatments that promote the functionality of the transferred T cells (e.g., administration of adjuvant drugs such as interleukin-2).

Other strategies genetically modify T cells for patients by introducing a synthetic T cell receptor (chimeric antigen receptor, or CAR) that allows any T cell to become a tumor-specific T cell. These have shown particular promise in treating certain leukemias: more than 75 percent of patients have experienced complete remissions (Maude et al. 2014).

Thus, in the space of a few short years the field of cancer immunotherapy has been revolutionized in the clinic, from a peripheral approach notorious for high toxicity and low efficacy, to a frontline treatment with the prospect of eliciting durable responses—and perhaps cures—in some patients.

## Role of Engineering in the Future of Cancer Immunotherapy

Immunology has advanced by embracing new technologies, from the early days of monoclonal antibody technology to the recent inventions of powerful mass spectrometry–based cellular analysis tools.

The field has also recently attracted the attention of a growing number of interdisciplinary scientists, who bring to bear a unique mindset and new approaches to problems in immunology and immunotherapy. Some of these techniques are rooted in engineering, leading to exciting advances in basic science and new approaches to vaccines and immunotherapies.

Engineers excel at creating model systems that break complex problems into manageable hurdles, and at drawing on applied chemistry, physics, and mathematics to create new technologies that solve practical problems. Engineering contributions to the evolution of cancer immunotherapy can be illustrated by recent examples in the areas of cancer vaccines and ACT. These by no means represent all the areas where engineers are actively working on cancer immunotherapy, but rather are two representative examples.

### *Enhancing Cancer Vaccines*

As mentioned, checkpoint blockade with anti-CTLA-4 or anti-PD-1 has elicited objective tumor regressions in a small proportion of patients. This incomplete response rate has motivated a strong interest in finding additional treatments that can be combined with these drugs to expand the responding population.

Because these drugs act to enhance T cell responses against tumors, one obvious strategy is to combine checkpoint blockade with therapeutic cancer vaccines, for patients whose spontaneous T cell responses to tumors may be too weak to be rescued by checkpoint blockade alone. To this end, a renewed interest in cancer vaccines has been kindled in both preclinical and clinical studies. However, cancer vaccines to date have generally been perceived as a failure, both because of their lack of objective responses in patients and their inability to elicit the kind of robust T cell priming that is believed to be necessary for tumor regression (i.e., T cell responses more like those to live infectious agents).

How can the efficacy of cancer vaccines be improved?

*Engineered Antigens*

Vaccines are generally based on the delivery of antigens (the protein, peptide, or polysaccharide target of the immune response) together with inflammatory cues that stimulate the immune system to respond to the antigens.

One of the simplest approaches that has been most extensively explored in the clinic is the use of peptide antigens combined with adjuvants as T cell–focused vaccines. But short peptides injected in vivo have several significant limitations: they are quickly degraded, they largely flush into the bloodstream rather than trafficking to lymphatics and lymph nodes, and they can be presented by any nucleated cell to T cells. The latter phenomenon, in which T cells are stimulated by random tissue cells rather than professional antigen-presenting cells (APCs) in lymph nodes, leads to tolerance or deletion of tumor-specific cells.

One way to deal with all of these challenges at once is to conjugate so-called "long" peptide antigens (that can be presented only by professional APCs) to an albumin-binding lipid tail through a water-soluble polymer spacer. Albumin constitutively traffics from blood to lymph, and, thus linking antigens to an albumin-binding lipid "tail," redirects these molecules efficiently to lymph nodes instead of the bloodstream after parenteral injection. In addition, the polymer/lipid linkage protects the peptide from degradation. A similar strategy can be used to create "albumin hitchhiking" adjuvants.

These simple chemical modifications lead to 15- to 30-fold increases in vaccine accumulation in lymph nodes, both enhancing the safety of the vaccine and dramatically increasing vaccine potency (Liu et al. 2014).

*Regenerative Scaffolds*

Engineers have also used methods developed in the regenerative medicine field to create implantable vaccine "centers" that coordinate multiple steps in an anticancer vaccine response. A common strategy in regenerative medicine is to create biodegradable polymeric scaffolds as artificial environments that can protect and nurture therapeutic cells on implantation in vivo.

Mooney, Dranoff, and colleagues demonstrated that a similar approach can be used to regulate the response to a vaccine (Ali et al. 2009). By loading polymeric sponges with tumor antigens, chemoattractants for APCs, and adjuvants, they coordinated a 3-step process of (1) APC attraction to the implanted scaffold, (2) uptake of antigen and adjuvant by the APCs, and (3) migration of the now activated APCs to draining lymph nodes, where they could initiate a potent antitumor immune response. This approach is currently being tested in a phase I clinical trial.

Thus chemistry and biomaterials approaches offer a number of ways to create enhanced cancer vaccines.

*Engineering contributions to cancer immunotherapy are evident in cancer vaccines and adoptive cell therapy.*

### *Engineering Adoptive Cell Therapy*

As noted above, adoptive transfer of tumor antigen-specific T cells is one of the two classes of immunotherapies to demonstrate significant durable responses in the clinic so far, but strategies to improve this treatment for elimination of solid tumors are still sought.

Engineers are contributing to the evolution of ACT treatments through the application of synthetic biology principles for the creation of novel genetically engineered T cells. Recently, for example, bioengineers have generated completely artificial ligand-receptor-transcription factor systems, which enable the introduction of a synthetic receptor and transcription factor pair into T cells to enable T cell recognition of a tumor-associated ligand to be transduced into production of an arbitrary biological response (Morsut et al. 2016; Roybal et al. 2016).

Another strategy introduces synthetic fragmented antigen receptors that are activated only when a small molecule drug is present, to allow precise control over the activity of therapeutic T cells in vivo (Wu et al. 2015). These are only a few representative examples of a rapidly moving and exciting area of research.

A third strategy chemically engineers T cells using an approach from the nanotechnology and drug delivery communities to "adjuvant" T cells with supporting drugs, such as cytokines that promote T cell function and proliferation. One promising approach is to attach drug-releasing nanoparticles directly to the plasma membrane of ACT T cells so that the modified cells carry supporting drugs on their surface wherever they home in vivo. This approach has been shown to greatly augment the expansion and antitumor activity of T cells when used to deliver supporting cytokines to the donor cells (Stephan et al. 2010). This basic demonstration also opens the potential to target supporting drugs directly to T cells in vivo, through targeted nanoparticle formulations (Zheng et al. 2013). Such studies show promise in preclinical models and are entering the early stages of translation into clinical testing.

## Conclusions

Cancer therapy is being revolutionized by the first successful immunotherapy treatments. It has also created exciting new opportunities for engineers to impact the field of cancer immunotherapy, by solving challenging problems to safely enhance the immune response to tumors.

The marriage of cutting-edge tools from engineering with the latest understanding of the immune response to tumors offers the promise of further advances toward the goal of curing cancer or rendering many cancers a manageable, chronic condition.

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# An Interview with . . .

## Kealoha

Kealoha. Photo credit: Alan Camou.

**RON LATANISION (RML):** Hello, Kealoha. We're so pleased to talk with you. For starters let me ask, How did you make the transition from being an MIT nuclear engineer to the world of arts and letters, and poetry in particular?

**KEALOHA:** It was definitely a process. The genesis of it was my internships, getting the hands-on experience of what an engineer does. What I realized was that I felt suffocated in the laboratory setting, with the fluorescent lighting, like being in a dungeon all day, the Excel spreadsheets, and then finally emerging into the world and having it be dark outside.

But there were a number of other factors at the time. My interest in the '90s was fusion energy. That's the reason I was in nuclear engineering, that's how I wanted to apply my engineering, math, and science. But in the '90s fusion energy was going through some major cutbacks. I was seeing tenured professors basically getting laid off, I was seeing them struggle. It seemed like the political climate and the budgetary climate—even though we were talking about climate change and the energy crisis, the same problems that we're talking about now—it seemed like the world and the nation weren't ready to move in that direction.

I thought, How can I be some kind of bridge between the engineering world and the policy or financial world? So I did a couple of other internships. After one at Los Alamos National Lab, I went to Washington, DC and dug my hands into policy work. I started to get into global climate change and focus on how we could shift the narrative toward more responsible sources of energy.

**CAMERON FLETCHER (CHF):** What kinds of policy work were you doing?

**KEALOHA:** I was working with the Institute for Defense Analyses. I contributed to a white paper that summer and the thesis of it was that a number of consequences of global climate change are going to affect the DOD's bottom line. We focused on operations other than war (we called them OOTWs) and made the argument that a lot of money gets spent by the Department of Defense on OOTWs—like, for example, the crises in Rwanda or Haiti, and large-scale migrations of people. With global climate change, there will be more of those and the DOD was going to have to deal with them. Now here we are in 2016 and there's Syria and problems that have been exacerbated by global climate change or changes in the ways people do things, and immigration due to change.

**RML:** The interesting thing to me is that, for someone who has honors math and science credentials, when you were at MIT and working on your bachelor's, you also had a writing minor. So you must have had an inclination toward writing from an early age?

**KEALOHA:** I did. I was sort of straddling both worlds, although not seriously in college. To graduate from MIT, you needed to take at least eight humanities classes, but to get a minor you needed only six or so classes in a specific subject. I figured, why don't I just take most of my humanities courses in the writing department and then I'll be well on my way to having a minor.

What's really cool is that one of my favorite books at the time was *Einstein's Dreams* by Alan Lightman—and he was faculty at MIT. I thought, I'm going to go see if he'll be my advisor. He agreed and was a really cool guy. I thought, oh my gosh, I'm meeting this dude who has influenced the narrative in my mind. And then I'd see Noam Chomsky when I was walking around the campus. All these really amazing thinkers! It was a well-rounded experience there.

*Alan Lightman at MIT was my advisor, and I'd see Noam Chomsky on campus. All these really amazing thinkers!*

**RML:** When I was teaching I always tried to emphasize to the students that writing and communication skills are just as important as technical skills. If you can't communicate whatever you're doing, to a client or the Defense Department or whoever it happens to be, you're not going to be very effective, even though you may be very bright. Communication skills have always been important. At MIT there is a writing program and people like Les Perelman and Alan Lightman and others have made it a major part of the undergraduate experience at MIT. I think that's a very, very good idea for an institute of technology.

How did you get involved with slam poetry?

**KEALOHA:** Well, even though I did a little coursework in writing at MIT, hardly any of it was creative writing. So during those four years the creative writing section of my brain just went into hibernation mode. It was huddling like a little abandoned animal in the corner who is cold and wet and shivering.

When I left MIT I got into business consulting in San Francisco, which basically sucked my life dry. One night I said to myself, 'You know what, I'm living in San Francisco and I am not experiencing this city at all.' So I opened the paper, I think it was *SF Weekly* or *The Guardian*, and looked at the "hot picks" and one of them was a slam poetry event. I had never heard of slam poetry and didn't know what it was. But I did know that I was into poetry. During high school and even in elementary school, I was listening to hip hop and writing poems.

This event was happening right near my house, so I decided to pop down and check it out. I pay my admission and I'm sitting there and I get presented with probably some of the best slam poets in San Francisco at that time—some of the nation's best poets. And I had my mind completely blown into 20,000 fragments that all wanted to grow and become like new living entities on their own. That night my brain was tingling, my spine was all warm, and I went home and could not stop writing.

**RML:** That's remarkable. And that launched your activities in slam poetry, which is competitive reading, is that correct?

**KEALOHA:** Yes. In tennis, for example, there's the grand slam, and the slam when it comes to poetry is exactly that—it indicates that this is competitive. Performance poets get up on stage and we compete against each other for a cash prize or bragging rights or whatever it is, to up the stakes. And it's sort of a trick that we play on the audience to get them more involved in what we're doing. At the end of the day, the winner is poetry.

**CHF:** What is the difference between your slam poetry and your written poetry, or is the only difference the fact that one is performed out loud?

**KEALOHA:** It is, but here's the deal. Once you make the decision in terms of 'Do I want to be performing this in front of people or do I want them to be reading it?,' the medium helps to sculpt and define and craft the piece. So how you approach your writing changes depending on whether you want to perform it in front of people or not.

For me 99 percent of the time I've written it, memorized it, and rehearsed it over and over again. I know the script backward and forward and then I perform it as best I can, knowing that the audience is going to react in certain ways and I, the performer, am allowed to stray from the script and improvise if the moment calls for it or change the way I'm performing, depending on what the moment needs. You can change your blocking, your movements, all those things. Everything is up for interpretation.

**CHF:** Do you write or perform in the Hawaiian language?

**KEALOHA:** I definitely infuse Hawaiian words whenever the moment calls for it. But those are specific pieces. If you look at my collection, maybe 5 percent incorporate Hawaiian words. Mostly I write in English—

that's what I was born and raised speaking and it's the way I think. However, I have a Hawaiian perspective in terms of the things I was taught, so to weave the tongue of Hawai'i into what I'm doing comes pretty naturally whenever the piece calls for it.

**RML:** How do you choose the thematic focus of your poetry? Is it oriented toward personal experiences or politics or maybe engineering in any way? How do you identify the area you want to focus on?

**KEALOHA:** For me the process has always been trying to live as rich a life as possible, to observe my environment and people as well as my internal workings, for example if I'm going through some kind of emotional experience. I'm continually trying to put myself in places that expand my mind. A lot of ideas I get sort of spawn from those observations and also from conversations.

My friends know that if we're having a conversation and it sparks something in my brain, I may pull out a journal or a piece of paper and start writing while we're talking. They're cool with it. You guys probably experience the same thing as writers. You know that when you have a thought or an idea, you have to get it on paper right then and there, otherwise it's gone.

So I think and write about everything under the sun. I expect if you look at the collection of my work, there is no one thematic idea or direction except that it comes from me.

**CHF:** You mentioned a moment ago wanting to live as rich a life as possible and I'm wondering: You clearly were drawn to mathematics and the sciences—what do you do to satisfy the left side of your brain now?

**KEALOHA:** That's a great question. Science and engineering is my brain—that is how I think so I'm always using that left side. In fact, I think both hemispheres in my brain are fairly even, but if I had to place my money on what is more developed and what fires stronger and faster, it's my left side. So I don't particularly view myself as a creative person, but when I do get a creative thought I use the left side of my brain to flesh out that thought. Usually my poetry is sort of analyzing creative things.

So that left side of my brain is always being used. In fact, I just threw myself into a four-year project, a profound idea that was the thing that I wanted my life to stand for. It's a production called "The Story of Everything," where I wanted to take the science that we know now (well, in 2011 when I had the thought and began the project), everything that we know about how

Kealoha in a performance of "The Story of Everything." Photo credit: James Kimo Garrett.

humans got here, starting from the Big Bang—a whole ton of processes that have led us to today. I wanted to tell that story in a way that was fun and had plot and characters that you could enjoy, with love and hate and conflict and resolution and all those good things that make a story. I wanted to bring that to the stage so that I could communicate complex scientific processes in ways that the normal average everyday person could enjoy.

**CHF:** Was this a one-person performance?

**KEALOHA:** I like to call it a one-person performance with many people: the narrative is all me but I've got dancers, musicians, a chanter, and visual artists who have created amazing works of art projected on a screen behind us. This is a six-part multimedia experience that is everything I love and everything that I could possibly use to communicate these really complex ideas from the Big Bang to astrophysics to our solar system—all

Dancers Lorenzo Acosta (top) and Jamie Nakama (bottom) in "The Story of Everything." Photo credit: James Kimo Garrett.

those interactions. And evolution too: once life is born as a single cell organism I've got to get to humans, and then I talk about the migration of humans from Africa throughout the rest of the world. The final scene is the future, in particular with regards to global climate change because that's the thing that we need to solve right now. The whole production is 13.7 billion years' worth of time, told in an hour and a half.

The world premiere was September 26, 2015, here in Honolulu. I had some of the best musicians here in these islands, and some of the best dancers—the best of the best helping me with this. We filmed it and now it's about putting the footage together in a way that is appropriate for this piece. There's a trailer on my website (www.kealohapoetry.com/the-story-of-everything.html). Since that initial production it's toured to San Francisco, Anchorage, Tahoe, and Idyllwild (CA).

**RML:** Wow, what a terrific accomplishment.

**KEALOHA:** It almost broke me. Imagine writing about or thinking about or trying to do something for four years straight. It basically took me a year to memorize this thing. It was a hardcore process.

**CHF:** Even more than a PhD dissertation.

**KEALOHA:** Yes, that's the way I view it, like this was my PhD thesis.

**RML:** Has it been in Boston or New York?

**KEALOHA:** Not yet but I would love, love, love to perform it in Kresge Theater at MIT. That would be amazing.

**RML:** I think that would be wonderful. If it becomes known to MIT that this is an interest of yours, I imagine there would be great interest in doing that.

Let me follow up on a couple of other things. You graduated from MIT in 1999, and you are now the poet laureate of the state of Hawai‘i, which is quite a remarkable accomplishment.

**CHF:** And you're the first one.

**RML:** When did you become poet laureate?

**KEALOHA:** Yes, I'm the first one, it's crazy. I was designated in 2012. A poet laureate is responsible for putting on performances, writing for state events, doing outreach to libraries and schools, traveling outside of Hawai‘i and performing, spreading the poetry of Hawai‘i—all these different things, and I had actually already been doing those things for years. When the former governor, Neil Abercrombie, was campaigning, we were at an event together and he said, 'Kealoha, when I win I want you to do the poem for my inauguration.' I was like, okay, cool, awesome, let's do it. He won, and the next thing you know I was inaugurating him and then he designated me as the poet laureate. To him it made sense: the things that a poet laureate is supposed to do I was already doing.

**CHF:** You mentioned that one of your responsibilities is to spread the poetry of Hawai‘i, which to me evokes the poetry of others or indigenous poetry. When you travel abroad representing Hawai‘i, do you spread the word of other or former poets from ages past, or the poetry of other Hawaiians?

**KEALOHA:** That's an interesting question. No, I don't. I do chant, though. If I'm doing a chant that's traditional and ancient, then yes, that is poetry from a long time ago. But it kind of goes against the general code of poets and performance poets especially to perform other people's work.

**CHF:** That makes sense. Can you give us an example of a chant, what that would sound like?

**KEALOHA:** [Chants]

**CHF:** What was the meaning of the syllables?

**KEALOHA:** That song or chant talks about opening yourself up to the wisdom of the universe and allowing it to aid in this moment of song making and of sharing the knowledge.

**CHF:** That sounds like the approach that you bring to your poetry.

**KEALOHA:** Exactly. Which is why it's a chant that I often perform to open my shows.

**RML:** I've discovered that there are poet laureates in most of the states but not all; for example, there's none in Massachusetts. Do you meet with your colleagues from other states on any regular (or irregular) basis? Is there any communication?

**KEALOHA:** Yes, there is communication, primarily online. Someone will have an idea to put together a book, for example, that includes the poet laureates from as many states as possible, so they'll communicate with us about that. Or they'll let us know, 'Hey, this thing is going on here, could you make it?'

**CHF:** It looks from your website (www.KealohaPoetry.com) like you do a lot of work with students, particularly at the middle school level. What do you aim for when you're working with or communicating with kids?

**KEALOHA:** My primary goal when I'm working with kids is to get them really excited about poetry or about thinking, and to be positive about themselves. Everything else sort of falls from that—the way I approach them, the way I talk to them, the way I introduce myself, it has to be stuff that gets them excited. It also has to be stuff that's cool, because with a middle school kid, or a high school or even college student, the moment they smell that you are inauthentic or not cool, you're wasting your time and theirs. So I've developed mechanisms to break through those walls quickly and efficiently and effectively.

**RML:** I also see on your website that you've done some acting.

**KEALOHA:** A big element of performance poetry is how you're performing, so to me doing acting gigs in the beginning was a great sort of cross training for the art form that I was primarily interested in. And in high school I acted a little too. I take a great interest in the ability to communicate, so why wouldn't you immerse yourself in every aspect of communication in order to make your message more powerful.

**CHF:** I see that you have corporate clients—Microsoft, Mitsubishi, Subaru. What kind of work have you done with corporate clients?

**KEALOHA:** A number of things. Some corporations hire me to write a poem for them. Some hire me to sit in on a conference they're having and then write a poem about it. Some invite me to interact with the employees and get them to write their own poetry. And some just hire me to come and perform for them.

**CHF:** It's pretty fabulous that you're able to make a living as a poet.

**KEALOHA:** Yes, there's a number of us out there. I don't know how many exactly—it's a small enough number that whenever I tell people I make my living as a poet they're pretty incredulous. But there's enough of us out there that we have created sort of "an industry of poets" who can support themselves.

*My goal when I'm working with kids is to get them really excited about poetry or about thinking, and to be positive about themselves.*

**RML:** I'd like to return for a moment to your interaction with the governor of Hawai'i. You're obviously very concerned about the quality of life and the human condition. Do you ever talk with the governor about issues related to those kinds of topics or have you had an opportunity to pursue them in any other way?

**KEALOHA:** Only very briefly. With those types of individuals the amount of time that they have to dedicate to those kinds of conversations—or to you—is minimal. But in those limited interactions, yes, you talk about whatever is in the moment and sometimes it does revolve around what's going on in the world and how we can make this world a better place.

**RML:** I think of global climate change and those kinds of concerns. They are clearly of interest to you, and they also have a rather odd political twist in that there are people in politics who just don't believe there's a global climate issue. Somehow technologists have got to make it clear that there are indications of climate change that are irrefutable. This is an important topic that just doesn't get attention of the right character because some people deny it happens. If you look at our current presidential process you know what I'm talking about. To me it's an indication of the fact that if people don't understand—I don't mean just political candidates but I mean the person who is interested in your poetry or in the performing arts broadly or in baseball—if people don't understand that this is a major issue for the planet, I think it may be too late when they do. That troubles me because unfortunately I meet a lot of people who just don't seem to understand that there's an issue, and whatever I may do to try to convince them otherwise, it becomes almost a political battle.

*It's frustrating to see science politicized, especially important science that has to do with the future of human civilization.*

**KEALOHA:** It's frustrating to see science politicized in this fashion, especially such important science that has to do with the future of human civilization. You can apply the same sort of framing or argument to almost every piece of science knowledge over the past hundreds of years. It's always been met with some kind of opposition from the religious or politically or financially motivated.

In all those historical instances, the thing that "solved" them is time. After a number of years or generations, eventually the scientific principles that are controversial at the time become accepted.

It's really hard to change someone's paradigm. Imagine living your life under a paradigm that is all of a sudden upheaved because of a scientific piece of knowledge that says 'Hey, the way you've been thinking about the world or the universe is wrong and you need to think about it this way.'

**CHF:** Some people were up in arms when they found out Pluto wasn't a planet, and that was small potatoes.

**KEALOHA:** Exactly. Now we start talking about the big potatoes, like say evolution or global climate change—these things are a huge sack of potatoes that changes the whole dish. If given time, we'll see that narrative change. But with global climate change the time is very limited for us to make these changes.

I guess that's why the frustration increases, because if we can't convince our leaders and the people who put them in office, if we can't convince industry, like the oil companies, and they have a huge stake in preserving their way of life or their technologies—if we can't convince them all that it's time to make significant changes, it will be too late. We may not have the kind of time necessary for scientific principles to be accepted among the general populace.

**CHF:** Do you put some of these concerns and ways of thinking into your poetry?

**KEALOHA:** Absolutely. The whole focus of part of "The Story of Everything" was global climate change and the possibilities of how that might play out as well as the solutions that we have now. I go into things like fusion energy, solar and geothermal—all framed in the context of Michael Jackson. It was a weird way to do it but when I found it I just couldn't stop laughing.

The idea was that when we were in Africa we were like Michael Jackson during his "Thriller" album: we were black and strong. Then when we migrated into Asia and the Americas and the Pacific and started to lose our pigment and become more brown, we were like Michael Jackson during the "Bad" album. And then when we migrated into Europe and just became white, we were like Michael Jackson during the "Dangerous" album. Now we're all, collectively, like Michael Jackson right before his final "This Is It" concert series: The premise is that he overdosed on prescription drugs—he was addicted to those things just like we're addicted to fossil fuels. Fossil fuels are the drug that may bring us down.

In my show there're all these references to his songs and I'm dancing, doing Michael Jackson moves and singing his songs—it's all incorporated into the poetry and that helps move the story forward. Because my whole career has been based on trying to communicate really complex ideas in an entertaining way so that people can swallow the "medicine," like a gel capsule that allows you to take a little bit of medicine that will get into you.

**RML:** That's an interesting perspective. I'm also curious, do you have any communication with people in nuclear engineering at MIT today? Do you talk to Neil Todreas or Mike Driscoll or any of the faculty that you may have known during those years?

**KEALOHA:** No, I don't. That'd be really cool but I've not been connected to them or had the opportunity. But if there's a reason or mode to communicate with them that you're aware of that would be interesting for both them and me then I'm game. I don't want to waste someone's time.

**RML:** I understand what you're saying. But I'm sure they know of your career. You're a very young man and you've accomplished a lot in a very short period since leaving MIT. It might be a nice thing for you to come back and visit because I'm sure the faculty and students would enjoy having this kind of discussion with you.

**KEALOHA:** I would jump at that opportunity. I have so much love in my heart for that campus and what it gave me. If it worked out, maybe I could get my crew up there and we could put on the production in its full form; and if not I'm totally open to going there solo.

**RML:** I still have a relationship at MIT—I have an office there, and I see the people I've just mentioned on a regular basis. So if you don't mind, I would be delighted to bring that up with them because I think this would be a great thing for the students and faculty there.

**KEALOHA:** Oh wow, please do, that would be awesome.

**RML:** I will gladly do that.

**KEALOHA:** Cool, thank you.

**RML:** Well, I'm just so impressed. You really have, in a very short period of time, distinguished yourself in a number of remarkable ways. And this is precisely what we wanted to accomplish with the column that we've introduced in *The Bridge*: to say that engineers not only build engineering systems but also accomplish a lot that affects the culture of the nation and the world and you're a wonderful example of that.

Kealoha. Photo credit: Michael KSC Wong.

**KEALOHA:** Oh man, thank you so much.

**RML:** Let me ask, as we do at the end of each of our conversations, is there any message you'd like to pass on to the readers? In addition to the NAE members, *The Bridge* is distributed to members of Congress and their staff, as well as engineering deans of all the research universities. Is there anything you would like to convey to them?

**KEALOHA:** Sure. I'd like to think that we're all going to be alive for a long time, which means that we have plenty of time to become proficient in a number of extremely different disciplines if we so choose. For you scientists and engineers out there, I urge you to dabble in an art form or to get involved with politics (heck, run for office if you are inspired)! For you politicians out there, I urge you to dabble in a field of science and to truly understand the scientific method (including the difference between a hypothesis and a theory, because they are really, really different)! Not only will your lives be better off by doing so, but *our* collective world will be better off because the generations after us will live through the consequences of our decisions. And the more rounded we are in our thinking, the better those decisions will be.

**RML:** That's a wonderful message. And your comment about getting involved in politics echoes some of my own thoughts.

**CHF:** Would you be willing to share with us one of your poems for publication along with this interview?

**KEALOHA:** Oh yes, that would be awesome.

**RML:** Thank you once again. This has been an extraordinary conversation and I really appreciate it.

**KEALOHA:** Right on, thank you guys so much for your time as well. To have this conversation with you is an honor for me.

**RML:** Great. We appreciate that.

**CHF:** Yes, thank you.

**KEALOHA:** All right, take care, you guys.

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**Zoom Out**

tonight . . . i want you to think about your life

i want you to think about what you stand for and realize that all the suffering you've ever experienced means nothing in the long term
for every year you live, the universe will be around for trillions
and for every friend you've made, there are billions yet to be born that you will never meet
in the grand scheme of things, we are nobody
and yet at the same time, *we* are *everything*
we are X and Y chromosomes
we are G, C, A, and T genomes
we are complex carbohydrates, simple proteins, soft tissue, hard-wired neurons . . .
we are strong bonds linked in nervous systems
and while this earth's surface is covered with 65% saltwater,
*we* are walking bags made of 65% salt water
merely mimicking the environment that we evolved from

and when we are done, this flesh we call our own returns home to the sea when we dissipate . . .
evaporate into water vapor
and these bones . . .
these bones will be broken down by the roots of the tallest trees
while this earth, hurling through space, will freeze and boil as it has for eons as it orbits the sun
which in five billion years will transform into a red giant and scorch all life as we know it,
its last blast before it fizzles into a whimper remembered by nobody,
or maybe charted by aliens as they peer through telescopes
logging our sun as a piece of data that came and went
and these aliens, whoever they may or may not be
i want them to think about their lives
i want you to think about your life as you study me through your primitive telescopes
and i want everybody, the aliens, you, and me, to realize that even when our hearts break,
or when work sucks or when rent's due or when someone somewhere says something stupid about you
even in the face of homicide, genocide, and suicide
in the face of racism, sexism, classism, and insert-really-bad-word-here–ism
no matter how hard life may get for you or for other people,

zoom out

zoom out and realize that all the evil in this world is transient . . .
heck all the good in this world is transient . . .
you, me, all of us . . . are transient . . .

you will not be you in the grand scheme of things, which makes all your suffering trivial
which makes your ecstasy the only thing worth remembering as part of the universe
expressing itself in one giant orgasm known as the big bang
we are its aftermath sigh
its alibi for not having a reason
you are the universe learning about itself
you are the universe asking itself why it's here
you will soon be the universe *not* learning or asking anything
you are everything and nothing at the same time
and no matter how hard it is to admit, no matter how afraid we get and how much we want to deny the truth, the truth is . . . well the truth is we're gonna die
maybe not tonight, tomorrow, or next year
but sooner or later we're all gonna die

but the truth is hard to swallow,
and so we do everything we can to avoid the big picture because the big picture is paralyzing . . .
and so we focus our eyes on the day to day dramas of our lives . . .

but not tonight
tonight i want you to think about your life right here
not here, whatever county/state/country you happen to be in right now
but here . . . this world . . . planet Earth
here . . . this galaxy . . . this universe
we are not cavemen anymore
there are no saber tooth tigers lurking in the shadows
yet most of us cling to our fears like the animals we evolved from
what are we so afraid of?
we've been etching the same patterns in the same predictable places for years
why do we live the way that they tell us to?
and who the heck are they, anyway?
it's about time we start doing what's in our hearts because that's all we've really got
i want you to think about all the things you wish you could do
and tonight, i want you to do one of them
and tomorrow, another
our lives are temporary art pieces . . .
we are works in progress . . .
so i say paint your butt off . . .
use florescent yellows and reds in the places where there aren't any color
dance for the moment
sculpt your life out of soil and make the universe smile
be the expressive process that is humanity

tonight, i want you to think about your life
and tomorrow, i want you to live it


*www.KealohaPoetry.com*

# NAE News and Notes

## NAE Newsmakers

**Lillian C. Borrone**, retired assistant executive director, Port Authority of New York and New Jersey, was **inducted into the National Academy of Construction** on October 20 during the NAC Annual Meeting. The NAC recognizes those who have distinguished themselves through stellar careers and contributions to the engineering and construction industry

**Vinton G. Cerf**, Chief Internet Evangelist, Google Inc., known as the "father of the Internet" for his pioneering work in creating the basic networking protocols, will be honored by Elon University with its first **Imagining the Internet Areté Medallion**. Areté is a word used to describe people who live up to their fullest potential in a life embodying goodness and excellence. The award was established to recognize innovators, change agents, and thought leaders who have dedicated their lives to initiating and sustaining significant contributions that have positively impacted the global future.

**Ingrid Daubechies**, James B. Duke Professor of Mathematics, Duke University, has received the **Math + X Investigator Award** from the Simons Foundation, which comes with $1.5 million. She was chosen for her groundbreaking work on a mathematical tool that compresses images, a key to consumer communication products. The award provides research funds to professors at American and Canadian universities to encourage collaborations between mathematicians and researchers in other fields.

**Bruce R. Ellingwood**, professor, Colorado State University, was awarded the **2016 Freudenthal Medal** by the American Society of Civil Engineers for his unique role in introducing concepts of probability, statistics, and structural reliability to structural engineering and for transforming structural reliability from an academic research specialty to a mainstream structural engineering practice. The medal recognizes distinguished achievement in safety and reliability studies applicable to any branch of civil engineering.

**William D. Gropp**, Thomas M. Siebel Chair of Computer Science, University of Illinois at Urbana-Champaign, has been named the recipient of the **2016 ACM/IEEE Computer Society Ken Kennedy Award** for highly influential contributions to the programmability of high-performance parallel and distributed computers. The award was presented at the International Conference for High Performance Computing, Networking, Storage and Analysis, in November in Salt Lake City. In bestowing the award, ACM and IEEE also cited Dr. Gropp's outstanding service to the field.

**Preston A. Henne**, retired senior vice president, Programs, Engineering, and Test, Gulfstream Aerospace Corporation, is a recipient of the **2016 Wesley L. McDonald Distinguished Statesman of Aviation Award**. The award, established in 1954 by the board of directors of the National Aeronautic Association, honors "outstanding Americans who, by their efforts over an extended period of years, have made contributions of significant value to aeronautics and have reflected credit upon America and themselves."

**Anil K. Jain**, University Distinguished Professor, Michigan State University, was **inducted as a foreign fellow of the Indian National Academy of Engineering** (INAE) on November 1. Dr. Jain was chosen for demonstrated eminence and outstanding accomplishments in engineering and technology. Only five foreign fellows are elected each year by the INAE. It is one of the highest professional distinctions accorded to an engineer in India.

**Graeme J. Jameson**, Laureate Professor and director, Centre for Multiphase Processes, University of Newcastle, Australia, and **Ponisseril Somasundaran**, director, NSF/IUCR Center for Surfactants and La Von Duddleson Krumb Professor, Columbia University, have been honored as recipients of the **IMPC Lifetime Achievement Award** at the International Mineral Processing Congress in Quebec City. The award recognizes a lifetime of distinguished achievement and outstanding contribution to the advancement of the art, science, and industrial practice of mineral processing, together with participation in and contribution to the IMPC. Professor Jameson is renowned for his invention of the Jameson Cell, a revolutionary mineral processing technology installed around the world. Well over 300 Jameson Cells are now in operation across 25 countries, with the invention estimated to have earned nearly $100 billion for the Australian economy. Dr. Somasundaran's newest program is the Green Surfactant Initiative, which seeks to design greener surfactant systems for an environmentally conscious market.

**Louis J. Lanzerotti**, Distinguished Research Professor, Department of Physics, New Jersey Institute of Technology, and retired Distinguished Member, Technical Staff, Bell Laboratories, Alcatel Lucent, has been selected for the **2016 William Kaula Award** by the American Geophysical Union. The award is given in recognition for "unselfish service to the scientific community through extraordinary dedication to and exceptional efforts on behalf of the Union's publications program." The award will be presented on December 14 at the AGU fall meeting in San Francisco.

**Cato T. Laurencin**, University Professor and Albert & Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery, University of Connecticut Health Center, has been **elected a foreign fellow by the Indian National Academy of Engineering** (INAE) for his outstanding accomplishments bridging engineering and medicine. His election makes Dr. Laurencin the first American-born scientist to be elected to both INAE and the Indian National Academy of Sciences, to which he was elected a foreign member in 2015.

The Franklin Institute in Philadelphia announced that **Krzysztof Matyjaszewski**, J.C. Warner University Professor of Natural Science, Carnegie Mellon University, and Mitsuo Sawamoto, professor of polymer chemistry at the University of Kyoto, have won its **2017 Benjamin Franklin Medal in Chemistry**. They will receive the award on May 4, 2017, during a ceremony at the Franklin Institute. Drs. Matyjaszewski and Sawamoto were cited for their seminal contributions to the development of a new polymerization process involving metal catalysts. This powerful process affords unprecedented control of polymer composition and architecture, making possible new materials including improved composites, coatings, dispersants, and biomedical polymers.

**Perry L. McCarty**, Silas H. Palmer Professor Emeritus, Stanford University, has been **designated a Stanford Engineering Hero**. Stanford University started the program to honor the pragmatists and problem solvers who tend to focus on outcomes and solutions, so much so that their accomplishments are often overlooked. Dr. McCarty is one of 35 engineers thus honored since the program's establishment in 2010. Each honoree has affected everyday life in many ways and with varying degrees of visibility.

**Kwadwo Osseo-Asare**, professor of metallurgy and geoenvironmental engineering, Pennsylvania State University, was recently **inducted into the Brazilian Academy of Sciences** during a ceremony in Rio de Janeiro. He was cited for "pioneering contributions and developing fundamental understanding of the aqueous processing and application of materials."

**Rebecca R. Richards-Kortum**, Malcolm Gillis University Professor, Rice University, was named a **2016 MacArthur Fellow**. Commonly known as a genius grant, the prestigious fellowship comes with $625,000 paid over five years. MacArthur Fellows represent all disciplines and are chosen for "exceptional creativity, as demonstrated through a track record of significant achievement, and manifest promise for important future advances." Recipients are chosen from about 2,000 confidential nominations each year, and fewer than 1,000 MacArthur Fellowships have been awarded since the program began in 1981.

**Rodolfo R. Rodriguez**, chief scientific officer and founder, Advanced Animal Diagnostics, has been inducted into the **George Washington University School of Engineering and Applied Science Hall of Fame**. He joined 60 others who have been so honored since 2006, when the program was established to celebrate those who have made significant strides in engineering, technology, management, or public service. Dr. Rodriguez developed and/or patented several breakthrough products, including the first automated blood separator.

**Roger W. Sargent**, emeritus professor of chemical engineering, Imperial College London, received the **Sir Frank Whittle Medal** for outstanding and sustained achievement at the Royal Academy of Engineering's Annual General Meeting on September 8. The medal is awarded to an engineer resident in the United Kingdom whose sustained achievements have had a profound impact on their engineering discipline. Dr. Sargent has spent his career of over 60 years championing the application of mathematics and computing to solve engineering problems in the process industries. He received the medal for outstanding achievement over the 40 years since the inaugural meeting of the Academy of which he is a founding fellow.

**Bridget R. Scanlon**, senior research scientist, University of Texas at Austin, has received the National

Ground Water Association's **2016 M. King Hubbert Award** for major science contributions to the knowledge of groundwater. The award is presented to a person who has made a major science or engineering contribution to the groundwater industry through research, technical papers, teaching, and practical applications. The award was presented to Dr. Scanlon during NGWA's 2016 Groundwater Week in early December in Las Vegas.

**Eric E. Schmidt**, executive chair, Alphabet Inc., will receive Princeton University's top honor for alumni, the **Woodrow Wilson Award**, on February 25, 2017. The university bestows the award annually on an undergraduate alumnus or alumna whose career embodies the call to duty in Wilson's speech "Princeton in the Nation's Service." At Alphabet, Schmidt is responsible for the external matters of the holding company's businesses, including Google Inc., advising their CEOs and leadership on business and policy issues.

**Gurindar S. Sohi**, John P. Morgridge Professor and E. David Cronon Professor of Computer Sciences, University of Wisconsin, Madison, has received the **2016 B. Ramakrishna Rau Award**. He was cited for "pioneering techniques enabling instruction-level parallelism and speculative multithreading via cooperative resource scheduling between offline compiler and runtime microarchitecture elements." The award was presented at the MICRO-49 Conference in October in Taipei.

**Gregory Stephanopoulos**, Willard Henry Dow Professor of Chemical Engineering and Biotechnology at MIT, has been selected to receive the **Eric and Sheila Samson Prime Minister's Prize for Innovation in Alternative Fuels for Transportation**. Awarded by the prime minister of Israel and totaling $1 million, the Samson Prize is the world's largest monetary prize awarded in the field of alternative fuels. Dr. Stephanopoulos shares the honor with Mercouri G. Kanatzidis of Northwestern University. The two researchers are being honored for "their innovative scientific and technological contributions that have the potential to lead to the development of alternative fuels for transportation, replacing the fast-depleting fossil fuels that are the major fuels used nowadays in transportation."

**Howard A. Stone**, Donald R. Dixon '69 and Elizabeth W. Dixon Professor, Princeton University, has won the American Physical Society's **2016 Fluid Dynamics Prize**. The annual prize was established to recognize and encourage outstanding achievement in fluid dynamics research. The citation honors Stone for "seminal contributions to our understanding of low Reynolds number flows, microfluidics, interfacial phenomena, and biological fluid dynamics, and for his inspirational contributions to teaching and communicating the beauty and power of fluid mechanics, physics, and engineering."

The American Institute of Chemical Engineers has selected **Doros N. Theodorou**, professor of chemical engineering, National Technical University of Athens, as its **John M. Prausnitz AIChE Institute Lecturer for 2016**. Previously called the Institute Lecturer Award, it was renamed this year in honor of NAE member **John M. Prausnitz**, one of chemical engineering's most extraordinary leaders. Dr. Theodorou delivered the inaugural Prausnitz Institute Lecture on November 16 at AIChE's annual meeting in San Francisco.

The establishment of the **ASME Savio L-Y. Woo Translational Biomechanics Medal** was announced at the 2015 Summer Biomechanics, Bioengineering, and Biotransport Conference (SB3C). The medal celebrates Dr. Woo's impact on bioengineering and translational research and recognizes the significant contributions of bioengineers whose work has resulted in the development of a medical device or equipment, contributed to new approaches of disease treatment, or established new injury treatment modalities. The award—consisting of $1,000, a bronze medal, and certificate—is given to an active member of the ASME Bioengineering Division. The inaugural award was given to B. Barry Lieber, a professor in the department of neurosurgery at Stony Brook University and director of the CerebroVascular Center for Research, who was recognized for significantly advancing brain aneurysm treatment through the engineering and development of flow diversion technology.

[*Editor's note*: In 1998 **Savio L-Y. Woo** received the **Olympic Prize for Sports Science** from the International Olympic Committee at the Nagano Games in Japan. "His innovative use of computer modeling combined with robotics technology in studying joints and the effects of ligament injuries have helped define the beneficial effect of motion to the healing process" (PRNewsWire, Feb. 2, 1998). This honor was not reported in the *Bridge* at the time.]

The American Geosciences Institute has recognized **Mark D. Zoback**, Benjamin M. Page Professor, Geophysics, Stanford University, with the **AGI Award for Outstanding Contribution to Public Under-**

**standing of the Geosciences**. The award is presented to individuals or organizations for contributions that have led to a greater public understanding of the role of geosciences in the affairs of society. Dr. Zoback is recognized for contributions to rock physics and geomechanics.

ASM International honored several NAE members at its award dinner in Salt Lake City on October 25. **Diran Apelian**, Alcoa-Howmet Professor of Mechanical Engineering, Worcester Polytechnic Institute, was awarded the **ASM Gold Medal** for "his leadership and vision for establishing and executing a model for industry-university collaborative research, and for his pioneering work in metal processing." **David K. Matlock**, University Emeritus Professor and Armco Foundation Fogarty Professor, Colorado School of Mines, received the **Albert Easton White Distinguished Teacher Award** for "his accomplishments in materials education that have positively impacted generations of students and the research and industrial community over several decades." **Bhakta B. Rath**, associate director of research and head, Materials Science and Technology Directorate, Naval Research Laboratory, was honored with the **Medal for the Advancement of Research** for "leadership in promoting basic research and advanced exploratory developments in multidisciplinary fields of materials science and engineering and promoting technological innovation for commercial sector and for national security." **Alton D. Romig, Jr.**, NAE executive officer, was given **Honorary Membership in ASM International**, for "outstanding contributions to the science and technology of materials and their application to innovative research and development on defense systems."

## 2016 Annual Meeting

NAE members, foreign members, and guests gathered in Washington, DC, in October for the NAE annual meeting. It began on Saturday afternoon, October 8, with an orientation session for new members in the National Academy of Sciences (NAS) Building on Constitution Avenue. That evening a dinner with the NAE Council in the NAS Building Great Hall honored the 80 new members and 22 new foreign members.

NAE chair **Gordon R. England** opened the public session on Sunday, October 9, with brief remarks encouraging the new members to be actively engaged in NAE programs and activities. President **C. D. Mote, Jr.** then provided his annual address to the members and guests in a talk on "Mega-Engineering Initiatives and the Grand Challenges for Engineering." He noted that the theme for this year's meeting is mega-engineering, which is critical to our global engagement. (Please see www.nae.edu for text of the address.)

The induction of the NAE Class of 2016 followed President Mote's address, with introductions by NAE executive officer **Alton D. Romig, Jr**.

Class of 2016.

Anniversary members: front row, l to r: H. Norman Abramson (1976), Daniel Berg (1976), Odd M. Faltinsen (1991); back row, l to r: Charles Fairhurst (1991), Douglas W. Fuerstenau (1976), Morton M. Denn (1986).

The awards program started with the recognition of former NAS president (2005–2016) Ralph J. Cicerone as an NAE Distinguished Honoree. This unique recognition is awarded by decision of the NAE Council. Dr. Cicerone—only the fifth person to be thus recognized—was honored because, as NAS president, he rendered great service to the engineering profession in the United States and to the National Academy of Engineering through his deep understanding and appreciation of the interplay of science and engineering and their importance to the national welfare, as well as his lasting contribution in the formation and public presentation of the National Academies of Sciences, Engineering, and Medicine, a visionary and transformational statement of the balance of responsibilities and partnerships of the three national academies. (Sadly, Dr. Cicerone passed away on November 5; see page 77.)

The program continued with the presentation of the 2016 Founders and Bueche awards. The 2016 **Simon Ramo Founders Award** was presented to **Ruzena K. Bajcsy**, NEC Chair Professor of EECS and director emerita of CITRIS, University of California, Berkeley, "for seminal contributions to the fields of computer vision, robotics, and medical imaging, and technology and policy leadership in computer science education and research." **Henry T. Yang**, chancellor and professor of mechanical engineering, University of California, Santa Barbara, received the **Arthur M. Bueche Award** "for seminal research in aerospace, civil, and mechanical engineering; superb contributions to national science and technology policy; and enhancements to international technological development and cooperation."

The **Bernard M. Gordon Prize for Innovation in Engineering and Technology Education Lecture** featured the four 2016 winners: **Diran Apelian**, Alcoa-Howmet Professor of Engineering and founding director of the Metal Processing Institute at Worcester Polytechnic Institute (WPI); Arthur C. Heinricher, dean of undergraduate studies; Richard F. Vaz, director of the WPI Center for Project-Based Learning; and Kristin K. Wobbe, associate dean for undergraduate studies. The speaker, Richard Vaz, described the institute's project-based curriculum, the WPI Plan.

NAE chair Gordon R. England, former NAS president Ralph Cicerone, and NAE president C. D. Mote, Jr.

It engages students in real-world project work across all four years, both in and out of the major, and is centered on the demonstration of knowledge and skills through application to authentic problems both domestically and around the world.

All WPI undergraduates complete the following projects:

- A Humanities and Arts Project serving as the capstone to an 18 credit-hour requirement in these areas. Students choose an area for in-depth study, culminating in a 3 credit-hour practicum (creative work) or seminar project (original research) done under the supervision of a faculty member. The goal is to develop a lifelong interest in a particular area.
- An Interactive Qualifying Project, a 9 credit-hour research project tackling a problem related to social issues and human needs. Students from different disciplines work in small teams to tackle problems posed by nonprofit organizations, NGOs, and government agencies, under the direction of WPI faculty. The educational objectives include the development of research skills, communication, teamwork, problem solving, critical thinking, and understanding of the social and cultural contexts of science and technology.
- A Major Qualifying Project, a 9 credit-hour capstone in the major, which for engineering students involves either a design experience or a research experience. This project is completed in small teams, often for corporate sponsors. The educational objectives include application of major-specific knowledge to an authentic problem, communication, teamwork, and professional preparedness.

In addition:

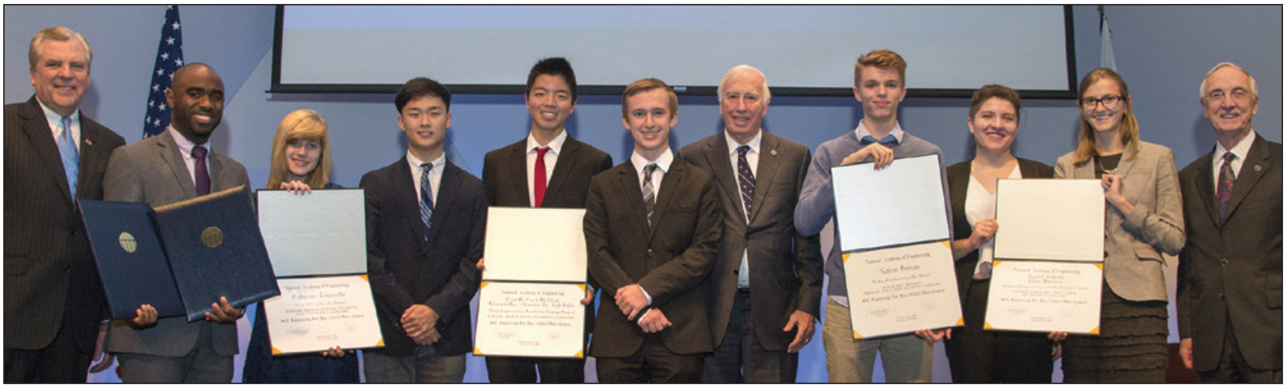
- Over 70 percent of all students complete at least one of these projects through full-time immersion at one of 50 project centers in Africa, the Americas, Asia/Pacific, and Europe through the WPI Global Projects Program. Faculty accompany cohorts of students to guide their work with local organizations on locally defined problems.
- Over 30 percent of all students complete a 6 credit-hour Great Problems Seminar in the first year, tackling a problem related to a Grand Challenge area such as energy, water, public health, sustainable development, or food systems, under the direction of a team of faculty from different areas of expertise. Learning objectives include research and communication skills, teamwork, and an understanding of issues through different disciplinary lenses.
- Courses both in and out of the major feature project work across all four years.

Vaz shared findings from a study in which WPI alumni attributed a wide range of professional skills and personal attributes to their project work at WPI. While all groups reported gains in areas such as leadership, communication, project management, and character development, women reported more positive benefits than men in 36 of 39 areas, consistent with research showing that women are highly motivated by collaborative work that can help others. Engineering majors and those who completed off-campus projects similarly reported greater benefits than other groups.

Vaz described the work done through the WPI Center on Project-Based Learning, which helps other colleges and universities advance project work in their curricula, and announced that proceeds from the Gordon Prize would be used to subsidize teams of engineering faculty to attend the center's 2017 Institute. In closing, Vaz noted that the class of 2020 has arrived on campuses around the nation, meaning that the "Engineers of 2020" will have experienced whatever curriculum is now in place at those campuses.

After a break, Dr. Mote introduced the plenary speakers who spoke of

C. D. Mote, Jr. with plenary speakers Rolf-Dieter Heuer, Gwynne Shotwell, and Robert J. Nicholls.



E4U3 video contest winners.

*Mega-Engineering Initiatives*. The first speaker was Gwynne Shotwell, president and COO of SpaceX, who gave "A Glimpse into the Future." Rolf-Dieter Heuer, former director general of the European Organization for Nuclear Research (CERN), spoke on "The Large Hadron Collider: A Project of Unimaginable Complexity—Particle Physics and Engineering at Its Best." And Robert J. Nicholls, professor of coastal engineering at the University of Southampton, discussed "Adaptation to Sea Level Rise," setting the stage for the next day's forum topic.

The program concluded with the presentation of the winners of the third Engineering for You Video Contest (E4U3), the theme of which was Mega Engineering. The public was asked to submit 1- to 2-minute videos introducing a particular mega-engineering project, highlighting its importance and contribution to people and society, and suggesting ways to develop it.

The **Best Video Overall Award** was given to Nehemiah Mabry for his video "Future Cities with Intelligent Infrastructure," which also won in the People's Choice category. The video was a poetic call to action for addressing the nation's crumbling infrastructure. A grand prize of $25,000 was awarded to


Forum panel and moderator.

Mabry in addition to the $5,000 People's Choice prize. Awards of $5,000 were given to the winners of the following categories:

- **Middle School and Younger Category Winner:** "Wave Wings for the Future" by Catherine Tomasello
- **High School Category Winner:** "The Ocean Cleanup Project" by Alexander Li, Kyle Fuller, and Leonardo Ko
- **Tertiary Education Category Winner:** "Systems Engineering and the Refugee Crisis" by Clara Stoesser and Rachel Andrade
- **Tertiary Education Honorable Mention:** "Engineering for You: Colonizing the Moon" by Nathan Benson

A judging committee chaired by **Rob Cook**, Pixar Animation Studios' emeritus vice president of advanced technology, selected the winning videos based on the following criteria: (1) creativity in the selection and presentation of content, (2) anticipated breadth of public appeal and interest, and (3) effectiveness in describing a mega-engineering project and its impact on people and society. The **People's Choice Award** was chosen by the public through voting on the NAE website. The day ended with a reception for members and their guests.

Monday began with the annual business session for members, during which Dr. Mote spoke about the NAE and answered questions. Next was the Forum, on "Adaptation to Sea Level Rise," in which a panel discussed the challenge and how mega-engineering solutions will improve the lives of people and society along the coasts. The panelists were Bart de Jong, Counselor for Infrastructure and the Environment, Royal Netherlands Embassy; Bret J. Muilenberg, Rear Admiral and Commander, Naval Facilities Engineering Command; Robert J. Nicholls, professor of coastal engineering, University of Southampton; David Pearce, Department Manager of Regional Engineering, Consolidated Edison; and Kathleen White, civil engineer, US Army Corps of Engineers. Ali Velshi, global affairs and economics journalist, moderated a discussion exploring the many questions surrounding the challenge of adapting to rising sea level and what might be the next steps. The video of the forum is 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 meeting concluded with a reception and dinner dance at the JW Marriott. After dinner the Capitol Steps entertained the guests with their political humor, and then dance music was provided by the Odyssey Band.

The next annual meeting is scheduled for October 8–9, 2017, in Washington, DC—*mark your calendars!*

## Remarks by NAE Chair Gordon R. England

Gordon R. England

Good morning and welcome. If we have not met, I am Gordon England, the new chair of the NAE, and it is my privilege and distinct honor to be with you today and to represent this important and impressive organization.

Let me start by saying *thank you*. Thanks to Chad Holliday for his four years of distinguished leadership as the prior chairman. From Chad, I have inherited a smoothly operating and effective Council and organization. Thanks also to Dan Mote, president of the NAE, for his leadership and for his energy and infectious enthusiasm in making the Engineering Grand Challenges the centerpiece for engineering around the globe. You will be hearing from Dan shortly. Thanks also to each of you for being here today and for helping to advance the mission of the NAE. A special welcome and congratulations to all the new inductees.

Today, I have an important message that involves each of you.

First, a few words about your membership. While it is a great honor and privilege to be a member of the NAE, and you have earned the respect and accolades of your coworkers, friends, and family, the Academy is not an honor society but rather a service organization—specifically for service to the nation.

Therefore, membership in the NAE carries with it a personal responsibility to serve, to make a difference to the nation and the world.

A few months ago in this building, Dan Mote and I heard a dinner speaker state that “the first person to live to be 150 years old has already been born.” Now that is admittedly a controversial projection and none of us will be around to know if that projection is true or not; unless of course one of us is that lucky person! But we do know that the average human life expectancy is increasing and that progress is largely due to the confluence of engineering, science, and medicine, with engineering as the foundation.

Consider that medical scientists use engineering know-how to make new discoveries at every level of inquiry. Medical professionals use engineering tools and instruments for diagnostics, while medical doctors use engineering-designed robots for surgery and a host of other designed equipment for treatments. Anyone here have a replacement knee, hip, or shoulder, a pacemaker, stent, or insulin pump, or are you using a mobility device? Literally, the foundation of almost every medical discovery, cure, and treatment is engineering based. Similar examples can be cited for almost every aspect of human endeavors.

I mention this because engineering is now so pervasive in every part of everyday life, and even in increasing life expectancy, that engineers need to be more involved in the societal consequences of their profession. For example, and as you well know, our economic system is ill prepared to deal with any modest increase in average life expectancy. Yet our politicians, and the economists and public policy advisors that surround them, are seemingly unaware of many important engineering advances taking place—and the consequences of those advances for society. The shifting job market is another example. It is my judgment that engineers need to be more involved and more influential at the state and national levels. It starts here, at the NAE.

More fundamentally, it starts with resources. The NAE receives no government appropriation. Rather, it receives about a third of its funding from NRC overhead recovery, a third from philanthropy, and a third from external project funding. The NAE is more dependent on philanthropy than the great majority of universities and cannot function without it. Dan Mote and I will continue to solicit funding from corporations and foundations, but you the membership need to do your part.

Dan and I have a common objective: Increase the promotion and expansion of the Grand Challenges for Engineering and the Grand Challenges Scholars Program. Further, we will strive to make the NAE more relevant and influential at the national decision-making level. However, the Academy can only do what it can afford to do and presently there is no financial margin to do more. Therefore, my goal during my tenure as chair is to provide sustainable funding for the Academy as the means to continuously improve the engineering profession and the standing of the profession in the world. Engineering is changing society and this organization needs to be a leader in that change.

I am a member of Section 1, Aerospace Engineering. As an incentive for Section 1 members to more fully support the Academy, I am today creating a personal, unrestricted $100K matching challenge grant. All contributions from Section 1 members to the Academy between now and the next annual meeting will be matched by me, up to $100K. Section 1 has a large and highly successful membership so I expect that your contributions will far exceed the matching amount.

I am also asking for someone in each of the other sections to establish a matching challenge grant for an amount of their choosing, and for the membership of each section to then respond to the very best of their ability. Thanks to Fran and George Ligler who have already stepped forward with a $100K challenge grant for Section 2. We need to hear from the other sections.

Money is always a difficult subject to address but it is the oil that keeps the machinery running. This is a challenging time for countries and for peoples around the globe and engineering can play an ever important role in improving the well-being and security of all the world’s citizens. Each of us is extraordinarily fortunate to be at the peak of our careers. With that good fortune comes responsibility and the Academy needs your help.

Thank you for your service to the engineering profession and for your commitment to the National Academy of Engineering. Last, thank you for the courtesy of your attention and for your consideration of the fundraising matching grant proposal. Have an enjoyable, pleasant, and productive time at the annual meeting.

# Mega-Engineering Initiatives and the Grand Challenges for Engineering: Remarks by NAE President C. D. Mote, Jr.

C. D. Mote, Jr.

## Welcome

It is my privilege to welcome all our members, foreign members, and friends to this year's annual meeting of the National Academy of Engineering. I extend an especially warm welcome to our newly elected members and foreign members and can assure you that this induction day, just like last evening's dinner, will be one you will remember. And I would be remiss in not extending a special welcome to all the spouses who so graciously support our service to the academy.

Today, I will divide my remarks between the themes of the meeting, *mega-engineering initiatives* and the academy's *Grand Challenges for Engineering*, which is a mega-engineering initiative too.

## Mega-Engineering Initiatives

People have long been inspired by mega-engineering initiatives, whether they involve landing humans on Mars, identifying subatomic particles, or protecting the planet from natural disasters. Mega-engineering initiatives extend the bounds of human capabilities and the services they provide to society. Importantly, they not only solve problems of great importance but also define new limits that become the technical "records to be broken" in the minds of the public and coming generations of engineers, scientists, and others who are dedicated to advancing our world.

This dual role of mega-engineering initiatives through solutions delivered and those inspired has advanced societies throughout history. Countries have relied on this dual role to enhance their national capabilities, advance their competitive strengths, and set their vision and goals for advancements. There was an outpouring of national pride when Neil Armstrong first walked on the moon, when Charles Lindbergh first solo-piloted an aircraft across the Atlantic, or others erected the tallest building in the world, or created a global communications network allowing everybody to talk to everybody.

Mega-engineering deserves recognition because it shapes our future just as it has our past. Accordingly, public understanding of engineering requires that mega-engineering initiatives be seen as engineering—as creating solutions to problems of people and society. In public reflections on these initiatives, I am puzzled frequently by the absence of appropriate recognition given to the engineering that created them, even though it is usually remarkable and unique.

## Plenary Lectures

Today we have three plenary lectures on distinctly different mega-engineering initiatives spanning domains from inside the atom to across the seven seas to human life outside of this world. Ms. Gwynne Shotwell, a mechanical engineer and president and chief operating officer of SpaceX, will speak on the engineering challenges in the SpaceX human mission to Mars. Professor Rolf-Dieter Heuer, a particle physicist and former director general of the European Organization for Nuclear Research (CERN), will speak on the role of engineering in the design and development of, and the conduct of experiments on, the Large Hadron Collider, which revealed the Higgs boson. And Professor Robert J. Nicholls, Faculty of Engineering and the Environment at Southampton University, will speak on the coastal engineering challenges in adapting to sea level rise that are beginning to transform life on the planet. We are fortunate to have these distinguished experts speak to us today, and I thank the many friends who assisted with their recruitment.

## Engineering for You: 3rd Video Competition (E4U3)

Not surprisingly, the academy's third annual video competition has a mega-engineering theme too. The prize-winning 2-minute videos will be shown interspersed in today's program. The winners are the Grand Prize video, meriting a $25,000 award, plus videos in the following categories that will receive $5,000 each: middle school, secondary, and tertiary school students, and the people's choice. The awards and the Grand Prize video will be presented at the end of today's program. We thank ExxonMobil for its generous financial support of the video competition and for its participation on the prize selection committee, which was chaired for the third time by NAE member **Robert L. Cook**.

### Forum: Adaptation to Sea Level Rise

Continuing the theme of mega-engineering initiatives, the 3-hour forum scheduled for tomorrow morning brings together an international panel of experts to address problems posed by sea level rise in different sectors of society: Mr. Bart de Jong, Counselor for Infrastructure and the Environment, Royal Netherlands Embassy; Mr. David Pearce, Consolidated Edison; Adm. Bret J. Muilenburg, Commander, Naval Facilities Engineering Command; Dr. Kathleen D. White, Team Lead of the Institute for Water Resources, Climate and Global Change, US Army Corps of Engineers; and Dr. Robert J. Nicholls, Professor of Coastal Engineering, Faculty of Engineering and the Environment, Southampton University. There will be opportunity for the audience to pose questions to the panel, moderated by Mr. Ali Velshi, journalist and frequent moderator of academy panels.

### The Grand Challenges for Engineering

Now I wish to speak about our academy-initiated initiative. Such initiatives are distinct from requests for counsel from government agencies or others, which comprise the great majority of the academy's studies in its capacity as an advisory organization. However, the academy can initiate actions too, as it did with the Grand Challenges for Engineering in 2008. To justify the significant academy focus needed to develop a particular initiative, the initiative must (1) have high potential value to the nation, (2) have the potential for transformational impact when it succeeds, and (3) be appropriate for leadership by the academy. Choices are constrained to those that meet these conditions. The focus for an academy initiative today must also serve the NAE's five-year strategic plan goals introduced at the 2015 annual meeting:

1. **Membership representation**—Increase representation in the NAE among business, female, younger, foreign, and underrepresented members
2. **Industry collaboration**—Increase the value of the NAE to industry
3. **Public understanding**—Demonstrate to the public how engineering creates a better quality of life
4. **Ensuring engineering talent**—Promote and inspire highly competitive engineering talent in the workforce
5. **Global engagement**—Engage globally in support of national interests
6. **Effective advising**—Enhance the effectiveness of advice to the nation.

The span of these goals embraces the academy organization and initiatives. Goal 1 primarily addresses the NAE organization, while the others guide expectations of academy initiatives during this 5-year period.

The *Grand Challenges for Engineering*, including the *Grand Challenges Scholars Program* and the *Global Grand Challenges Summits*, which I will describe in a moment, provide the right focus for an academy initiative that addresses goals 2–5 and meet the standards for an academy initiative. Because we are increasing attention to them, allow me to summarize briefly the Grand Challenges for Engineering and our related initiatives.

In 2008 an international expert committee convened by the NAE published a report, called *Grand Challenges for Engineering*, presenting its vision for what engineering needs to accomplish for life on the planet to continue in this century, and the goals that must be satisfied to achieve that vision.

The vision is **"Continuation of life on the planet, making our world more sustainable, safe, healthy, and joyous."**

The goals are the **Grand Challenges for Engineering**.[1]

Many, if not most, of you have heard about the Grand Challenges for Engineering. Satisfaction of all of the 14 Grand Challenges over the planet is required for achievement of the vision. If one or more of the challenges is not satisfied, the vision as presented above may not be realized unless a compensatory goal is created.

The vision underpinned by the Grand Challenges is the first

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[1] The 14 goals are: 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; Engineer the tools of scientific discovery.

engineering vision for the planet that mandates global perspectives. It cannot be delivered by a few nations, though a few nations can inspire attention to it. It is greater than a university vision, a company vision, or a national vision. Each Grand Challenge needs to be achieved in all global locales and circumstances. For instance, the challenge to *Provide access to clean water* is for everyone alive today and for those yet to be born in this century, including those with contaminated water and those with no water at all. Each challenge is to be fulfilled globally through solutions as needed locally.

Because the vision is about life for all, this is a rare circumstance where people everywhere, across diverse cultures and countries, share in the importance of the Grand Challenges. Communities the world over see their interests and national needs in the Grand Challenges for Engineering, a rare circumstance indeed.

The approaches to solution of the Grand Challenges fall into two groups: An *initiative group* seeks contributions to the solution(s) of one or more of the Grand Challenges, and a *talent group* seeks to prepare a workforce to address global problems like these Grand Challenges. These two groups will play collaborative roles in achievement of the vision. To varying degrees Initiative Group attention is currently being paid to the Grand Challenges in the private sector and government. Targeted efforts with special facilities and substantial financial support particularly stand out. For instance, the challenge of the Obama administration to revolutionize understanding of the brain, as described in a press release when the Brain Initiative was launched in 2013, will contribute substantially to addressing the Grand Challenge to *Reverse-engineer the brain*. It received $300 million in federal support this year. The need to develop the Talent Group at scale led to the creation of the *Grand Challenges Scholars Program*.

## Grand Challenges Scholars Program

In 2009 deans of engineering Thomas Katsouleas, then at Duke University, **Yannis Yortsos** at USC, and President **Richard Miller** of Franklin W. Olin College of Engineering created a brilliant program to prepare talent among students in *every country and culture* to undertake problems like the Grand Challenges. Their program requires student competency in five areas not normally found in engineering curriculums to prepare them for Grand Challenge–like problems while providing maximum local flexibility in program design. Each university determines how, and whether, its program students sufficiently achieve these five competencies through their program and experiences. The competencies may be part of the regular academic curriculum or may be arranged otherwise as determined by each student and university. The five competencies are:

1. **Research/creative**—Mentored research or project experience related to a Grand Challenge to enhance technical competence
2. **Multidisciplinary**—Understanding gained through experience of the multidisciplinary character of implementable and viable Grand Challenge solutions
3. **Business/entrepreneurship**—Understanding gained through experience that viable business models are necessary for successful implementation of Grand Challenge solutions
4. **Multicultural**—Understanding gained through experience that serious consideration of cultural issues is mandatory for all viable Grand Challenge solutions
5. **Social consciousness**—Deepened social consciousness and motivation to address societal problems, often gained through service learning, because serving people is the vision served by the Grand Challenges

Student engagement is invaluable to achieving the competencies. As Confucius noted in his Analects 25 centuries ago, "I hear and I forget, I read and I remember, I do and I understand." The Grand Challenges Scholars Program is about "doing."

In 2015 more than 100 deans of engineering—about 1/3 of all engineering deans in the US—signed a letter to President Obama committing to graduate 20,000 Grand Challenges Scholars within 10 years. The number of committed US deans has increased since then. And Grand Challenges Scholars Programs are under way in Australia, Botswana, China, Egypt, Hong Kong, India, Kuwait, Malaysia, and Singapore too. In June of this year I presented a plenary lecture on the program to the annual meeting of the Chinese Academy of Engineering to inspire it to join the NAE in promotion of the Grand Challenges Scholars Program globally. I received positive responses about it. Next month I will present the program in a plenary address to 1,500 deans of engineering and others from 70 countries at the annual meeting of the World Engineering

Education Forum and the Global Engineering Deans Council in Seoul, to further expand interest in the program globally. In short, interest in the Grand Challenges Scholars Program is increasing nationally and internationally at an accelerating rate.

The attractiveness of the program and its expansion nationally and globally have been driven at the grass-roots level without a centralized organization or financial backing. The support of the academy has been instrumental during this period. But national and global expansion calls for coordination of these grass-roots efforts to support and facilitate the development of existing and new programs, to memorialize and benefit from successful program designs, and to document the influence of the program on its scholars' interests and careers. This central coordination, data- and information-sharing phase of the program development and evaluation is just under way at the NAE. It will be important for this program and for assessing its value to engineering education.

## 3rd Global Grand Challenges Summit

The Chinese Academy of Engineering, the Royal Academy of Engineering, and the US National Academy of Engineering cosponsored Global Grand Challenges Summits in London in 2013 and in Beijing in 2015, and the third summit, led by the NAE, is scheduled for Washington, DC, next summer, July 18–20, 2017. These summits inspire the vision of the Grand Challenges and highlight the progress on them to the global communities. Plenary speakers present advances on the challenges to date and student business plan competitions stimulate the next generation's interest in the Grand Challenges. At the 2017 summit we're planning for 800 attendees from China, the UK, and the US, with about half of them students from the three countries.

An additional feature that will immediately precede next year's summit is the inaugural FIRST Global Invitational robotics competition—FIRST, founded by Dean Kamen in 1989, stands for *For Inspiration and Recognition of Science and Technology*. This competition is for young people ages 14 to 18 along with their parents, schools, and mentors, and the goal for the international robotics teams will relate to the Grand Challenges for Engineering. This will be the first reach of the Grand Challenges into this younger, large, global population. Engaging the interest of young people and their communities in the Grand Challenges is important to inspire the future talent needed for their solution and for engineering generally.

## Concluding Thoughts

The Grand Challenges Scholars Program aligns with the goals of the NAE five-year strategic plan and it also prepares talent for today's engineering system problems. At the same time, the Grand Challenges are global goals to deliver the vision of "Continuation of life on the planet, making our world more sustainable, safe, healthy, and joyous." Consequently, the leadership of other national academies and organizations is needed to cultivate contributions to and engagement in the Grand Challenges in their locales.

The Grand Challenges for Engineering has the structure of a movement more than a project, where inspiration is driven by the power of the idea while the decisions to contribute are made locally and independently. There is no central authority or financial support. Time will tell how far the idea of the Grand Challenges can propagate, but in the meantime, after eight years, attention continues to grow in a direction that can reshape engineering education and mean more to engineering than do the Grand Challenges themselves.

Thank you for your support of the academy as it moves along this transformational path. I hope that you approve of the spirit of this mission and are inspired by the importance and global sweep of this adventure.

# 2016 Simon Ramo Founders Award: Acceptance Remarks by Ruzena K. Bajcsy

NAE chair Gordon R. England, Simon Ramo Founders Award recipient Ruzena K. Bajcsy, NAE president C. D. Mote, Jr., and Cato T. Laurencin, 2016 NAE Awards Committee chair.

*The 2016 Simon Ramo Founders Award was presented to Ruzena K. Bajcsy, NEC Chair Professor of EECS and director emerita of CITRIS, University of California, Berkeley, "for seminal contributions to the fields of computer vision, robotics, and medical imaging, and technology and policy leadership in computer science education and research."*

First I want to thank my nominator for nominating me for this distinguished award, and the award committee for bestowing it upon me.

Second I want to thank my immediate family and my extended family for their love and support. They give me the peace and comfort that enable me to work and pursue what I love most, which is science and engineering.

I was born in 1933 in Bratislava, which at that time was in Czechoslovakia. My birth certificate says gender: girl, religion: Jewish. This was the year Hitler was elected chancellor of Germany.

I experienced the fear of the Nazis, though my family was not religious. In fact in 1938 my family converted to the Catholic faith, though this did not save them. My parents and all my close and distant family members were executed either in Auschwitz or in local graveyards in Slovakia. I survived because of some good Slovaks who were willing to hide me. War brings out the best and the worst in people.

In 1948 Czechoslovakia became Communist and I experienced the Stalin dictatorship and oppression again.

All these experiences made me who I am today. They taught me that while I love mathematics, engineering, and science in general, the most important thing in life is caring for people. I made it my life mission to create the best possible environments I know how for colleagues and students to do the best science they can. This is what I tried to do at the University of Pennsylvania, establishing the GRASP Lab, and what I continue to do at UC Berkeley.

All my life I worked on robotics with the aim and belief that robots can help people. In 1972 when I began my career at UPenn, it was very clear to me that I would not be able to compete with MIT (where **Marvin Minsky** headed the AI lab), Stanford (where **John McCarthy** headed the AI lab), and CMU (where **Allen Newell** and Herbert Simon headed the lab) unless I was creative.

Motivated by psychologist J.J. Gibson, I started to develop the engineering version of active perception, which connected data acquisition, signal processing, and control theory. I said, We not only see but we look, and we don't only touch but we feel. This opened a very new direction in robotics and offered many opportunities to be creative for my colleagues and students. This was the genesis of the GRASP Laboratory—GRASP stands for General Robotics, Automation, Sensing & Perception. I am happy to say that today it is flourishing and has grown to 100+ members from the computer science, electrical engineering, and mechanical engineering departments and others.

In 1999 I moved to NSF as director of Computer & Information Science & Engineering, again in the spirit of serving the computer science and engineering community. In 2001 I went to UC Berkeley as the founding director of the newly formed Center for Information Technology Research in the Interest of Society (CITRIS). Again the main force for me to take this position was the use of science and technology in service to society. After 3 years, I stepped down and became a regular professor, teaching robotics to both undergraduate and graduate students.

My current research area is using system identification methods for a measurement and computational platform to create kinematic and dynamic models for individuals to predict their physical abilities. Once we can assess individual physical abilities, we can design assistive devices. The challenge in this work is to find cost-effective, noninvasive measurement devices that can tell us how strong or weak an individual's muscle, tendons, and bone structures are.

It is very gratifying to me to see how achievements in science and technology can help people, not only in health care but also in restoring cultural heritage, disseminating knowledge to places that are hard to reach, monitoring, making transportation accessible, and many other ways.

I am lucky that I have my health and have lived to see all the advances that my generation only dreamt about. I am lucky to witness it, and in my small way I still can contribute to it.

## 2016 Arthur M. Bueche Award: Acceptance Remarks by Henry T. Yang


NAE chair Gordon R. England, Arthur M. Bueche Award recipient Henry T. Yang, NAE president C. D. Mote, Jr., and Cato T. Laurencin, 2016 NAE Awards Committee chair.

*Henry T. Yang, chancellor and professor of mechanical engineering, University of California, Santa Barbara, received the 2016 Arthur M. Bueche Award "for seminal research in aerospace, civil, and mechanical engineering; superb contributions to national science and technology policy; and enhancements to international technological development and cooperation."*

Thank you all. Thank you very much.

I am honored to be here this afternoon, among my engineering colleagues and friends, to accept this award. I could not have dreamed up a more rewarding way to celebrate my 25th anniversary as a member of the NAE. I am genuinely humbled that this esteemed group has chosen to recognize me, because every one of my accomplished NAE peers is deserving of the same.

As I reflect on this memorable moment, I am reminded of the people and experiences that have influenced my life and career.

Let me trace back to my early career, beginning with my appointment as assistant professor in the School of Aeronautics and Astronautics at Purdue University—right around the time the Boilermakers won the Rose Bowl and our alumnus **Neil Armstrong** landed on the moon. I was honored to become the dean of engineering after 15 years, while also holding the Neil Armstrong Distinguished Professorship.

One of my first challenges as dean was inviting visionary leaders, who have very busy schedules, to serve on my visiting committee. I went to Neil Armstrong for help and, to my surprise, he agreed to serve—he served during my entire tenure of a decade. When the committee roster started with the name Neil A. Armstrong, it seemed easier to convince other prominent members to join!

An original thinker, visionary leader, and, of course, an NAE member, Neil's wisdom and guidance helped define a fundamental core value of engineering education, research, and service for the next century and beyond.

And he always added an unassuming touch of humor. Upon arriving at one of our meetings, we saw him step out of a passenger van into the snow—backward! He responded to our questioning looks with a chuckle, saying, "As you know, I had a lot of practice on this." This was his "small step."

At the time, he was living on his farm near Cincinnati. The farm had a landing strip so he could keep up with his hobby flying his Beech Bonanza and later his Cessna 310. And, no doubt fascinated by the moon, he used the *Old Farmer's Almanac*—a lunar calendar.

Neil rarely agreed to public speaking engagements, so I was honored when he traveled to UC Santa Barbara for my inauguration as the new chancellor, 21 years ago. He spoke with sincerity and conviction about breaking boundaries, stretching the human perspective, and the importance of strength of character.

Just as Neil Armstrong has inspired me, every one of you is an inspiration to our engineering community and our future engineers. Together, we have made remarkable progress in science and technology, and witnessed its contributions to society in the interest of humanity.

### Evolution of Engineering in Our Time

Now, as I take in the collective brilliance represented in this room, I see more than a few faces from my generation. Some of you probably remember being college students in the '60s.

I still remember using a slide rule, which we carried on our belts around campus. We later encountered a mechanical calculator. We had to wait for this mechanical machine to crank out numbers, with far more consecutive digits than the slide rule. Then there was the electronic calculator.

I remember my first experience using the IBM 1620 computer. We carried boxes of cards, punched holes, fed these into a reader, and waited for the printout. I remember sending my first fax across the Pacific in 1985. And not until 1989 did I have the amazing experience of sending my first email and receiving an instant reply.

It wasn't until the year 2000 that I first used a cell phone. My students now seem to think that cell phones and email have always existed—and they certainly have never seen, or even heard of, a slide rule!

Over the past decades, we see that there were hundreds, or even thousands, of technological breakthroughs. And paving the way centuries earlier were our US patent laws of 1790, which, according to President Lincoln, "added the fuel of interest to the fire of genius, in the discovery and production of new and useful things."

At the heart of each was an engineer. Theodore von Kármán said: "Scientists discover the world that exists; engineers create the world that never was." Royal Society president Sir George Porter once said, "There are only two kinds of science: applied and not-yet-applied."

And this is our life's work—not only making basic discoveries, but taking basic research and building once-inconceivable technologies.

### Chancellorship: Retention and Recruitment of Talents

As chancellor of UC Santa Barbara for over two decades, there are many experiences and perspectives I could share. But allow me to focus on just one important aspect: the retention and recruitment of talents.

I am honored and fortunate to serve on a campus where six colleagues have won Nobel Prizes during my tenure. I humbly offer, as examples, two of my engineering faculty colleagues, both proud NAE members.

Let's go back 40 years to 1976, when **Herbert Kroemer** joined the faculty at UC Santa Barbara, before my time. Professor Kroemer decided to focus not on silicon semiconductors but rather gallium-nitride, a semiconductor material that was "notoriously difficult" to use. Decades later, he was awarded the Nobel Prize in Physics "for developing semiconductor heterostructures used in high-speed and optoelectronics."

His original vision was, and has been, upheld by our university with unwavering support. Supporting such vision and creating an intellectual environment are two of the most important ingredients for retention and recruitment.

Professor Kroemer's work, first proposed in 1963, is the foundation of the blue laser and LED's efficiency in converting electricity into light. He said in his Nobel acceptance speech that his original paper was rejected, ignored, refused—rejected by *Applied Physics Letters*; ignored once published in the *Proceedings of the IEEE*; and finally, he was refused resources to develop this new laser.

About 30 years after submitting that paper, while at a conference in Berlin in 1996, Professor Kroemer witnessed what he said was "the beginning of the end of the lightbulb" when a young engineer from Japan, **Shuji Nakamura**, demonstrated his bright blue laser.

Kroemer later said, "We are not talking about doing things better, but about doing things we never could before."

In the quest for talent, we went to Japan to recruit Dr. Nakamura to our faculty. As I'm sure you all agree, when it comes to the recruitment of talent, there are no borders.

Just one year later, Professor Kroemer won his Nobel in 2000. Then we wondered, would Professor Nakamura ever get a Nobel for his invention?

As we know, it is not very common to receive a Nobel Prize for invention. Even Thomas Edison did not win a Nobel. I have heard that, for invention, one needs to demonstrate a richness of consequences. And what would that look like for the blue laser and LED?

Professor Kroemer predicted, "Nakamura will win his Nobel when LEDs are sold in Costco." In 2013, when I saw the shelves of Costco stocked with LED lightbulbs, I knew the time had come. The following year, Professor Nakamura received his Nobel Prize in Physics: for an invention with a richness of consequences—for our field, for our economy, and for our world—through affordable, energy-efficient lighting.

This is our calling and contribution as engineers—to create endless innovations at the endless frontiers of science.

Today, I am honored to stand among you, the world's most accomplished engineers, as part of a prestigious academy that has played a revolutionary role in shaping our nation's education, technology, policy, and economy over the five decades since the NAE's founding in 1964.

And looking ahead, the NAE is leading the way to overcome the challenges of our future and uphold our country's long-standing scientific leadership in an increasingly collaborative, competitive, globalized world.

I am honored to thank the NAE for this award. Thank you!

## NAE Chairman's Challenge

Gordon R. England

At this year's annual meeting, **Gordon England**, the new NAE chairman, announced that he is personally funding a $100,000 matching gift challenge for his section, Section 1, and he encouraged others to do the same for their sections.

As he stated in his opening remarks, his goal as chair is to provide sustainable funding for the academy as the means to continuously improve the engineering profession and the standing of the profession in the world. The NAE and its members are uniquely situated to foster the growing momentum of the Grand Challenges for Engineering to tackle major issues and inspire students to pursue engineering. "While it is a great honor and privilege to be a member of the NAE, and you have earned the respect and accolades of your coworkers, friends, and family," Mr. England explained, "the academy is not an honor society but rather a service organization—specifically for service to the nation."

The NAE cannot provide that service if it is not adequately funded. It receives no government appropriation for its operations and about a third of its funding comes from philanthropy. The NAE is more dependent on philanthropy than the great majority of universities and cannot function without it.

Chairman England has asked all NAE sections to join him in his efforts and create matching gift challenges for an amount of their choosing for their section. Several sections have already stepped up. Section 2's $100,000 matching gift challenge was launched by George and **Fran Ligler** in 2014, and **James J. Truchard** was moved to create a $100,000 challenge to match gifts/pledges for members of Section 7 after hearing Mr. England's remarks. In addition, **Sanjit K. Mitra** and his family are funding a $100,000 challenge for newer members—those elected in 2013, 2014, 2015, and 2016—to encourage their lifelong commitment and support of the academy.

Contact Radka Nebesky, NAE director of development, at 202.334.3417 or RNebesky@nae.edu if you are interested in initiating a challenge or for more information on ways to make a gift, or visit our website (www.nae.edu/giving). We will communicate new challenges to the appropriate section members and post them on the website.

## 2016 Golden Bridge Society Dinner

On Sunday, October 9, NAE president **C. D. Mote, Jr.** and his wife Patsy hosted an intimate dinner honoring NAE's most generous members and friends at the Smithsonian Castle, a historic building on the National Mall. Completed in 1855, the Castle was the first Smithsonian building, designed by architect James Renwick, Jr. The elegant building housed all aspects of Smithsonian operations—research, administration, lecture and exhibit halls, library, laboratories, collections storage, and living quarters for the secretary until 1881. Today, the Castle houses administrative offices and the Smithsonian Visitor Center. Walt Ennaco, deputy of the Smithsonian's Office of Facilities Engineering and Operations, provided brief remarks on the building's history.

The Sunday 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—as well as our newest, the Loyalty Society. The Einstein Society celebrates donors who have made commitments of $100,000 or more during their lifetime. The Golden Bridge Society recognizes donors who have given or pledged between $20,000 and $99,999 over their lifetime. The Heritage Society recognizes members who have included the NAE in their estate plans or made some type of planned gift to the academies, and the Loyalty Society, created in 2014, recognizes donors who have made gifts to the academies for at least 20 years.

This year eight new members/couples were welcomed in the Golden Bridge Society and the following were in attendance at the dinner: **Nadine Aubry** ('11) and her husband John Batton, **Paul Boulos** ('14), **Tom** and Bettie **Deen** ('98), **Doug** and Peggy **Fuerstenau** ('76), **Claire L. Parkinson** ('09), and **Bob** and Mary **Schafrik** ('13).

Mary Kay Friend, wife of **William L. Friend** ('93), was on hand to receive the Heritage Society Medal on behalf of her and Bill. Unfortunately, Bill was unable to attend the dinner.

We also had the honor of presenting three new Einstein Society statuettes as a token of the NAE's gratitude to **Dan** ('76) and Frances **Berg**, **Wayne** ('90) and Anne **Clough**, and **Jim Ellis** ('13) and **Elisabeth Paté-Cornell** ('95).

This was the first time our Loyalty Society members were invited to the dinner, and we had the pleasure of thanking 10 donors/couples for their steadfast support over the years, including **Norman** ('76) and Idelle **Abramson**; Tina Bueche, who is also a member of the Golden Bridge and Heritage Societies; Virginia Bugliarello, who is also a member of the Einstein Society; Marilyn Forney, also an Einstein and Heritage Society member; **Anita K. Jones** ('94), also an Einstein and Heritage Society member; **Bob** ('71) and Lila **Loewy**; **William Schowalter** ('82); and Mavis White, also an Einstein Society member.

Dr. Mote expressed his deep appreciation to all members and friends who support and invest in the NAE and its programs. If you have any questions or would like to make a gift to reach the Einstein, Golden Bridge, Heritage, or Loyalty Societies, please contact Radka Nebesky, NAE director of development, at 202.334.3417 or RNebesky@nae.edu.

### NAE Estate Planning Session during Annual Meeting

On Sunday morning, Jamie Killorin, CPA/PFS, CFP®, director of gift planning for the National Academies, presented the estate planning session for NAE members and guests over a delicious brunch. During this interactive discussion, participants learned why the changing environment requires looking at estate and tax planning in a new way, and learned the best three planning tips for 2016. For the fifth consecutive year, the planning brunch was a popular way to start an engaging day of NAE awards and public programs. If you would like the planning tips or information about the topics of this year's session, please contact Jamie Killorin at JKillorin@nae.edu.


Golden Bridge Society dinner at the Smithsonian Castle.

## 2016 US Frontiers of Engineering Held at Beckman Center

US FOE attendees network at the meeting.

On September 19–21, 2016, the NAE held the annual US Frontiers of Engineering symposium at the Beckman Center in Irvine. NAE member **Robert D. Braun**, professor in the Department of Aerospace Engineering Sciences at the University of Colorado Boulder, chaired the organizing committee and the symposium. The sessions were Pixels at Scale: High-Performance Computer Graphics and Vision; Extreme Engineering: Extreme Autonomy in Space, Air, Land, and Underwater; Water Desalination and Purification; and Technologies for Understanding and Treating Cancer.

The first session, on computer graphics and vision, addressed the question, "What do we do with all the pixels brought about by advances in computer graphics hardware, high-resolution displays, and high-resolution, low-cost digital cameras?" The speakers focused on four interrelated technology and application areas: computer vision and image understanding, modern computer graphics hardware, computational display, and virtual reality. The first speaker discussed the relatively new field of computational near-eye display, which operates at the boundary of optics, electronics, and computer graphics to design innovative display systems with new capabilities. This was followed by a talk on pioneering virtual reality headsets, where the display is an inch from the eyes and controlled by one's head and requires performance and resolution significantly beyond what current systems offer. The third speaker covered the pairing of image recognition with learning from that recognition, which has applications in visual search, and first-person vision where the camera wearer is an active participant in visual observation. The session concluded with a presentation on the challenges and opportunities of processing live pixel streams on vast scales with applications ranging from the personal to the societal.

Recent breakthroughs in decision making, perception architectures, and mechanical design are paving the way for autonomous robotic systems to carry out a wide range of tasks of unprecedented complexity. The session Extreme Engineering: Extreme Autonomy in Space, Air, Land, and Underwater provided an overview of four domains where recent algorithmic and mechanical advances are enabling the design and deployment of robotic systems where autonomy is pushed to the extreme. The session started with a presentation on the challenges of precision landing for reusable rockets, the technology required, and what will be needed to extend precision landing to planets other than Earth. The next presentation focused on autonomous microflying robots with design innovations inspired by avian flight. This was followed by a talk on the robotic cheetah, the first four-legged robot to run and jump over obstacles autonomously, and the management of balance, energy, and impact without human interaction. The fourth and final presentation covered motion guidance for ocean sampling by underwater vehicles.

Securing a reliable supply of water is a global challenge due to a growing population, changing climate, and increasing urbanization; therefore, alternative sources to augment freshwater supplies are being explored. The third session focused on four critical areas of water desalination and purification: new materials development, analytical characterization techniques, emerging desalination technologies, and innovative system design and operation. The session began with an overview of reverse osmosis technology, applications, and membrane chemistry innovations, which was followed by a talk on scalable manufacturing of layer-by-layer membranes and the advanced membrane characterization techniques that drive breakthrough innovations. The third presenter introduced new materials that advance emerging desalination treatment technologies. The final speaker asserted that desalination may present the same challenge for the next 100 years as building the Hoover Dam, which solved water scarcity issues that arose in the 1920s and 1930s. He discussed various high-recovery treatment options that utilize challenging solution chemistries or result in zero liquid discharge.

The organizers of the final session, Technologies for Understanding and Treating Cancer, noted that cancer is a complex group of more than 100 diseases characterized by uncontrolled cell growth, and that approximately 40 percent of people will be diagnosed with a form of cancer in their lifetime. Cancer presents challenges that engineers from different disciplines are working to address, through, for example, the development of more selective tools to detect cancer, new methods to deliver drugs to cancer cells, and better imaging methods to identify smaller tumors and assist surgeons in removing only cancerous cells. The session opened with a talk on how extracellular signals and the microenvironment around cancer cells influence their uncontrolled growth and expansion. This was followed by a presentation on advances in noninvasive methods using microfluidics to detect rare cancer cells. The third speaker described therapeutic molecules that block the ability of cancer cells to leave the initial tumor and start new tumors. The last speaker talked about immunotherapy—strategies for harnessing the immune system to target cancer cells using methods that control and sustain antitumor immune responses specific for different types of cancer.

On the first afternoon of the meeting, participants gathered in small groups for "get-acquainted" sessions where they each presented a slide and then 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. Discussions focused on how to inspire and train future engineering leaders (from K through PhD), industry-academic-government collaboration, sustainable energy systems, wearable technology, and change management in industries and disciplines where technology is rapidly improving, among others.

NAE member **John A. Orcutt**, distinguished professor of geophysics at the Scripps Institution of Oceanography and the University of California, San Diego, gave the first evening's dinner speech, "The Arctic: Scientific and Engineering Challenges for Measuring Rapid Change." He made a compelling case for climate research by enumerating significant pan-Arctic changes—reduction in sea-ice thickness, warming of Arctic waters and permafrost, rising temperatures, melting of the Greenland ice sheet, and consequent increase in human activities and escalation of economic and geopolitical importance—resulting from climate change. He described the importance of sensing networks such as Arctic Watch that employ communication, underwater navigation, and acoustic remote sensing technologies to observe, monitor, and collect data in situ year-round.

Participants at the meeting will be eligible to apply for The Grainger Foundation Frontiers of Engineering Grants, which provide seed funding for US FOE participants who are 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 2017 US FOE, which will be hosted by United Technologies Research Center in East Hartford, Connecticut, September 25–27. The 2017 topics are mega-tall buildings and other future places of work, machines that teach themselves, energy strategies to power our future, and unraveling the complexity of the brain.

Funding for the 2016 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 the participants are 30 to 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 www.naefrontiers.org or contact Janet Hunziker in the NAE Program Office at JHunziker@nae.edu.

## 2016 EU-US Frontiers of Engineering Held in Helsinki, Finland

On October 17–19 the EU-US Frontiers of Engineering symposium was held at Aalto University in Espoo, Finland, near Helsinki. The NAE partnered with the European Council of Applied Sciences, Technologies and Engineering (Euro-CASE) to carry out the event, with organizational support for the EU side provided by Technology Academy Finland (TAF). Harri Kulmala, CEO of DIMECC Ltd., chaired the symposium. The late **Christodoulos Floudas**, director of the Texas A&M Energy Institute, was US cochair of the organizing committee until his untimely passing in August.

The meeting brought together approximately 60 engineers, ages 30–45, from US and European universities, companies, and government labs for a 2½-day meeting to discuss leading-edge developments in four areas: The Road to Future Mobility; Frontiers of Carbon Capture, Utilization, and Storage; Integrated Photonics; and Smart Systems for Personalized and Connected Health Care. Participants attended from 11 EU countries: Belgium, the Czech Republic, Denmark, Finland, France, Hungary, Norway, Poland, Romania, Sweden, and the United Kingdom.

The integration of energy, transportation, cyber, and communication networks and advances in pervasive sensing combine to produce an unprecedented volume of data that makes it possible to observe, measure, and evaluate critical infrastructures. And the explosion of data from citizen sensors via social media provides an opportunity to understand human dynamics in transportation. Speakers in the session on the Road to Future Mobility discussed how a data-driven understanding of complex connected vehicle technologies impacts the observation, measurement, analysis, and modeling of mobility. The first speaker provided an overview of the state of the art in traffic monitoring leading to new results in routing games, which offer a powerful model of congestion in traffic networks. The next presenter described work in the field of simulation-based optimization, which addresses the challenges presented by individuals becoming "real-time optimizers" of their trips within large-scale transportation systems. This was followed by a talk on the application of data-driven macroscopic traffic models to solve optimization and control problems in urban transportation systems. The session concluded with a presentation on the challenges brought by autonomous vehicles based on experiences from Volvo's Drive Me project, in which 100 customers have the chance to use their vehicles in autonomous driving mode on public roads in Gothenburg, Sweden.

Carbon capture, utilization, and storage (CCUS) is one of the most urgent technological and societal challenges faced by humanity

Attendees at 2016 EU-UE Frontiers of Engineering Symposium. Photo credit: Rosa Lehtokari.

because of the extreme scales of physical and temporal $CO_2$ emission. The session on CCUS covered new understanding, models, technologies, assessment tools, and implementation plans for CCUS technologies. The first speaker set the stage for novel materials research in carbon capture by reviewing the capabilities and limitations of various $CO_2$ capture materials. This was followed by a presentation on recent advances in biochemical conversion of $CO_2$ to chemicals. The third speaker discussed $CO_2$ storage and utilization. The final presenter talked about optimizing electricity generation, water treatment, and carbon capture and storage processes in coal-fired generating facilities.

Integrated photonics, the topic of the third session, is a field that incorporates multiple photonic elements (e.g., light sources, amplifiers, couplers, multiplexers, switches, and detectors) on a single substrate. The photonic integrated circuit is a promising technology that may curb the increase of energy consumption in telecommunications and data centers, meet the demand for high-speed information processing and transmission, and enable a wide range of compact sensors with applications in medicine, biosensing, and security. The session began with an overview on photonic systems ranging from the physical layer to networks to new photonic-based architectures for data communications and exascale computing. The second speaker addressed recent developments that combine the fields of ferroelectric and photonic sciences with the tools of nanotechnology and integrated optics, and discussed their implications for ultrafast signal processing and potential applications in sensing and the life sciences. The next presenter focused on integration of III-V optoelectronics and Si photonics and new developments and application opportunities in this field. The session concluded with a talk on nontraditional photonic integration methods using organic and hybrid organic-inorganic materials and devices and presented some of their applications in biomedical sensors, digital displays, and solar cells.

Future healthcare delivery and medicine will heavily rely on personalized healthcare systems, which will be connected to people's everyday lives using consumer devices and electronics. Creating these smart systems—which will become irreplaceable in disease prevention, diagnosis, and monitoring and in medical therapies—requires multidisciplinary engineering approaches spanning various fields. The first speaker in the session Smart Systems for Personalized and Connected Health Care covered the state-of-the-art electronic materials and manufacturing technologies for wireless healthcare systems. The next presentation concerned wireless systems for neurological rehabilitation that may improve the quality of life of millions of people who suffer from severe neurological conditions, such as paralysis. The final speaker introduced emerging approaches in clinical informatics and image-based diagnosis, including mobile and cost-effective platform implementations that are especially suitable for telemedicine and mobile health applications.

In addition to the formal sessions, a poster session preceded by flash poster talks was held on the first afternoon. This served as both an icebreaker and an opportunity for participants to share information about their research and technical work. On the second afternoon the group enjoyed a bus tour of Helsinki, where attendees made stops at sites such as Sibelius Park and Senate Square and learned much about Finland from the guides. Dinners at the event were hosted by Sitra, an organization that promotes Finland's development, economic growth, and international competitiveness and cooperation, and Nokia, the multinational telecommunications and information technology company. At Nokia attendees visited the showroom, which featured demos of technologies they are working on.

Financial support for the symposium was provided by The Grainger Foundation, US National Science Foundation, Aalto University, the city of Espoo, Sitra, and Nokia.

The next EU-US FOE will be hosted by the University of California, Davis, on November 16–18, 2017. Technology Academy Finland will continue its organizational role for the EU side, and Harri Kulmala will remain as EU cochair. The US cochair is **Michael Tsapatsis**, professor and Amundson Chair in the Department of Chemical Engineering and Materials Science at the University of Minnesota.

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

# *EngineerGirl* Essay Contests: Responsible Engineering (2016), Animals (2017)

2016 essay contest winners.

*EngineerGirl*'s annual essay competition, hosted on the website (www.engineergirl.org), aims to introduce students to engineering and get them thinking and writing about ways that engineers influence their daily lives.

The 2016 *EngineerGirl* essay competition asked students to describe a technology and the improvements it could provide in at least one of the four areas of engineering responsibility: safety, health, well-being, and environmental sustainability. The 2016 winners are listed below:

Grades 3–5:

- First place: Gitanjali Rao, 5th grade, Edmondson Elementary School, Brentwood, TN, for "Emerging Biometrics Technology for Securing Cyberspace"
- Second place: Julia Kincaid, 5th grade, Brunson Elementary School, Winston Salem, for "Pop Water into Your Mouth, Literally"
- Third place: Madeleine Anders, 4th grade, Lakewood Elementary, Rockville, MD, for "Photovoltaic Textiles: Responsible Engineering"
- Honorable mention: Sofie Fenstermacher, 4th grade, Puesta del Sol Elementary, Bellevue, WA, for "Sleeping Bag Incubator"

Grades 6–8:

- First place: 8th grader Allison Harry, Durgee Junior High School, Baldwinsville, NY, for "Plight of the Smart Bandage"
- Second place: Jessie Gan, 7th grade, San Diego Jewish Academy, for "Heal My Broken Heart"
- Third place: Sydney Vernon, 7th grade, Open Window School, Bellevue, WA, for "The Veggie: One Giant Leap"
- Honorable Mention: Madelyn Heaston, home-schooled 6th grader, Issaquah, WA, for "Wearable Sensor Engineering Technology"
- Honorable mention: Annie Stewart, 7th grade, Harpeth Hall School, Nashville, for "Evaluating the Ethics of the Modular Artificial Reef Structure"

Grades 9–12:

- First place: Katherine Collins, 11th grade, Newton South High School, Newton, MA, for "Engineered Safeguards for Synthetic Probiotics"
- Second place: Clio Holman, 11th grade, Ann Richards School for Young Women Leaders, Austin, for "Engineering a Cure for Cancer: Opportunities, Challenges, and Responsibilities"
- Third place: Richa Gupta, 11th grade, International School Bangalore, India, for "The Ascent of the Fuel Cell Vehicle"
- Honorable mention: Goutam Gadiraju, 11th grade, Thomas Jefferson Classical Academy, Shelby, NC, for "Engineering Principles in Thorium Nuclear Fission Reactors"
- Honorable mention: Amy-Doan Vo, 9th grade, Westwood High School, Austin, for "The Curly Solution to Water Wastage"

"It is inspiring to see students exploring the meaning of responsible engineering, for it is a primary concern for engineering in advancing our society," said NAE president C. D. Mote, Jr.

The topic of the 2017 *EngineerGirl* national essay contest was announced September 15: How might engineers improve life for vulnerable and endangered animals? The contest deadline is February 1, 2017.

Prizes are awarded to students in three categories based on grade level. Awards are $500 for first place, $250 for second place, and $100 for third place, with certificates for honorable mention.

Both the 2016 and 2017 *EngineerGirl* essay contests are sponsored by Chevron Corp. and the Kenan Institute for Engineering, Technology, and Science. The winning essays for 2016 and the contest information for 2017 are posted on the *EngineerGirl* website (www.engineergirl.org/Contest.aspx).

The *EngineerGirl* website is designed for girls in elementary through high school and offers information about engineering fields and careers, questions and answers, interviews, and other resources on engineering. A survey of 2016 contest participants indicated that 66 percent of girls were more likely to consider an engineering career after writing their essay. *EngineerGirl* is part of the NAE's ongoing efforts to increase the diversity of the engineering workforce.

## Calendar of Meetings and Events

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|---|---|
| October 7 | 2016 NAE Grand Challenges Scholars Program Annual Meeting |
| November 29–30 | Educator Capacity Building in PreK–12 Engineering Education Committee Meeting |
| **2017** | |
| January 1–31 | Election of new NAE members and foreign members |
| January 1–April 1 | NAE Awards Call for Nominations |
| January 10–12 | Workshop on Overcoming Challenges to Infusing Ethics into the Development of Engineers |
| February 1 | *EngineerGirl* National Essay Contest Deadline |
| February 8 | Announcement of Class of 2017 newly elected NAE members and foreign members |
| February 8–9 | NAE Council Meeting<br>Irvine, California |
| February 9 | NAE National Meeting<br>Irvine, California |
| February 21 | 2017 Fritz J. and Dolores H. Russ Prize dinner and ceremony (by invitation) |
| March 31–April 2 | German-American Frontiers of Engineering<br>GE Aviation, Evendale, Ohio |

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

# Former NAS President Ralph J. Cicerone (1943–2016)

It is with a very heavy heart that I share the news that Dr. Ralph J. Cicerone, president emeritus of the National Academy of Sciences, passed away on November 5, surrounded by his family at his home in New Jersey.

Dr. Cicerone was devoted to service to the nation through his humanistic values and through his profound personal knowledge of and respect for science and engineering. Always concerned about what is right—for the Academies, for the communities of science, engineering, and medicine, and for the nation—his impact on the Academy complex was profound. I believe he will go down in the institution's history as the leader

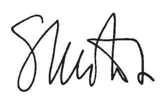
Ralph J. Cicerone

who steered the Academies toward the vision of Abraham Lincoln in 1863. We would not be what we are today without his quiet, effective, and principled leadership.

At the NAE Annual Meeting last month Dr. Cicerone was designated an NAE Distinguished Honoree, only the fifth time the honor has been bestowed. He accepted the distinction with characteristic dignity, grace, and appreciation.

The formal NAS announcement cites many of his accomplishments; it is available on the Academies website, www.nationalacademies.org.

We have lost a man of surpassing intellect, integrity, and vision.



C. D. Mote, Jr.

## In Memoriam

**LEO L. BERANEK**, 102, president emeritus, American Academy of Arts and Sciences, died October 11, 2016. Dr. Beranek was elected to the NAE in 1966 for applied acoustics.

**B. PAUL BLASINGAME**, 97, retired manager, Delco Electronics Division, General Motors Corporation, died November 13, 2015. Dr. Blasingame was elected to the NAE in 1971 for contributions to inertial guidance systems and applications to space flight and commercial air navigation.

**EDWIN L. CARSTENSEN**, 96, senior scientist in electrical and computer engineering and Arthur Gould Yates Professor of Engineering Emeritus, University of Rochester, died June 24, 2016. Dr. Carstensen was elected to the NAE in 1987 for contributions to the understanding of ultrasonic and dielectric properties of biological media and the biological effects of ultrasound and extremely low frequency electric fields.

**DALE L. CRITCHLOW**, 84, retired fellow, IBM Corporation, died May 6, 2016. Dr. Critchlow was elected to the NAE in 1991 for technical leadership and key contributions to the development of metal-oxide semiconductor (MOS) devices and dynamic random access memory (DRAM) technology.

**IRA DYER**, 91, professor emeritus of ocean engineering, Massachusetts Institute of Technology, died October 9, 2016. Dr. Dyer was elected to the NAE in 1976 as a founder of research and educational programs in ocean engineering and an authority on noise and turbulence.

**HELEN T. EDWARDS**, 80, scientist, Fermilab (FNAL), and scientist, Deutsches Elektronen Synchrotron (DESY), died June 21, 2016. Dr. Edwards was elected to the NAE in 1988 for leadership in the design and construction of the TEVATRON, the first superconducting synchrotron and the world's highest-energy particle accelerator.

**ROBERT MARIO FANO**, 98, Ford Professor of Engineering Emeritus, Massachusetts Institute of Technology, died July 13, 2016. Dr. Fano was elected to the NAE in 1973 for pioneering work in the development of the first interactive time-sharing computer system and contributions to communication theory.

**CHRISTODOULOS A. FLOUDAS**, 56, director, Texas A&M Energy Institute, and Erle Nye '59 Chair Professor for Engineering Excellence, died August 14, 2016. Professor Floudas was elected to the NAE in 2011 for contributions to theory, methods, and applications of global optimization in process systems engineering, computational chemistry, and molecular biology.

**ROBERT C. FORNEY**, 89, retired executive vice president, E.I. du Pont de Nemours & Company, died August 3, 2016. Dr. Forney was elected to the NAE in 1989 for leadership of chemical engineering research, innovative process developments, and creative technology management.

**GEORGE W. GOVIER**, 99, president, Govier Consulting Services Ltd., died February 22, 2016. Dr. Govier was elected to the NAE in 1979 for contributions to the understanding of multiphase flow and leadership in applying technology to energy conservation and utilization.

**GEORGE S. GRAFF**, 98, retired president, McDonnell Aircraft Company, died January 24, 2016. Mr. Graff was elected to the NAE in 1981 for contributions to the aerodynamics and the general technical development of US fighter aircraft, missiles, and spacecraft.

**THOMAS J. HANRATTY**, 89, professor emeritus of chemical engineering, University of Illinois at Urbana-Champaign, died August 24, 2016. Dr. Hanratty was elected to the NAE in 1974 for contributions in the analysis and design of turbulent, gas-liquid, and solid-liquid flow systems.

**JOHN L. HUDSON**, 79, Wills Johnson Professor, Department of Chemical Engineering, University of Virginia, died August 6, 2016. Dr. Hudson was elected to the NAE in 2008 for advances in the understanding and engineering of complex dynamic chemical-reaction systems.

**NOEL JARRETT**, 94, retired director, Chemical Engineering, R&D Aluminum Company of America, died May 24, 2015. Mr. Jarrett was elected to the NAE in 1976 for contributions to the development of a new energy-saving aluminum smelting process and leadership in aluminum production and treatment technology.

**RUDOLF KALMAN**, 86, professor emeritus, University of Florida, and independent research scientist, died July 2, 2016. Dr. Kalman was elected to the NAE in 1991 for pioneering contributions to the estimation and control of dynamical systems.

**ENEAS D. KANE**, 96, retired vice president, Technology and Environmental Affairs, Chevron Corporation, died July 14, 2013. Dr. Kane was elected to the NAE in 1977 for contributions in the development of rarefied gas dynamics research, in low-pressure wind tunnel design, and in the fixed-bed phosphoric acid polymerization process.

**LEONARD J. KOCH**, 95, retired vice president, Illinois Power Company, died May 5, 2015. Mr. Koch was elected to the NAE in 1981 for contributions to fast reactor development, applying nuclear power to electricity generation, and articulating the facts about nuclear power.

**WILLIAM W. LANG**, 90, retired president, Noise Control Foundation, died October 23, 2016. Dr. Lang was elected to the NAE in 1978 for contributions and leadership in the field of noise control engineering.

**ANGELO MIELE**, 93, research professor and Foyt Professor Emeritus, Rice University, died March 19, 2016. Dr. Miele was elected to the NAE in 1994 for contributions to flight mechanics and control.

**DAVID H. PAI**, 80, retired president, Foster Wheeler Development Corporation, died July 23, 2016. Dr. Pai was elected to the NAE in 1994 for contributions to the development of design standards for high-temperature nuclear components.

**STANFORD S. PENNER**, 95, Distinguished Professor Emeritus of Engineering Physics, Department of Mechanical and Aerospace Engineering, University of California, San Diego, died July 15, 2016. Dr. Penner was elected to the NAE in 1977 for contributions to aerothermochemistry and its application to combustion theory, radiative heat transfer, and reentry phenomena.

**HOWARD RAIFFA**, 92, professor emeritus, managerial economics, Harvard University, died July 8, 2016. Dr. Raiffa was elected to the NAE in 2005 for contributions to decision analysis, negotiation analysis, and engineering decision making.

**EDWARD H. SUSSENGUTH**, 83, retired fellow, IBM Corporation, died November 22, 2015. Dr. Sussenguth was elected to the NAE in 1992 for technological contributions and engineering leadership in the architecture of computer and communications systems.

**JOSEPH F. SUTTER**, 95, consultant, Boeing Commercial Airplane, died August 30, 2016. Mr. Sutter was elected to the NAE in 1984 for exceptional technical leadership in the design and development of commercial transport aircraft.

**CHARLES L. WAGNER**, 90, retired consulting engineer, Westinghouse Electric Corporation, died August 5, 2014. Mr. Wagner was elected to the NAE in 1999 for contributions to electric power system engineering and standards.

**DEAN A. WATKINS**, 91, retired chairman, Watkins-Johnson Company, died May 17, 2014. Dr. Watkins was elected to the NAE in 1968 for invention and development of electron tubes and solid-state devices.

**ROBERT L. WIEGEL**, 93, professor of civil engineering emeritus, University of California, Berkeley, died July 9, 2016. Mr. Wiegel was elected to the NAE in 1975 for leadership in applying scientific findings in oceanography to the solution of civil engineering problems in the ocean.

**MOSHE ZAKAI**, 88, Distinguished Professor Emeritus, Technion-Israel Institute of Technology, died November 27, 2015. Dr. Zakai was elected to the NAE as a foreign member in 1989 for pioneering contribution to the theory of nonlinear filtering and to the theory and application of stochastic processes.

# Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Academies of Sciences, Engineering, and Medicine. 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 (*www.nap.edu*) or by phone (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 20.** 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 engineering accomplishments of the deceased. The expertise and credibility that the NAE brings to its responsibilities 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.

**Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions.** Aviation $CO_2$ emissions account for only about 2.0–2.5 percent of total global annual $CO_2$ emissions, yet research to reduce them is urgent because (1) such reductions may be legislated as commercial air travel increases, (2) it takes new technology a long time to propagate into and through the aviation fleet, and (3) the impacts of global $CO_2$ emissions continue to grow. This report presents a national research agenda for reducing $CO_2$ emissions from commercial aviation, focusing on propulsion and energy technologies for reducing carbon emissions from large, commercial aircraft (single-aisle and twin-aisle aircraft that carry 100 or more passengers) because they account for more than 90 percent of global emissions from commercial aircraft. To reduce the contribution of aviation to climate change, it is essential to improve the effectiveness of efforts to reduce emissions and initiate research into new approaches.

NAE members on the study committee were **Meyer J. Benzakein**, assistant vice president for aerospace and aviation, Ohio State University; **Alan H. Epstein**, vice president, Technology and Environment, Pratt & Whitney; **Hratch G. Semerjian**, former chief scientist, National Institute of Standards and Technology; and **Subhash C. Singhal**, Battelle Fellow Emeritus, Pacific Northwest National Laboratory. Paper, $41.00.

**Optimizing the Air Force Acquisition Strategy of Secure and Reliable Electronic Components: Proceedings of a Workshop.** In 2012 the National Defense Authorization Act (NDAA) outlined new requirements for industry to serve as the lead in averting counterfeits in the defense supply chain. In its report on the FY 2016 NDAA, the House Armed Services Committee noted that the pending sale of IBM's microprocessor fabrication facilities to Global Foundries created uncertainty about US access to trusted state-of-the-art microelectronic components and called for an assessment of the Department of Defense's actions and measures to address this threat. The National Academies of Sciences, Engineering, and Medicine convened a workshop for industry, academic, and government experts to (1) define the technological and policy challenges with maintaining a reliable and secure source of microelectronic components, (2) review Air Force acquisition processes for acquiring reliable and secure microelectronic components, and (3) explore options for business models in the national security complex that would be relevant for the Air Force acquisition community. This publication summarizes the workshop presentations and discussions.

NAE members on the workshop steering committee were **Michael Ettenberg**, Dolce Technologies; **Bernard S. Meyerson**, chief innovation officer, International Business Machines Corporation; and **Paul D. Nielsen**, director/CEO, Software Engineering Institute, Carnegie Mellon University. Paper, $40.00.

**Transitioning Toward Sustainability: Advancing the Scientific Foundation—Proceedings of a Workshop.** In 1999 the National Academies released *Our Common Journey: A Transition Toward Sustainability*, which emphasized the need for place-based and systems approaches to sustainability, proposed a research strategy for scientific and technical knowledge to better inform the field, and highlighted priorities for actions that could contribute to a sustainable future. The years since then have brought significant advances in observational and predictive capabilities for natural and social systems; the development of other tools and approaches useful for sustainability planning; and other frameworks for environmental decision making, such as those that focus on climate adaptation or resilience. In January 2016 the National Academies of Sciences, Engineering, and Medicine convened a workshop to discuss progress since the 1999 report, opportunities for advancing the research and use of scientific knowledge to support a transition toward sustainability, and challenges in establishing indicators and observations to support sustainability research and practice. This report summarizes the presentations and discussions from the workshop.

NAE members on the workshop planning committee were **David A. Dzombak** (chair), Hamerschlag University Professor and head, Department of Civil and Environmental Engineering, Carnegie Mellon University, and **Thomas E. Graedel**, Clifton R. Musser Professor of Industrial Ecology, Yale University. Paper, $36.00.

**A Vision for the Future of Center-Based Multidisciplinary Engineering Research: Proceedings of a Symposium.** In 1985 the National Science Foundation (NSF) created the Engineering Research Centers (ERCs) with the goal of improving engineering research and education and helping to keep the United States competitive in global markets. Since then NSF has funded 67 ERCs across the country. Each is funded for up to 10 years, during which time it builds partnerships with industry, universities, and other government entities to sustain it upon graduation from NSF support. To ensure that the ERCs remain a source of innovation, economic development, and educational excellence, NSF asked the National Academies of Sciences, Engineering, and Medicine to convene a one-day symposium in April 2016. The event featured four plenary panel presentations: on the evolving global context for center-based engineering research, trends in undergraduate and graduate engineering education, new directions in university-industry interaction, and emerging best practices in translating university research into innovation. This publication summarizes the presentations and discussions from the symposium.

NAE members on the study committee were **Maxine L. Savitz** (cochair), retired general manager, Technology/Partnerships, Honeywell Inc.; **David R. Walt** (cochair), University Professor and director, Tufts Institute for Innovation and Howard Hughes Medical Institute Professor and Robinson Professor of Chemistry, Tufts University; **Nadine Aubry**, dean of engineering, Northeastern University; **Cheryl R. Blanchard**, CEO, Microchips Biotech Inc.; **Robert D. Braun**, David & Andrew Lewis Professor of Space Technology, Daniel Guggenheim School of Aerospace Engineering, Georgia Institute of Technology; **Fred C. Lee**, University Distinguished Professor and director, Center for Power Electronics Systems, Virginia Polytechnic Institute and State University; **Philip M. Neches**, founder, Teradata Corporation; **Richard F. Rashid**, chief research officer, Microsoft Corporation; **S. Shankara Sastry**, dean of engineering and director, Richard C. Blum Center for Developing Economies, and Roy W. Carlson Professor of Engineering, University of California, Berkeley; **Edwin L. Thomas**, William and Stephanie Sick Dean of Engineering, professor of mechanical engineering and materials science and of chemical and biomolecular engineering, Rice University; and **Yannis C. Yortsos**, dean, Viterbi School of Engineering, University of Southern California. Free PDF.

**Exploring Encryption and Potential Mechanisms for Authorized Government Access to Plaintext: Proceedings of a Workshop.** In June 2016 the National Academies of Sciences, Engineering, and Medicine convened a workshop at which participants discussed potential encryption strategies to enable access to plaintext information by law enforcement or national security agencies with appropriate authority. Although the focus of the workshop was on technical issues, there was some consideration of the broader policy context, and discussion of encryption and authorized exceptional analysis frequently addressed open policy questions as well as technical issues. This publication summarizes the presentations and discussions from the workshop.

**Dan Boneh**, professor, computer science and electrical engineering, Stanford University, was a member of the workshop planning committee. Paper, $42.00.

**A National Trauma Care System: Integrating Military and Civilian Trauma Systems to Achieve Zero Preventable Deaths After Injury.** Advances in trauma care have been spurred by the significant burden of injury from the wars in Afghanistan and Iraq. But knowledge and advances in trauma care developed by the DOD from experiences in the two wars may be lost when they end, with implications for the quality of trauma care in the civilian setting as well, where adoption of military advances has improved the response to civilian casualty events. Steps to codify and harvest the lessons learned in the military's trauma system are needed and will require partnership across military and civilian sectors and a sustained commitment from trauma system leaders at all levels to ensure that knowledge and tools are not lost. This report defines the components of a learning health system to enable continued improvement in trauma care in the civilian and the military sectors and provides recommendations to ensure that recent lessons learned from military experiences are sustained and built upon for future combat operations and translated to the US civilian system.

**Cato T. Laurencin**, University Professor; Van Dusen Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering, of materials science and engineering, and of biomedical engineering; director, Institute for Regenerative Engineering; and director, Raymond and Beverly Sackler Center, University of Connecticut, was a member of the study committee. Paper, $75.00.

**Achieving Science with CubeSats: Thinking Inside the Box.** Space-based observations have transformed understanding of Earth, its environment, the solar system, and the universe at large. Driven by increasingly advanced science questions, space observatories have become more sophisticated, more complex, and more costly. Small satellites (ranging in mass from 500 kg to 0.1 kg) are gaining momentum as an additional means to address targeted science questions in a rapid, and possibly more affordable, manner. CubeSats, a space platform defined in terms of (10 cm × 10 cm × 10 cm)–sized cubic units of approximately 1.3 kg each, have caught the attention of parts of the US space science community, and the first science results from them recently became available. This report reviews the scientific potential and technological promise of CubeSats and provides a list of sample science goals for them.

NAE members on the study committee were **Alan M. Title**, senior fellow, Space Technology Advanced R&D Labs, Lockheed Martin, and **A. Thomas Young**, retired executive vice president, Lockheed Martin Corporation. Paper, $85.00.

**NASA Space Technology Roadmaps and Priorities Revisited.** The United States has been a world leader in aerospace endeavors in both the government and commercial sectors. A key factor in this leadership is continuous development of advanced technology, which is critical to US ambitions in space, including a human mission to Mars. To sustain progress, NASA is executing a series of aeronautics and space technology programs using roadmapping to identify technology needs and improve the management of its technology development portfolio. In 2010 NASA created 14 draft technology roadmaps for the development of space technologies, and in 2015 it issued revised roadmaps. A significant new aspect of the update has been the effort to assess the relevance of the technologies. This report prioritizes new technologies in the 2015 roadmaps and recommends a method for independent review of future updates to NASA's space technology roadmaps, which are expected every 4 years.

NAE members on the study committee were **Arden L. Bement Jr.**, Emeritus David A. Ross Distinguished Professor of Nuclear Engineering and director, Global Policy Research Institute and Global Affairs Officer, Purdue University, and **Alan M. Title**, senior fellow, Space Technology Advanced R&D Labs, Lockheed Martin. Paper, $55.00

**National Security Space Defense and Protection: Public Report.** In just over a half-century, humankind has become highly dependent on orbiting satellites. Sensors, receivers, transmitters, and the satellites that carry them are components of complex space systems that include terrestrial elements, electronic links among components, organizations to provide management, care and feeding, and launch systems. Many of these space systems interact with terrestrial systems; for example, a long list of Earth-based systems cannot function properly without information from the Global Positioning System (GPS). Space systems are fundamental to the information business, and the modern world is information-driven. In addition to navigation and imagery, many space systems support military, intelligence, and other national security functions of the United States and other nations. This report reviews the options available to address threats to space systems, in terms of deterring, defeating, and surviving hostile actions, and assesses strategies and plans to counter threats. The report also recommends architectures, capabilities, and courses of action to address affordability, technology risk, and potential barriers or limiting factors in implementing such courses of action.

NAE members on the study committee were **James O. Ellis Jr.**, USN (ret.) (cochair), Annenberg Distinguished Visiting Fellow, Hoover Institution, Stanford University, and retired president and CEO, Institute of Nuclear Power Operations; **Michael D. Griffin**, chair and CEO, Schafer Corporation; **John A. Montgomery**, director of research, US Naval Research Laboratory; and **Thomas E. Romesser**, retired vice president and chief technology officer, Northrop Grumman Aerospace Systems. Paper, $50.00.

**Pathways to Urban Sustainability: Challenges and Opportunities for the United States.** Cities have captured over half the world's population and more than 80 percent of the globe's economic activity. They offer social mobility and economic prosperity to millions by clustering creative, innovative, and educated individuals and organizations. But clustered populations can compound both positive and negative conditions, and many urban areas exhibit growing inequality, debility, and environmental degradation. The spread and growth of urban areas present concerns for a sustainable future, particularly if cities cannot adequately address the rise of poverty, hunger, resource consumption, and biodiversity loss in their borders. This study examines nine cities in the United States and Canada—Los Angeles, New York, Philadelphia, Pittsburgh, Grand Rapids, Flint, Cedar Rapids, Chattanooga, and Vancouver—chosen to represent a variety of metropolitan regions, with consideration given to city size, proximity to coastal and other waterways, susceptibility to hazards, primary industry, and several other factors.

NAE members on the study committee were **Linda P.B. Katehi** (chair), chancellor, University of California, Davis, and **Chris T. Hendrickson**, Hamerschlag University Professor, Carnegie Mellon University. Paper, $69.00.

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