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The
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Editor's Note

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NAE News and Notes

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

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Editor's Note

Kristi Anseth

Exploring the Frontiers of Engineering

Every year the US Frontiers of Engineering (FOE) Symposium brings together approximately 100 outstanding young engineers, ages 30 to 45, to share ideas and learn about cutting-edge research on a wide range of engineering topics. A unique characteristic of the symposium series is that participants are competitively selected from researchers working across the spectrum of engineering disciplines in academia, industry, and government. FOE provides these emerging engineering leaders with a rare opportunity to learn about the latest research in engineering areas other than their own and to meet and network with promising engineers working in different fields. The meeting is truly memorable, and I encourage you to nominate your eligible colleagues. I attended my first US FOE symposium in 1998 as a new assistant professor, and it is now my great privilege to serve as chair of the organizing committee and meeting.

The eighteenth US FOE Symposium was held September 13–15, 2012, at General Motors Technical Center in Warren, Michigan. It was organized into four sessions with the following themes: climate engineering, vehicle electrification, serious games, and engineering materials for the biological interface. Seven papers based on this year's presentations are included in this issue of *The Bridge*.

The session on climate engineering was organized by David Sholl of the Georgia Institute of Technology and Armin Sorooshian of the University of Arizona. Climate engineering is the concept of proactively and artificially modifying the Earth system in ways that might combat human-induced changes in the planet's radiative balance. Two presentations from this session are included in this issue. Eli Kintisch, of *Science* Magazine, provides an overview of climate engineering and of important considerations before such intervention is undertaken. In the second article, Lynn Russell, a researcher at the Scripps Institute of Oceanography, describes the role of atmospheric aerosols in climate engineering and gives examples of recent field projects that have attempted to shed light on the basic science and physics of cloud brightening.

The second session, chaired by Michael Degner of Ford Motor Company and Sanjeev Naik of General Motors, was about advances in vehicle electrification. Presentations focused on current research on, and challenges in, technology enablers such as energy storage systems, electric machine drives, and electrical system integration and control. In Keeping Up with the Increasing Demands for Electrochemical Energy Storage, Jeff Sakamoto of Michigan State University reviews recent improvements in automobile electrical energy storage systems, where reductions in cost, size, and weight are necessary to increase the adoption of plug-in hybrid and battery electric vehicles (PHEVs and BEVs). He describes some of the recent improvements in battery technologies, industry targets to enable widespread adoption of PHEVs, and some of the ongoing research to meet these targets.

Today's drivers have high expectations for the safety, reliability, comfort, and connectivity of their vehicles. Rahul Mangharam of the University of Pennsylvania discusses technical approaches to enhance vehicle safety through remote diagnostics, networking, recalls, and software upgrades. He and his colleagues are working on several products to enhance traffic networking that will suggest alternate routes to avoid congestion, expedite auto safety recalls and system repairs, and support vehicle-to-vehicle communications that alert drivers to sudden braking or accidents on the road ahead.

Serious games were the focus of the third session, chaired by Li-Te Cheng of Google and Ben Sawyer of Digitalmill. The term—best understood as a medium of many design, engineering, and technical domains rather than a specific technology—applies to the increasing use of video game technologies in nonentertainment domains. Initially, serious games were a training tool, with a second wave of applications in therapeutic and health behavior change efforts. A new generation of serious games supports innovative crowd sourcing activities that tackle scientific, organizational, and social challenges through video game play. In Playing to Win: Serious Games for Business, Phaedra Boinodiris of IBM provides pointers for the adoption of serious games for process optimization and complex problem solving.

The final session of the meeting, chaired by Karen Burg of Clemson University and Ali Khademhosseini of Harvard Medical School, covered the topic of engineering materials for the biological interface. The session focused on the cell-cell or cell-tissue components of the biological interface of, say, tendon to bone or cartilage to bone. Repairs of tissues across interfaces are quite complex because of very diverse tissue properties (e.g., tissue mechanics) and corresponding interfacial interactions. To simulate these interactions, researchers are studying the design of materials, control of cells, and design of bioreactors in which to grow and assess these systems. In her presentation, Helen Lu of Columbia University described engineering tissue-to-tissue interfaces for the formation of complex tissues. Matthew Gevaert of Kiyatec then covered the translation of these ideas to commercial application through the cultivation of 3D tissue systems to better mimic relevant events in the body.

In addition to the presentations, FOE symposia provide lively Q&A sessions, panel discussions, and other activities that encourage personal discussions and networking. The dinner speaker, a traditional highlight of FOE programs, was **Alan Taub**, professor of materials science and engineering at the University of Michigan and former vice president of global R&D at General Motors. In his remarks on the reinvention of the automobile for 21st century sustainability, he described various stages in the automotive industry from development of the internal combustion engine to the oil shock of the 1970s and the subsequent focus on fuel efficiency and safety. He noted that today's primary challenge is accommodating the number of vehicles that the world can afford as personal income in developing countries increases, with the primary issues being energy and emissions, safety, congestion, and affordability. Dr. Taub concluded his talk by pointing out that if engineers are motivated to save the world, the automotive industry is a good place to do so.

It was my great pleasure to serve as chair of the Organizing Committee for this year's US FOE Symposium. I want to close by expressing my gratitude to Janet Hunziker, NAE senior program officer, Vanessa Lester, program associate, and Lance Davis, NAE Executive Officer, for their contributions to the planning and implementation of this pioneering series. I also thank the sponsors of the 2012 symposium: General Motors, The Grainger Foundation, Air Force Office of Scientific Research, Department of Defense ASDR&E Research Directorate–STEM Development Office, National Science Foundation, Microsoft Research, and Cummins Inc.

Adaptation to climate change may include two types of geoengineering: solar radiation management (SRM) and carbon dioxide removal (CDR).

Overview of Climate Engineering

Eli Kintisch

Eli Kintisch is a correspondent with *Science* magazine and Knight Science Journalism fellow at the Massachusetts Institute of Technology.

Top science institutions around the world, including the US National Academies and the UK Royal Society, have called for studies into deliberate tinkering with the planet's climate or atmosphere to partially offset global warming, a practice known as climate engineering or geoengineering. Various characteristics distinguish the two major types of geoengineering: solar radiation management (SRM; e.g., orbiting sunshades, aerosols sprayed into the stratosphere) and carbon dioxide removal (CDR; e.g., carbon-sucking machines, catalysis of oceanic algal growth). The number of scientists studying both is steadily increasing, and several companies are conducting CDR engineering research, but the United States has yet to follow the lead of a number of European countries that have dedicated programs for geoengineering research.

Efforts at global carbon dioxide pollution abatement remain stalled even as the effects of a warming planet become increasingly apparent. Research findings suggest that the planet may be closer to global tipping points, such as the release of methane from permafrost, than previously thought. As the global climate crisis intensifies, taboos once held by scientists and policymakers are falling by the wayside. Adaptation, the organized response to a warming planet and its myriad local impacts, was once viewed by top officials as a distraction from the main priority of mitigating global greenhouse gas emissions. Now local and national governments around the world are creating plans to respond and adapt to warmer temperatures, higher seas, more pervasive drought, and other environmental challenges.

Geoengineering is a radical form of adaptation. The publication in 2006 of a controversial paper by Nobel Prize winner Paul Crutzen entitled "Albedo Enhancement by Stratospheric Sulfur Injections: A Contribution to Resolve a Policy Dilemma?" both jumpstarted the discussion of geoengineering and lent credibility to an idea that had until then existed largely in the shadows of academia.

Every serious researcher or policy expert who studies climate engineering, including Crutzen, believes that cutting greenhouse gas emissions is at least as important as developing geoengineering technologies, if not more urgent.

It is useful to consider abatement, carbon dioxide removal, and solar radiation management in proper context with one another. In Figure 1, each large circular element represents a process that drives the next step in the chain. The central items are interventions that mitigate the impact between two linked terms; for example, efficiency lowers the consumption of energy that results from consumption of goods and services. Three abatement steps—using less energy ("conservation"), using energy more efficiently ("efficiency"), and producing energy less carbon-intensively ("low-carbon energy")—can together lower global greenhouse gas emissions. Next are geoengineering options. The round-tipped "arrows" indicate a more tenuous relationship than the other links.

As shown in Figure 1, CDR goes a step further than abatement. By pulling gases out of the atmosphere it gets at the heart of the problem: if lowering emissions is akin to reducing one's exposure to a virus that causes a fever, CDR is like using an antiviral medication. SRM is one step further still. It does not change the level of CO_2 in the atmosphere but instead serves to reduce its climatic effects. Temperature is the most prominent of those effects, and SRM lowers the planet's thermostat by directly reducing the amount of solar energy absorbed by the planet. Perhaps the metaphorical equivalent is using a cold compress to alleviate fever.

Both CDR and SRM techniques attempt to mimic natural processes that scientists mostly understand. But that is where their similarities end. In their technical aspects, the political dynamics that might govern their deployment, and their feasibility, the differences between them are stark. That's one reason that many scientists try to avoid using the terms "geoengineering" or "climate engineering" to generalize between the two.

Planetary Sunblock: Solar Radiation Management

"Fast, cheap, imperfect and uncertain" is how Harvard physicist David Keith (2011), one of the leading thinkers on both methods, describes SRM. The most commonly explored technique for blocking sunlight from the planet is to mimic the natural cooling effect of volcanoes by spreading sulfurous particles in the stratosphere. The following paragraphs explain Keith's characterization.

Fast: The 1991 eruption of the Mount Pinatubo volcano sprayed 5 million tons of sulfur aerosol into the stratosphere as sulfur dioxide, which scattered light away from Earth and cooled the planet by 0.5°C (Kravitz 2013). Modeling studies (e.g., Caldeira and Matthews 2007) suggest that if a similar quantity of sulfur aerosol were artificially injected into the stratosphere, the cooling could be essentially instantaneous.

Cheap: A recent study by an aerospace research firm suggests that the costs of deploying a global SRM scheme to offset anthropogenic warming "are comparable to the yearly operations of a small airline" (McClellan et al. 2010).

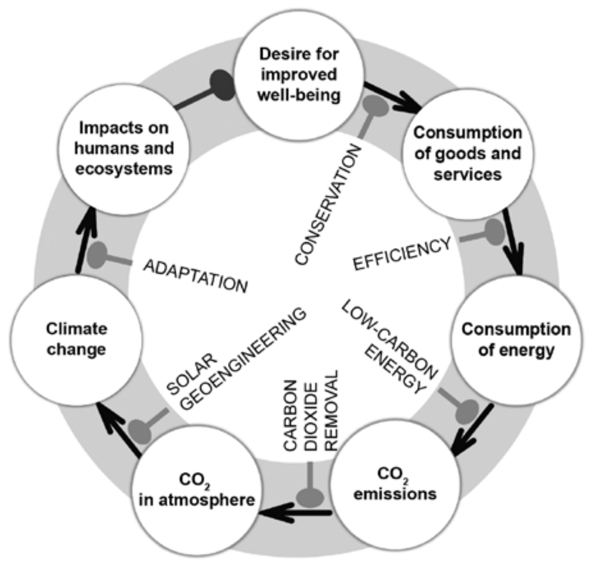

Figure 1 Connections among various factors in terms of the climate challenge. See text for discussion. The round-tipped "arrow" between the "impacts on human systems" and "desire for improved well-being" indicates that the former drives the latter. Reprinted with permission from Caldeira et al., forthcoming.

Imperfect: A number of modeling studies have suggested various side effects of this technique, including depriving the planet of solar energy that influences rainfall, leading to less precipitation (Ricke et al. 2010). This effect could disrupt the southeast Asian monsoon season or weather in South America, potentially exacerbating droughts.

Uncertain: Many aspects of the climate system are not fully understood, so tinkering with a fundamental variable that drives the system—the amount of solar energy entering it—may have serious unexpected or unintended consequences.

Since Crutzen's landmark paper, research into SRM has evolved from proof-of-concept modeling into more sophisticated efforts. The Geoengineering Model Intercomparison Project (GeoMIP) involves 19 different global climate models. Each has run separate simulations with four standardized scenarios in which solar radiation management is deployed in different ways (Kravitz et al. 2011). Because different climate models employ different assumptions, characteristics, and physics, use of the same initial conditions, the thinking goes, may yield more robust results about the environmental effects of various SRM strategies. One example of the increasingly sophisticated modeling research on stratospheric aerosols is a recent study that found that sulfate aerosols deployed to offset warming caused by a doubling of CO_2 concentrations would make the sky 3 to 5 times brighter—and less blue—than it is currently, which could affect photosynthesis in plants and people's psychological moods (Kravitz et al. 2012).

In the United States, David Keith and Harvard colleague James Anderson, an atmospheric chemist, are planning "to develop in situ experiments to test the risk and efficacy of aerosols in the stratosphere" (Keith 2012).

The most visible effort to explore stratospheric approaches through actual experimentation is the Stratospheric Particle Injection for Climate Engineering (SPICE) project, led by Bristol University and supported by the British government at £1.6 million for 3½ years. Along with ongoing work to design particles and computer modeling, the project originally included a planned field experiment to spray 150 liters of water 1000 meters in the air to test how a balloon would behave in the wind during spraying, a feasibility test. The field experiment was cancelled because of public concern about lack of regulations on SRM as well as worries over a patent application that one of the research participants had filed before receiving UK funds for the project (Watson 2012).

Thinning the Greenhouse Layer: Carbon Dioxide Removal

Scientists have proposed a variety of techniques for removing CO_2 from the atmosphere. These range from engineering forests to be more carbonaceous, to growing massive algal blooms at sea, to sucking carbon dioxide out of the atmosphere.

> *Many aspects of the climate system are not fully understood, so tinkering with a fundamental variable may have serious unexpected or unintended consequences.*

Few credible scientists believe CDR techniques to be a panacea. The approach has attracted somewhat less attention and different kinds of controversy than SRM, which Keith (2011) calls "slow, expensive and effective," as explained below.

Slow: Global yearly emissions of CO_2 are 34 million cubic metric tons, resulting in an accumulation of 500 billion tons of anthropogenic CO_2 in the atmosphere. Relying heavily on CDR as part of a climate response strategy means creating a massive industry—perhaps the biggest engineering project in human history—to steadily remove this mass of gas from the atmosphere one molecule at a time.

Expensive: A 2011 study by the American Physical Society concluded that collecting CO_2 directly from the atmosphere "is not currently" economically viable despite "optimistic" technical assumptions (APS 2011). It estimated that the basic cost of a system that could be built today would be about $600/ton, an order of magnitude more than the estimate for low-carbon energy sources.

Effective: CDR methods build off commercial techniques that work in submarines and space shuttles to clean air of CO_2 gas, and promise fewer side effects than SRM methods.

A number of startups are focusing on different techniques for CDR. In 2007 Sir Richard Branson launched a $25 million contest called the Virgin Earth Challenge to encourage the development of technologies that "will result in the net removal of anthropogenic, atmospheric greenhouse gases each year for at least ten years without countervailing harmful effects."[1] The eleven contest finalists represent a decent survey of leading commercial entities in this area, including firms that propose to sequester carbon in biochar added to soil, to directly capture atmospheric CO_2 through chemical methods, or to burn biofuels and sequester the resultant CO_2 in the ground.

European governments have more organized programs to support climate engineering research than the United States.

Geoengineering Research Policy and Public Opinion

Several European governments have supported organized programs to support climate engineering research. The United States has none. Studies on the governance of climate engineering approaches are being conducted by a coalition co-led by the UK Royal Society (SRM Governance Initiative), an Oxford University group on a two-year grant (Climate Geoengineering Governance project), and the European Transdisciplinary Assessment of Climate Engineering project, led by the Institute for Advanced Sustainability Science in Potsdam, Germany.

Meanwhile, work on the ethics of climate engineering has yielded, among other things, the so-called "Oxford Principles," proposed to restrict research into SRM and CDR (Rayner et al. 2009). They include the following guidelines:

- That SRM be regulated as a public good
- That the public be involved in research related to SRM decisions, including field experiments
- That research plans and results be transparent and shared publicly
- That bodies independent of researchers studying climate engineering assess the environmental and socioeconomic impacts of research
- That decisions about deploying technology on a global scale be made only when "robust governance structures" to oversee such efforts are in place.

A number of expert panels (e.g., Long et al. 2011) have urged the United States to create a dedicated research program in this area. But although the National Science Foundation has supported a handful of studies on SRM, and funds from various agencies have supported work applicable to CDR approaches, there is no integrated, organized effort in the federal government.

Several studies exploring public opinion on climate engineering technologies have been published. In August 2011 Cardiff University released results of a quantitative public engagement research project involving about 35 people that met for a day and a half. "Very few people were unconditionally positive about either the idea of geoengineering or the proposed [SPICE] field test. However, most were willing to entertain the notion that the test as a research opportunity should be pursued" (Parkhill and Pidgeon 2011).

An Internet poll of 3,105 American, Canadian, and British individuals published in 2011 found that 8% and 45% of respondents, respectively, correctly defined the interchangeable terms "geoengineering" and "climate engineering" (Mercer et al. 2011). In the same survey, respondents were asked to rate statements from 1, for "strongly disagree," to 4, for "strongly agree." For the statement "If scientists find that Solar Radiation Management can reduce the impacts of global warming with minimal side effects, then I would support its use," the average response was 3.01. The statement "Solar Radiation Management will help the planet more than it will hurt it" received an average response of 2.49. The results suggest that geoengineering could be viewed favorably by the public.

Conclusion

As the world's population contends with the challenge of climate change, respected scientists will continue studying climate engineering as part of a suite of responses—the most important of which is the immediate curtailing of greenhouse gas emissions. For

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[1] Virgin Earth Challenge announcement; posted online at www.virgin.com/subsites/virginearth/ (accessed July 28, 2012).

policymakers and researchers in this area, the following considerations will have to be taken into account: the need to address risks inherent to the two types of climate engineering through research despite a lack of dedicated funding for such work in the United States; the conduct of such studies, including possible field studies, in an ethical way; and ongoing, open debate on the study and use of climate engineering while mindful of public opinion, still nascent, on the prospect of deploying the technology.

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Research shows that the judicious targeting of clouds and selection of the size and composition of particle emissions can produce substantial cooling effects.

Offsetting Climate Change by Engineering Air Pollution to Brighten Clouds

Lynn M. Russell

Lynn M. Russell is a professor of atmospheric chemistry at the Scripps Institution of Oceanography of the University of California, San Diego.

Natural, industrial, and residential combustion produces both aerosols that cool the Earth and CO_2 that warms it, and the amount of combustion worldwide has increased substantially since the invention of the steam engine as well as with the increase in populations relying on wood and char burning. Natural and early man-made combustion processes emitted aerosols and CO_2 roughly proportionally, although the ratios of emission types were dependent on burning conditions. In the wake of smog-induced respiratory-health-related deaths in London in 1952, and ensuing legislation in favor of limiting emissions in the United States and Europe, "air quality engineering" was developed to reduce combustion-related aerosol emissions. But the reductions—without corresponding reductions in CO_2 emissions—led to more warming (with some offset for reductions in absorbing aerosol emissions). One approach to "climate engineering" is to undo these reductions in aerosol emissions in a way that avoids the health and visibility impacts of pollution but still allows for particles to cool the Earth both by reflecting sunlight directly and by brightening clouds (which magnify the scattering of light with water). The engineering challenge with this approach is that clouds are the least understood component of the climate system, and current models cannot reliably predict their formation and properties. Recent research in the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 illustrates that judicious selection of the meteorological regime and the size and composition of particle emissions can achieve substantial cooling effects. However, socioeconomic questions about climate engineering remain—such as the possibility that, if implemented, sudden cessation of enhanced particle emissions could exacerbate the climate effects on ecosystems and might interfere with oceanic and terrestrial ecosystem processes—thus requiring cautious and comprehensive research.

Background

The fundamental physics that control the global mean surface temperature are well understood: about one-third of the incoming solar radiation is reflected back to space by the Earth's albedo and the remaining two-thirds is absorbed at the surface, then emitted as longwave energy. In this way the incoming and outgoing energy at the top of the atmosphere largely balances the energy leaving, after partially trapping some of the energy by the greenhouse effect of atmospheric water vapor and clouds as well as greenhouse gases (IPCC 2007). These interactions constitute the Earth's radiative energy balance, as illustrated in Figure 1. Higher surface mean temperatures (T_{surf}) are due to the greenhouse effect, caused by the man-made release of CO_2 and other greenhouse gases. Increasing albedo (α) can offset CO_2-enhanced greenhouse warming by increasing the shortwave reflection of clouds. And clouds can be brightened to increase their reflectance by adding aerosol particles, which increase the number and decrease the mean size of cloud droplets. An example of such brightening is provided by the "ship tracks" created by the emissions of cargo ships crossing the Pacific Ocean, as shown in Figure 2.

Keeping in mind that maintaining global mean surface temperature does not imply that regional temperatures or precipitation patterns are kept constant, engineering the global mean surface temperature to reduce changes from present-day conditions could be sufficient to alleviate some of the most severe effects of global warming. Adding aerosol is straightforward, since particle production is a side effect of most combustion processes as well as a result of vaporization of liquids in condensable conditions. The real challenge in engineering aerosol particles to offset climate change by brightening clouds is predicting how the Earth system, and in particular its clouds, will affect the albedo response to increased particles.

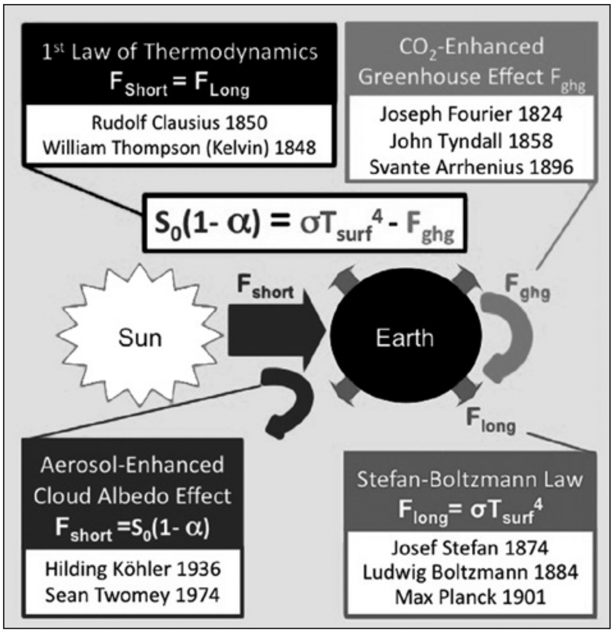

Figure 1 Diagram illustrating a simplified version of the Earth's energy balance between incoming shortwave radiation (F_{short}) from the sun and outgoing longwave radiation (F_{long}) from the surface, showing the two underlying equations (the 1st law of thermodynamics and the Stefan-Boltzmann equation) and two enhanced effects (the CO_2-enhanced greenhouse effect and the aerosol-enhanced cloud albedo effect), along with the key scientists who made seminal contributions in each area. The Stefan-Boltzmann is constant σ, the Earth's albedo is α, the global mean surface temperature (approximating the Earth as a black body) is T_{surf}, and F_{ghg} is the radiation reemitted to Earth by greenhouse gases (and other longwave-absorbing components in the atmosphere). This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

Recent Model Simulations of Cloud Brightening

Model simulations have established the climate impacts of distributing enough particles to modify enough clouds to offset sufficient global warming to delay or lessen some of the effects expected in the Earth's changing climate (Latham 1990, 2002; Latham et al. 2008). Some schemes focus on a perceived need for engineering and development of new technology, such as Flettner rotors and high-efficiency seawater atomization (Salter et al. 2008). Other studies use detailed global modeling investigations to show what fraction of clouds are brightened, with more aggressive increases in brightening resulting in exacerbation of climate in some regions even as others are improved (Rasch et al. 2009). Global simulations have also shown that where clouds are targeted is important, as some choices result in exacerbation of drought conditions in some regions (Korhonen et al. 2010; Rasch et al. 2009). In addition, recent studies have investigated the complexities of aerosol cloud interactions, including

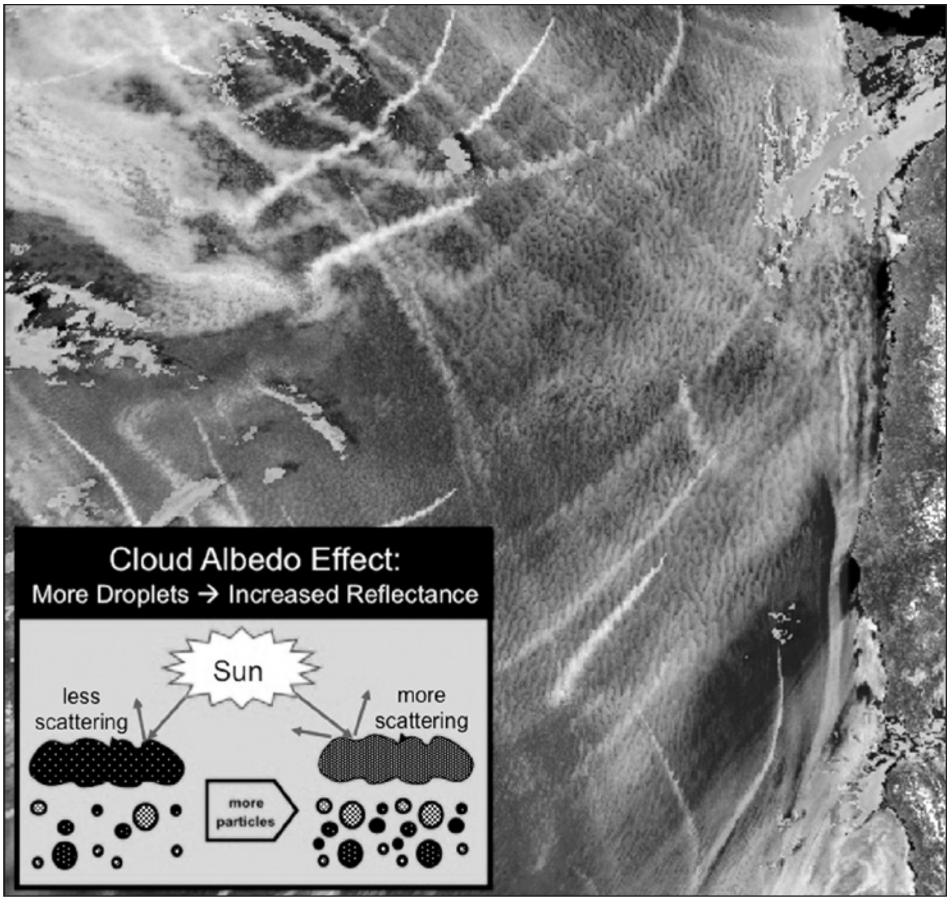

Figure 2 Enhanced multispectral image of the west coast of North America on June 21, 1994 from the NOAA Advanced Very High Resolution Reflectance (AVHRR) satellite, showing reflectance of low clouds (gray) with tracks from cargo ships (white). High clouds (light gray with shadow), land (dark gray on right side), and clear sky over ocean (along coast at right). Compiled by Kurt Nielsen of the Naval Postgraduate School (reproduced with permission). This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

the damping of cloud brightening by reductions in cloud supersaturation (Korhonen et al. 2010) and by overlapping plumes[1] of particles (Wang et al. 2011).

However, aerosol-cloud-radiation interactions are widely held to be the largest single source of uncertainty in projections of climate change due to increasing anthropogenic emissions. The underlying causes of this uncertainty in modeled predictions are the gaps in fundamental understanding of cloud processes (IPCC 2007). Although there has been significant progress with both observations and models, and the qualitative aspects of the indirect effects of aerosols on clouds are well known, the quantitative representation of these processes is nontrivial and limits the ability to represent them in global climate models. Current global models lack (1) accurate aerosol particle activation, with associated implications for the profiles of supersaturation, vertical velocity, liquid water content, and drop distribution; (2) realistic microphysical growth and precipitation processes that control the formation and impacts of drizzle on cloud structure, lifetime, and particle concentration; and (3) eddy-based transport processes that control the effects of entrainment on cloud thickness and lifetime as well as the dispersion of aerosol plumes. These basic scientific issues have not been addressed by climate models or by climate engineering proposals that involve perturbing marine stratocumulus; the following section describes work by our multi-institution collaboration to address them.

New Experimental Evidence of Cloud Brightening

To learn more about the cloud physical processes that affect aerosol-cloud-radiation interactions, we designed the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 as a targeted aircraft campaign with embedded modeling studies, using the Center for Interdisciplinary Remotely Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft and the R/V *Point Sur* in July 2011 off the coast of Monterey, California, with a full payload of instruments to measure particle and cloud number, mass, composition, and water uptake distributions (Russell et al. 2013; Shingler et al. 2012). Three central aspects of the collaborative E-PEACE design are described below, followed by highlights of the findings.

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[1] Cloud brightening is nonlinear, so two plumes of particles that overlap each other do not typically produce twice as much brightening.

1. Controlled particle sources were used to separate particle-induced feedback effects from natural variability. We have investigated three types of sources of different particle sizes and compositions to characterize specific aspects of aerosol-cloud interactions: (1) ship-emitted particles at rates of 10^{16} to 10^{18} s^{-1} with dry diameters between 50 and 100 nm (Coggon et al. 2012), (2) shipboard smoke generator particles at rates of 10^{11} to 10^{13} s^{-1} with dry diameters between 50 nm and 1 μm, and (3) aircraft-based milled, coated salt particles at rates of 10^{9} s^{-1} with dry diameters between 3 and 5 μm. The shipboard smoke generators are shown in Figure 3.
2. Satellite observations showed that not all ship tracks cause cloud brightening (Chen et al. 2012), indicating a variety of cloud feedback responses to increased particle concentrations. These observations were compared to the features predicted by large eddy simulations and aerosol-cloud parcel modeling of the impacts of turbulence, precipitation, and other cloud processes on the number concentration and size distribution of cloud drops (Lu and Seinfeld 2005, 2006; Russell et al. 1999).
3. The track from the controlled emission of smoke-generated particles demonstrated efficient cooling of clouds at very low warming cost, using existing technology and minimal resources. We noted that cooling outweighed warming by a factor of 50 on the day that a track was observed (Russell et al. 2013). This cooling effect exceeds that of commercial shipping, for which track-making ships induce twice as much cooling as warming (on days when tracks formed).

One of the most interesting results of E-PEACE was the activation into cloud droplets of smoke particles composed almost entirely of organic constituents (Shingler et al. 2012). This result was surprising because many organic components are hydrophobic and do not serve as effective cloud nuclei at supersaturations below 0.2%. The large diameter of smoke particles makes it possible for them to activate with fewer soluble constituents.

A second finding is the formation of tracks from the smoke particles in cloud-covered marine boundary layers. The organic smoke particles not only activated to cloud droplets but also did so in sufficient numbers to form a track with a detectable increase in brightness. However, there was a range of brightening observed for the many different tracks formed by particle emissions from fairly similar cargo ships (Chen et al. 2012), indicating that cloud feedback processes play an important role in determining cloud brightening.

The third important finding of E-PEACE was the frequency of low clouds with multiple layers, which reduce the impact of particles on clouds. Tracks did not

FIGURE 3 Operation of smoke generators aboard the research vessel (R/V) *Point Sur* for E-PEACE in July 2011. This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

form every day because of either the absence or structure of clouds near the ship. To produce a track with a significant albedo effect, the cloud layer needed to be uniform and single-layered. In addition, for rapid mixing of particles into the cloud layer, the layer needed to be below approximately 500 m. During the 12 days of the E-PEACE cruise, multiple cloud layers of 100 to 1000 m were present on more than half. Since particles emitted by ships on the ocean surface are usually transported only to the lowest cloud layer, their modification of droplet distributions does not appreciably change the albedo seen from above the top cloud layer. In such cases, particles have little effect on the radiation balance. The presence of low cloud layers overlying the layers affected by the smoke particles resulted in a low frequency of track formation. This finding is significant because it shows the need for representing small-scale cloud structure in global climate models in order to improve predictions of aerosol-induced cloud albedo changes.

> *The E-PEACE results provide a proof of concept that cloud brightening to reduce global mean warming is possible on small scales for limited time.*

Implications for Climate Engineering

The E-PEACE results provide a proof of concept that cloud brightening to reduce global mean warming is possible, with existing, decades-old technology, for some cloud conditions (but it will not reduce drought or ocean acidification). Track formation requires sufficient particle production to increase droplet number by 100 to 300 cm^{-3} over well-mixed boundary layers 100 m to 600 m high and spanning track widths of several kilometers. Cargo ships and portable smoke generators can both easily emit 10^{16} to 10^{18} s^{-1}, which is sufficient at wind speeds of up to 10 m s^{-1} to make tracks in unpolluted marine air. The advantage of smoke generators for climate engineering is that the lower fuel consumption by the much smaller ship has a substantially lower CO_2 cost, making cooling more efficient.

However, the radiative effects are not the only ones to be considered before deploying on a large scale (Russell et al. 2012). In particular, careful research is needed to assess the impacts of particle deposition on ocean and downwind terrestrial ecosystems; sustained changes in particle deposition could have deleterious impacts on ocean and land biota. Furthermore, shifts in precipitation patterns and direct radiation at the surface, if substantial, could affect crop production. And implementation of cloud brightening in regions near susceptible human populations could affect health.

Conclusions

Although the technology for particle emission and distribution exists, the engineering required for cloud brightening is hardly trivial. The most critical challenges to engineering the design of large-scale cloud brightening are (1) cloud feedback processes that affect the cloud response to aerosol enhancements and reduce the expected brightening, (2) multilayered clouds that mask changes in underlying clouds, and (3) ecosystem impacts of particle deposition (Russell et al. 2012). These issues require region-specific observations and small-scale, short-duration testing to determine realistic constraints for modeling. In addition, although particle production is feasible with existing technology, there are ample opportunities for optimizing the efficiency of particle emission processes and for minimizing their ecosystem impacts.

Knowledge of aerosol-cloud interactions remains sufficiently uncertain that consideration of their use for climate engineering is premature. Substantial advances are needed in understanding of aerosol and cloud physics to quantify their role in climate change, and such advances require experimental as well as modeling studies. If such studies demonstrate the effectiveness of particles for cloud brightening, it may be possible to use this method to offset some of the warming to the global mean surface temperature caused by greenhouse gases.

Going Forward

The seriousness of the consequences of global warming merits research into the possibility of using cloud brightening for climate engineering. However, while cloud brightening will target atmospheric emissions outside of national boundaries (since offshore marine stratocumulus have some of the largest impact on albedo) in areas that largely lack environmental regulations, any large-scale implementation should involve multinational agreement and cooperation, as well as compensation for unexpected and harmful consequences.

Furthermore, as with any solar reflection method that does not also reduce greenhouse gases, once initiated the cessation of cooling would likely cause accelerated warming as the system returns to the nonmasked warming (Russell et al. 2012).

In summary, while cloud brightening could be appropriate to prevent tipping points (such as massive sea ice loss, which some predict may occur as early as 2015[2]), implementation of cloud brightening to offset climate warming should be considered as an option only after sufficient research is devoted to better constraining aerosol-cloud-radiation interactions.

Acknowledgments

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[2] See for example an article in the September 14, 2012, issue of *The Guardian*, "Arctic expert predicts final collapse of sea ice within four years"; available online at www.guardian.co.uk/environment/2012/sep/17/arctic-collapse-sea-ice?newsfeed=true (accessed November 9, 2012).

Electric vehicles show promise in minimizing reliance on fossil fuels, but their widespread use will likely require a revolutionary advance in energy storage technology.

Keeping Up with Increasing Demands for Electrochemical Energy Storage

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The interest in vehicle electrification is unprecedented. Several automotive manufacturers are producing or planning to produce hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fully or battery electric vehicles (BEVs). Lithium-ion (Li-ion) battery technology is the current leading candidate to meet the near- and medium-term needs for electric vehicles. Leveraging considerable growth and development from the manufacturing of batteries for microelectronics, Li-ion technology has advanced significantly in the last decade. However, the leap from small-scale microelectronic batteries (tens of watt hours) to electric vehicle battery packs (tens of kilowatt hours) is not trivial. Performance metrics such as cost/kilowatt hour, specific energy (Wh/kg), specific power (kW/kg), safety, and cycle life are considerably more demanding for electric vehicles than for laptops and cell phones. Electric vehicles (EVs) show promise in minimizing reliance on fossil fuels, but their widespread use will likely require a revolutionary advance in energy storage technology. Research in sophisticated and efficient power electronics, battery/cell telemetry, safety, thermal management, and schemes to recycle/reuse EV batteries can help to establish a solid foundation for the development and use of EVs. This article provides an overview of energy storage technology for vehicle electrification, highlights challenges, and discusses opportunities at the frontiers of battery research.

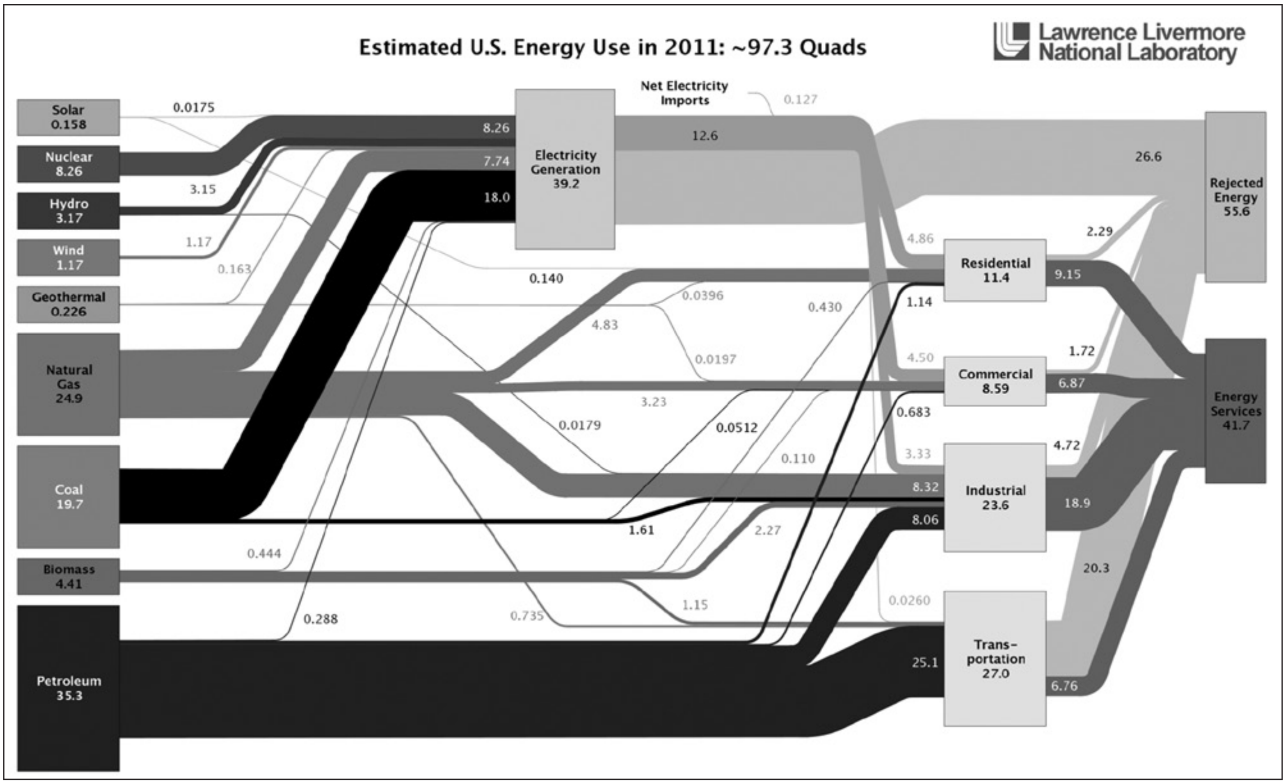

FIGURE 1 Energy use in the United States in 2011. This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

The Need for Advanced Energy Storage

In terms of sustainability, minimizing dependence on fossil fuels and reducing CO_2 emissions are compelling arguments to electrify vehicles. And from a practical perspective, EVs can take advantage of existing infrastructure for electrical power production and transport—infrastructure that will soon be bolstered by efforts to augment renewable energy production whose primary byproduct is electrical power (e.g., through photovoltaic cells and wind turbines).

If electrical energy becomes the preferred form of energy, electrochemical energy storage is a natural fit. In contrast, hydrogen fuel cell technology requires an entirely new infrastructure to efficiently produce hydrogen and then transport, store, and reconvert it to electrical energy.

To put into perspective the amount of energy consumed by the transportation sector, of the total 2.85×10^{16} watt-hours (1 Quad = 2.93×10^{14} watt-hours) of energy used by the United States in 2011 27.7% (7.91×10^{15} watt-hours) went to transportation (Figure 1).[1] However, due to the relatively low chemical-to-mechanical energy conversion efficiency of internal combustion engine technology (ICE), the ratio of serviceable to rejected energy is disproportionately low compared to other energy use sectors.

If EVs can improve energy efficiency in the short term and the technology for non-fossil-fuel-based/renewable electrical power generation can be realized in the long term, the benefits to our country's current and future sustainability are clear. Assuming the latter, the following discussions focus on electrical energy storage, specifically batteries.

Challenges for Electrochemical Energy Storage and Use in EVs

Defining the ideal battery for EVs is complicated because of the numerous powertrain configurations involved in HEVs, PHEVs, and BEVs; for example, the capacity (kWh), power (kW), and cycle life can be considerably different for an HEV compared to a BEV (Khaligh and Lee 2010). To simplify discussion, this article focuses on BEVs with battery characteristics that can power a four-seat vehicle for approximately 100 miles on a single charge, criteria favorable

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[1] These data and the accompanying figure are from the Lawrence Livermore National Laboratory website, https://flowcharts.llnl.gov/content/energy/energy_archive/energy_flow_2011/LLNLUSEnergy2011.png, accessed November 9, 2012.

for widespread adoption.[2] Figure 2 shows the necessary performance attributes of an effective EV battery.

Vehicle range is determined by the amount of energy stored in the battery and the rate at which the energy is expended to propel the vehicle. A 23 kWh battery used to power a ~70k W electric motor is believed to be sufficient to achieve a range of about 160 km. The mass and volume of the battery should be minimized to reduce the vehicle mass while maximizing vehicle cabin volume, respectively.

Vehicle acceleration is determined by specific power (kW/kg) or how quickly the stored energy can be extracted per unit mass of battery. A common metric is in the single to multi-kW/kg range (e.g., 1–3 kW/kg).

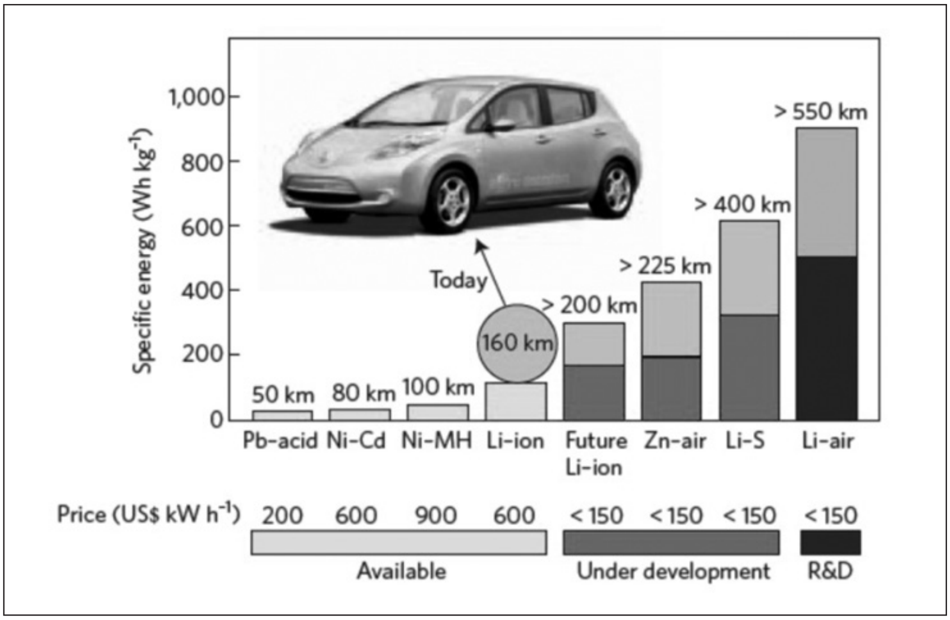

Figure 3 Comparison of battery technologies currently available and under development (Bruce et al. 2012). Darker shading in the bars indicates the specific energy values in laboratory scale prototypes; lighter shading indicates the range of anticipated specific energy values for Li-S and Li-air technologies, respectively. Cd, cadmium; Li, lithium; MH, metal hydride; Ni, nickel; Pb, lead; Zn, zinc. This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

Replacement of the ICE powertrain with an electric powertrain should not considerably add to the vehicle cost, and the cost of the battery pack should be less than $5,000.

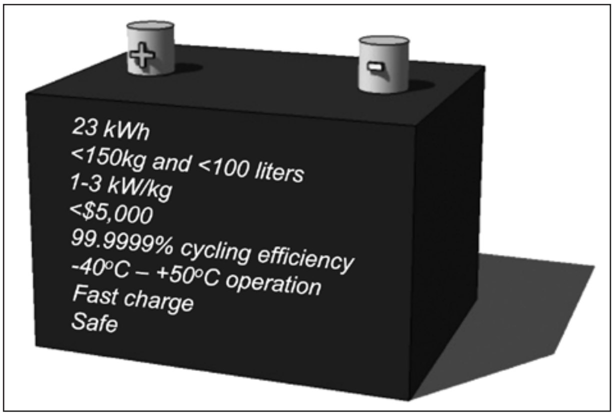

Figure 2 Battery performance criteria to power the next generation of battery electric vehicles.

Ensuring consistent, long-term vehicle range requires a charging efficiency of 99.9999% such that approximately 80% of the original battery capacity is available at the end of the vehicle's life.

Widespread use of BEVs will entail operation in dramatically different climates, so the battery must be capable of operating at relatively low and high ambient temperatures.

Although it is difficult to quantify how fast is fast enough, the issue of range anxiety may be addressed if a battery pack can be charged at a charging station as quickly as a gasoline tank can be filled at a gas station.

Last, and perhaps most importantly, the battery technology must be safe and reliable.

Li-ion Batteries

Of the battery chemistries available today (Figure 3), Li-ion has the highest specific energy (Tarascon and Armand 2001) and is the only technology capable of meeting the criteria shown in Figure 2. While other energy storage technologies such as supercapacitors, flywheels, and compressed air are in development, only Li-ion batteries are mature enough or meet the necessary criteria or both (Dunn et al. 2011). Li-ion batteries also have the distinct advantage of both intrinsically high cell voltage (>3 V) and the capacity to store lithium ions

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[2] Whether this BEV performance standard is specifically required to significantly impact energy consumption is not yet known, but agencies and auto companies generally agree with this definition (Bruce et al. 2012; CCC 2012; Thackeray et al. 2012).

in the solid state, resulting in high specific energy and low cell volume (energy density), respectively.

In a typical Li-ion cell (Figure 4), lithium ions are shuttled, with relatively high efficiency, between the anode and cathode via a liquid Li-ion electrolyte (EVSAE 2012). Graphite (in powder form) is by far the most common anode that reversibly uptakes and releases lithium ions between graphene sheets. The cathode consists of a ceramic of nominal formula $LiMO_2$ (in powder form), where M stands for a transition metal such as cobalt (Co), manganese (Mn), or nickel (Ni) that can change valence states upon insertion/extraction of Li-ions. During discharge, it is more energetically favorable for the graphite anode to release its Li-ions and for the cathode uptake Li-ions to reduce the M valence charge (e.g., M^{4+} to M^{3+}). This shuttling of lithium ions from the anode to the cathode is accompanied by the simultaneous passing of electrons through an external circuit to power the electric vehicle.

Since their invention in 1991 by Sony and professor John B. Goodenough, Li-ion batteries have been integrated into cell phones, laptop computers, and other microelectronics (Figure 5). And some of the first Li-ion-powered EVs were not terrestrial but instead vehicles sent to survey the surface of Mars in 2003 through NASA's Mars Exploration Program (Huang et al. 2000). The Mars Exploration Rover Li-ion batteries started development in 1996 and were flight qualified and implemented in 2003, a testament to how quickly Li-ion battery technology can progress.

In 2008, a combination of factors led to a significant push to improve vehicle fuel efficiency, resulting in a rapid transformation of the auto industry with an emphasis on vehicle electrification. In 2011 GM rolled out the PHEV Volt and Nissan the BEV Leaf, and in 2012 Ford started selling the BEV Ford Focus.

These past and recent successes are impressive, but Li-ion battery packs still require considerable reductions in cost as well as increases in specific energy to extend vehicle range. The following section presents a materials perspective on opportunities in electrochemical energy storage and milestones whose achievement will address these issues.

Opportunities in Electrochemical Energy Storage

Unlike lead (Pb)-acid, nickel-cadmium (Ni-Cd), and nickel–metal hydride (Ni-MH) battery technologies, Li-ion technology performance has room for improvement, as shown in Figure 3. Advanced electrode and cell designs and electrode material breakthroughs (Thackeray et al. 2012) may enable a doubling in energy density and a fourfold reduction in cost compared to available Li-ion technology. Eventually, however,

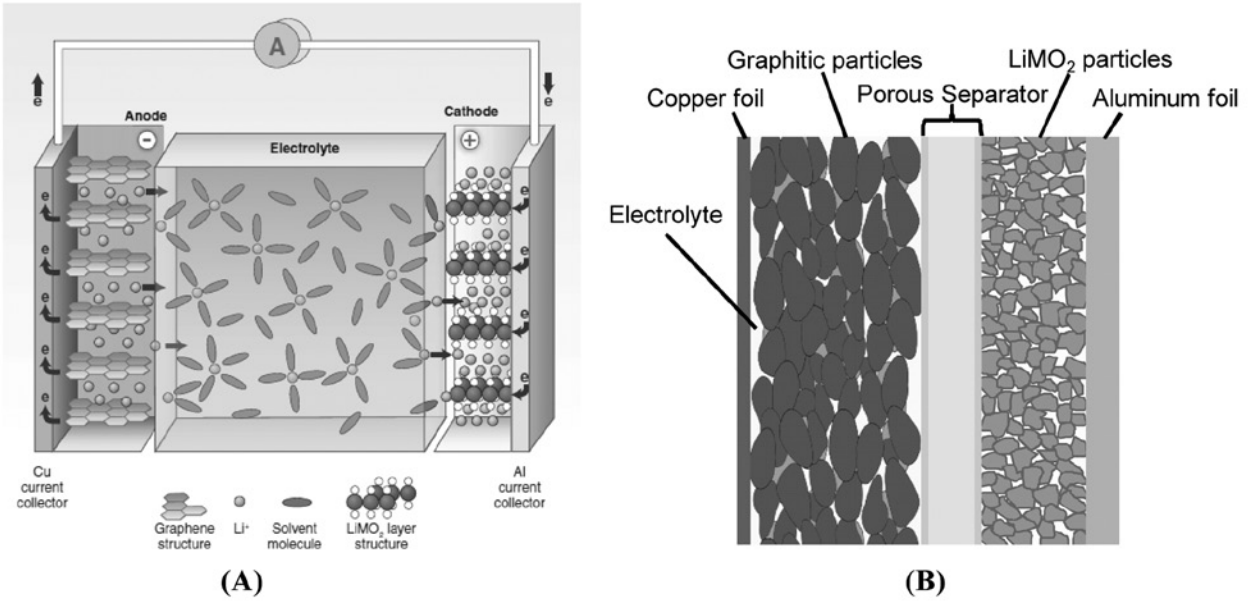

FIGURE 4 Schematic of a lithium (Li)-ion cell: (A) at the atomic scale (A, amperes; reprinted with permission from Tarascon and Armand 2001) and (B) at the microscopic scale (adapted from EVSAE 2012). This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

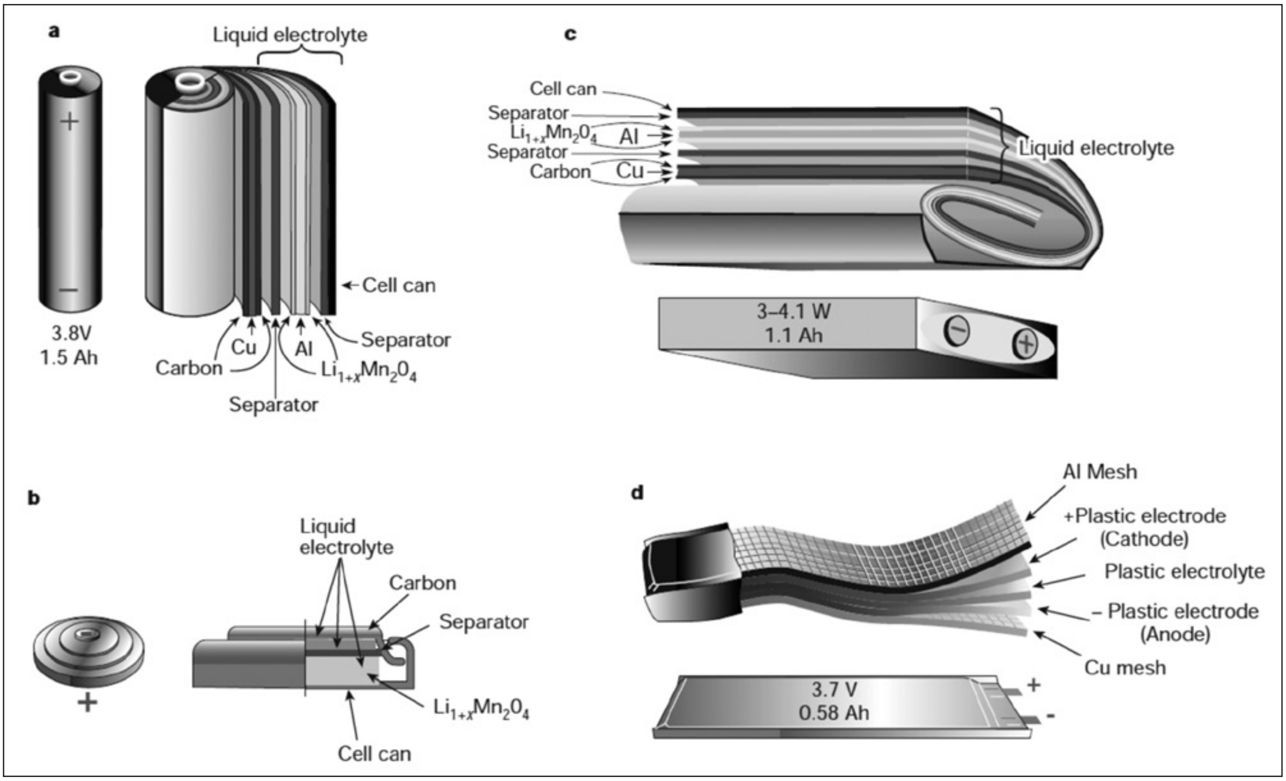

FIGURE 5 Li-ion batteries come in a variety of designs: (a) spiral wound cell, (b) button or watch cell, (c) prismatic cell, and (d) solid polymer (electrolyte) battery (Tarascon and Armand 2001). Ah, amp-hour; Al, aluminum; Cu, copper; V, volt. This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

Li-ion technology improvements will crest, requiring a breakthrough in battery technology to approach the cost target (~$150/kWh) and the range of an ICE powertrain vehicle (>400 km).

Several research and government agency reports (e.g., Bruce et al. 2012; CCC 2012) present complementary near-term roadmaps to guide battery research and development over the next two decades. Three milestones extrapolated from these roadmaps illustrate the frontiers of battery development, with substantial steps in 2015 and 2020 followed by a revolutionary leap in 2030.

2015 Milestone: Optimize Current Materials and Cell Component Design

In the short term the focus is on optimization of materials and conventional liquid electrolytes. At present, approximately 50% of a battery pack mass is dead weight (Johnson and White 1998). For example, in the cell cross-section shown in Figure 4b, only the graphite anode and $LiMO_2$ particles store lithium and therefore energy; the electrical current–collecting foils, electrolyte, separator, and hermetic container do not store energy.

Increasing the mass/volume fraction of active material is one strategy to improve specific energy. Making thicker, less porous electrodes is a popular approach to achieve this, but thicker and less porous active electrode layers impede the transport of ions in the electrolyte and thus reduce power (Buqa et al. 2005).

Furthermore, the nonuniform current in thicker electrodes can cause metallic lithium to deposit on the anode and oxygen gas to be released from certain $LiMO_2$ cathodes, which can be a safety hazard in the presence of heat and flammable electrolyte solvents. These challenges can be addressed through research on advanced electrode designs, powder processing, and coating technologies (DOE 2010).

Cycle life is another concern that requires attention. A passivation layer forms on the surface of a graphitic anode particle during the solid electrolyte interphase (SEI). As lithium intercalates and deintercalates from graphite particles, the corresponding swelling and contraction create fissures in the SEI, resulting in the continuous and irreversible consumption of lithium and diminishing capacity retention. Again, improved electrode designs to homogenize charge flow could address this concern, as could the development of new electrolytes and/or electrolyte additives to make the SEI more robust.

Economies of scale will probably not play a significant role in minimizing cost per kilowatt hour (\$/kWh) (Bruce et al. 2012; CCC 2012) by 2015. Rather, new materials with appreciably better performance and lower cost are needed to bring costs down to the target of approximately \$150/kWh.

2020 Milestone: Electrode and Electrolyte Materials Breakthroughs

The 2020 milestone focuses on reducing cost rather than increasing specific energy, although it is hoped that the latter will increase by more than a factor of two. Once the electrode and cell design have been optimized, increases in the specific energy will require new electrode and complementary electrolyte materials that can store more lithium or charge-per-unit mass/volume and that have higher voltage (energy = amps × volts × time). If the new materials can be made at comparable or lower cost, a byproduct of increased specific energy will be a commensurate decrease in cost/kWh (Figure 3).

Alloying anodes such as silicon (Si)- or tin (Sn)-based electrodes will likely constitute the next generation of Li-ion battery anodes (Thackeray et al. 2012). The term "alloying" is used to describe the reversible, electrochemical reaction between lithium and a pure element such as silicon or tin.

Specific capacity (milliamp hours per gram, or mAh/g), which refers to the amount of lithium that an electrode can uptake and release, is commonly used where one mole (6.94 grams) of lithium can provide 26.8 Ah of electrical charge. Graphitic anodes have a theoretical specific capacity of 372 mAh/g, and silicon and tin have specific capacities of 4009 and 960 mAh/g, respectively, making the interest in these anodes apparent.

However, a >300% change in volume accompanies the uptake and release of lithium from silicon and tin, creating significant mechanical stresses that cause decrepitation and poor cycle life (Deshpande et al. 2010). One solution is to reduce the powder particle size from the typical micron scale to the nano scale and thus decrease the magnitude of strain. Creating nano Si wires with <100 nm dimensions, originally demonstrated by the Cui group (Wu et al. 2012), reduces the overall strain to minimize decrepitation and improve cycle life. Another approach is to increase cycle life by embedding Si or Sn particles in an elastic or compliant carbon matrix to create an encapsulation effect (Zhao et al. 2011). Envia Systems recently announced a 400 Wh/kg Li-ion cell pack using Si-based anodes, but it has yet to be commercialized (Thackeray et al. 2012). Advanced materials processing and materials engineering could play a major role in optimizing alloying electrode performance and reducing cost.

> *New materials with appreciably better performance and lower cost are needed to bring costs down.*

On the cathode side, there are two promising approaches. First, the cathode system, a composite layered structure, enables the full extraction of one molecular unit of lithium, or $x = 1$ per formula unit of $x\mathrm{Li_2MnO_3}(1-x)\mathrm{LiMO_2}$ (M = Mn, Ni, Co) (Thackeray et al. 2012). This type of material, developed by Thackeray and colleagues at Argonne National Laboratory, can deliver nearly twice the specific capacity compared to conventional $\mathrm{LiMO_2}$ cathodes.

There are a few practical concerns associated with this material strategy, however. For example, the lithium must come from the anode (which is not the case with conventional $\mathrm{LiMO_2}$ cathodes) and the charging voltage (4.6 V) is outside the stability window of most conventional electrolytes, resulting in diminished cycle life.

The second approach involves increasing the cathode reaction voltage from about 4.0 V to approximately 5.0 V to result in a 20% increase in specific energy, provided the specific capacity is comparable to that of conventional cathodes. Examples of high-voltage cathodes include $\mathrm{LiMn_{1.5}Ni_{0.5}O_2}$ and $\mathrm{LiMPO_4}$ (M = Co, Ni) (Allen et al. 2011), both of which are relatively mature compared to the composite layered cathodes described above, but the lack of stable electrolytes limits their widespread implementation.

Higher cell voltage (cathode side) and a stable SEI (anode side) with advanced anodes both require significant improvements in electrolytes. One approach is to integrate additives to conventional electrolytes to improve the high-voltage (cathode) stability. The Kang group achieved this by increasing the electrolyte stability to enable the use of $LiCoPO_4$ (4.8 V) cathodes (von Cresce and Kang 2011). A completely different approach involves a solid electrolyte material breakthrough using a ceramic rather than liquid electrolyte. The advantages could include higher stability (0 to >6 V) and perhaps safety as a flammable liquid electrolyte is replaced by a highly thermal and chemically stable ceramic.

A class of ceramics referred to as "fast-ion conductors" conducts lithium ions about as fast as a conventional liquid electrolyte. Additionally, these ceramics have negligible electronic conductivity and the Li-ion conductivity improves with increasing temperature. Recent examples of promising solid electrolytes include sulfur (S)-based (Kamaya et al. 2011) and oxide-based electrolytes (Murugan et al. 2007; Rangasamy et al. 2011) that exhibit Li-ion conductivities comparable to conventional liquid electrolytes.

Next-generation Li-ion batteries will require new materials for anodes, cathodes, and electrolytes. Advanced materials and ceramic processing technology based on lessons learned from the 2015 milestone will play a key role in achieving the 2020 milestone. The development of new electrolyte materials, in particular, will advance progress toward the 2030 milestone of enabling new battery chemistry beyond Li-ion technology.

Next-generation Li-ion batteries will require new materials for anodes, cathodes, and electrolytes.

2030 Milestone: Beyond Li-ion Batteries

If electric powertrains are to replace ICE technology, without raising concerns about cost or range, a new battery technology is required (Bruce et al. 2012). Three of the most popular battery chemistries that represent the frontier of energy storage are Li-S, Zn-air, and Li-air (the metal air batteries are actually semifuel cells, but for brevity and consistency they are referred to as batteries). Because the challenges related to Zn-air technology are relatively well known (Lee et al. 2011), the focus here is on Li-S and Li-air batteries, which are not as well understood.

Li-S is attractive because of its high theoretical energy density (2199 Wh/l), high theoretical specific energy (2567 Wh/kg), and the low cost and abundance of sulfur (Bruce et al. 2012). Factoring in the mass of the electrolyte, electrical current–collecting foils, packaging, and other features, the practical specific energy is reduced to approximately 600 Wh/kg, which is still considerably higher than that of advanced Li-ion batteries. In a Li-S cell, elemental lithium and sulfur are the reactants, a nonaqueous electrolyte shuttles lithium ions between electrodes, and, because sulfur does not have sufficient electrical conductivity, a specific porous carbon (Ji et al. 2009) is added to increase the effective electrical conductivity of the S-cathode.

Two challenges remain: (1) prevention of deleterious mechanisms that result from the formation of soluble Li-S compounds during cycling and (2) achievement of a stable/cyclable Li-electrolyte interface, a challenge since the 1980s when it led to the demise of rechargeable lithium metal anode batteries.

Li-air batteries are of two types: nonaqueous and aqueous (Bruce et al. 2012); the "air" in question is the source of oxygen and, for the aqueous batteries, water vapor. Nonaqueous batteries involve the reaction of lithium with oxygen gas (O_2) to form Li_2O_2. (The reference to "air" may be a bit misleading since both water vapor and carbon dioxide must be excluded from the reaction/cell in the nonaqueous configuration.) During discharge, lithium is transported through a nonaqueous electrolyte and reacts with O_2 in the presence of a porous carbon network and a catalyst to form solid precipitates of Li_2O_2. The theoretical energy density of this system is (3436 Wh/l) and the theoretical specific energy is (3505 Wh/kg). Some of the key challenges for nonaqueous Li-air batteries are (1) development of an oxygen-permeable membrane that excludes carbon dioxide and water vapor, (2) development of effective cathode electrodes that prevent pore occlusion resulting from the formation of solid byproducts during discharge, and (3) effective integration of catalysts to improve reaction kinetics.

In the second type of Li-air battery an aqueous electrolyte is used to transport lithium ions into a carbon cathode electrode to form lithium hydroxide (LiOH) during discharge. At lower concentrations LiOH is soluble in the electrolyte, whereas at higher concentrations (i.e., greater degrees of discharge) it precipitates out as a solid. The theoretical energy density of the aqueous variant is (2234 Wh/l) and the theoretical specific energy is (3582 Wh/kg). Some of the challenges that remain for aqueous Li-air technology are technologies to (1) protect the lithium metal anode from the aqueous electrolyte using a ceramic electrolyte membrane, (2) prevent reactions with carbon dioxide from ambient air, and (3) prevent pore and electrolyte interface occlusion when/if LiOH precipitates at higher depths of discharge. Although there are few examples of advanced prototypes, the projected specific energy for both Li-air variants is expected to be about 1000 Wh/kg.

The majority of the challenges involve the discovery of new materials and development of an electrolyte to enable the use of metallic lithium anodes. The need for ceramic electrolytes that protect the lithium metal anode is one aspect common to Li-air and Li-S technology. In addition to poor cycle stability, excess lithium is required to counter the effects of poor cycling efficiency. For example, two- to fourfold excess lithium may be necessary, thus reducing the energy density. One recent material breakthrough (Murugan et al. 2007) identified a new class of ceramic oxide electrolyte that is believed to exhibit the unprecedented combination of stability against lithium with high, room-temperature ionic conductivity (Figure 6).

In addition to new electrolytes, advanced catalyst and catalyst support electrodes, similar to those found in fuel cells, are required to improve rechargeability and power.

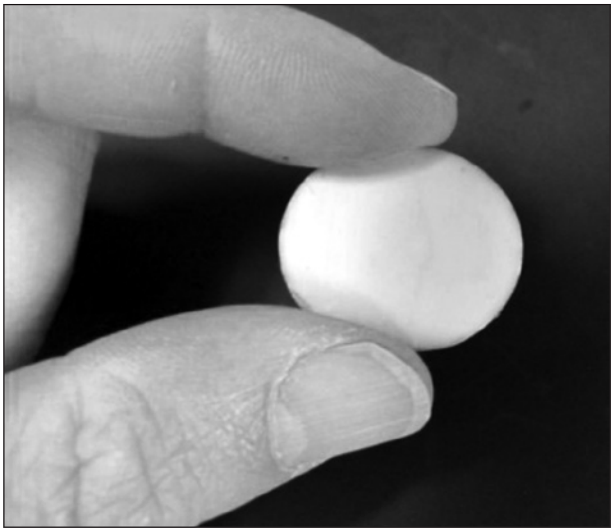

Figure 6 Ceramic electrolytes may enable the use of metallic lithium (Li) anodes. A new ceramic electrolyte referred to as LLZO ($Li_7La_3Zr_2O_{12}$) exhibits the unprecedented combination of high ionic conductivity and stability against metallic lithium and air. Shown above, a prototypical LLZO membrane fabricated in the Sakamoto lab using unique powder synthesis and sintering technology.

Conclusions

There is a compelling need for advanced electrochemical energy storage to power the next generation of electric vehicles. And interest in Li-ion technology is on the rise, if growing attendance at the 5-year-old annual symposium “Beyond Li-ion” is any evidence. But although Li-ion batteries offer substantial performance advantages over previous battery technologies, range capacity and cost are major challenges to overcome by 2015. Better electrode, cell, and pack design, together with advanced manufacturing and power electronics, will establish a solid foundation for future EV technology.

By 2020, material and electrolyte breakthroughs are expected to provide moderate improvements in BEV range—and dramatic reductions in cost. Anodes that are cheap (based on Si or Sn) are expected to uptake and release more lithium per unit mass. On the cathode side, the focus will be on increasing the voltage and lithium uptake and release per unit mass. Developing higher-stability liquid and solid electrolytes will complement higher-voltage cathodes and efforts to revolutionize energy storage in the long term (2030).

Provided the necessary electrical infrastructure is in place by 2030, a breakthrough in electrochemical energy storage is required if ICE technology is to be replaced by BEVs. Li-air or Li-S batteries may be the high specific energy, low-cost technology of the future, but significant materials and engineering challenges must first be overcome. Solving the lithium metal anode–electrolyte interface stability issue; developing novel catalyst/catalyst support cathodes; and creating stable, semipermeable solid electrolytes require further research and development if Li-air and Li-S technologies are to mature.

The frontiers of electrochemical energy storage are exciting from multiple perspectives, and are likely to generate significant engineering research and development opportunities in the coming decades.

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Informational needs in automobiles are transcending mechanical, electronic, and software boundaries to include programmed services for the driver and the vehicle itself.

The Car and the Cloud

Automotive Architectures for 2020

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Rahul Mangharam

Over the past two decades, automobile journey durations have doubled. Furthermore, travelers increasingly use their vehicle as a mobile office, meeting room, and even living room. With this evolution, informational and entertainment needs in the vehicle now transcend mechanical, electronic, and software boundaries to include services for the driver, passengers, and the vehicle itself.

Three trends are emerging in drivers' expectations for their vehicle: (1) continuous connectivity with both the infrastructure (e.g., smart traffic intersections) and other commuters, (2) enhanced levels of productivity and entertainment for the duration of travel, and (3) reduction in cognitive load through semiautonomous operation and automated congestion-aware route planning. To address these demands, vehicles should become more programmable so that almost every aspect of engine control, cabin comfort, connectivity, navigation, and safety will be remotely upgradable and designed to evolve over the lifetime of the vehicle.

Progress toward the vehicle of the future will entail new approaches in the design and sustainability of vehicles so that they are connected to networked traffic systems and are programmable over the course of their lifetime. To that end, our automotive research team at the University of Pennsylvania is developing an in-vehicle programmable system, AutoPlug, an automotive architecture for remote diagnostics, testing, and code updates for dispatch from a datacenter to vehicle electronic controller units. For connected vehicles, we are implementing a networked vehicle platform, GrooveNet, that allows communication between real and simulated vehicles to evaluate the feasibility and application of vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication; the focus in this paper is on its application to safety. Finally, we are working on a tool for large-scale traffic congestion analysis, AutoMatrix, capable of simulating over 16 million vehicles on any US street map and computing real-time fastest paths for a large subset of vehicles. The tools and platforms described here are free and open-source from the author.

New vehicle-to-vehicle communication technology will be able to issue safety alerts to approaching vehicles and prevent a pile-up.

Programmable Vehicles

Vehicles today are built in long design cycles and with electronic architectures that are static in both form and function. Technology adoption is considered only at the beginning of the design cycle, frozen for the lifetime of ownership of the vehicle (~12 years[1]), and often obsolete within 6 years.[2,3] In contrast, the vehicle of the future will be programmable with services for the long-term health and performance of both humans and vehicles.

Electronics and software for engine and cabin controls currently account for over 30% of the cost of an automobile, and this figure is expected to grow as vehicles evolve from mechanical to electronic to software-controlled to service-based mobile cyber-physical system (CPS) platforms. As new automotive electronic architectures are developed to enable remote diagnosis and reprogrammability throughout the life of the vehicle, drivers will be able to choose from a software component marketplace to enhance the safety, performance, and comfort of their vehicle.

Ensuring the safe and correct programming of the new service features is paramount. Automotive plug-and-play devices that communicate to and from the vehicle will allow new classes of services and customization such as online vehicle diagnostics, warranty management, networked infotainment, and integration of applications such as driver behavior and vehicle performance measurements for personalized insurance services.

Connected Vehicles

Every year, approximately 6.4 million car accidents occur in the United States, typically involving three people (two drivers and one passenger). That translates to roughly 19.2 million Americans injured in car accidents each year, or odds of 1:16 for every individual. Several sources[4] estimate that over 90% of vehicle crashes are due to driver negligence and therefore avoidable (Durić and Miladinov-Mikov 2008).

A vehicle's "safety bubble" is currently limited to its physical body, with integrated crash and proximity sensors (e.g., ultrasonic, LiDAR, radar). In the vehicle of the future, V2V and V2I wireless communication is expected to enhance safety. Such communication technology, when interfaced with the vehicle's powertrain and using audio and haptic feedback, will be able to issue safety alerts to all approaching vehicles during events such as sudden braking, loss of traction, or airbag deployment. Early warning messages communicated down the highway in a timely "multi-hop" manner (i.e., from one vehicle to another in a few hundred milliseconds) will allow for longer reaction and stopping time and thus prevent a pile-up.

Connected vehicle architectures for such safety-critical automotive systems require much work to ensure security and privacy together with the timely delivery of traffic alerts, warnings, and information updates.

Networked Traffic Systems

Delays due to traffic congestion cost Americans $78 billion in the form of 4.2 billion lost hours and

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[1] Polk.com. 2012. Average Age of Vehicles Reaches Record High, January 17. Available online at http://goo.gl/TN5Ow.

[2] US DOE Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program. 2010. Average Length of Light Vehicle Ownership, May 10. Available online at www1.eere.energy.gov/vehiclesandfuels/facts/2010_fotw622.html.

[3] Polk.com. 2012. Americans are keeping new vehicles an average of nearly six years, February 22. Available online at http://goo.gl/7R3N3.

[4] See, for example, *The Economist*. Look, No Hands: Automotive technology: Driverless cars promise to reduce road accidents, ease congestion and revolutionise transport, September 1. Available online at www.economist.com/node/21560989.

2.9 billion gallons of wasted fuel, and 35–55% of these delays are caused by point-based traffic incidents rather than recurring congestion. As the density of vehicles increases, there is a need for large-scale traffic congestion management such that real-time "eco-routing" can be provided to prevent, avoid, and alleviate traffic back-ups. Models and tools for nationwide traffic congestion management, with networked streaming vehicle data, are required to compute the fastest and most eco-friendly routes without new infrastructure costs.

In the Real-Time Systems Lab at Penn, we are investigating the design of such a platform to enable the scaling of traffic network operations to handle data processing for millions of vehicles, estimate and predict congestion, and facilitate route assignment as well as to model traffic operations and disaster response during congestion.

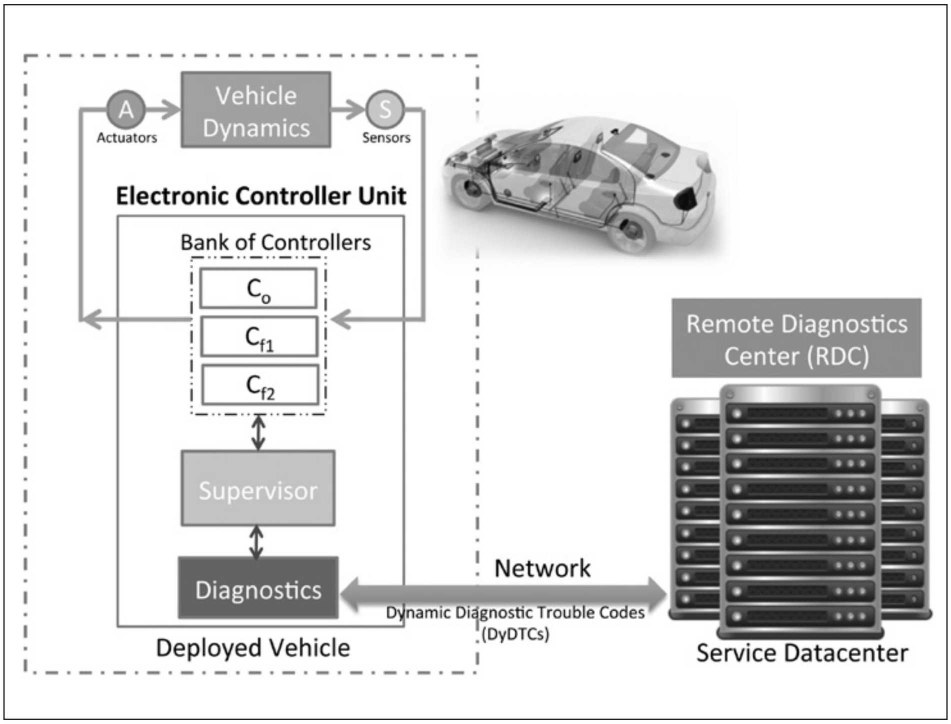

Figure 1 Remote diagnostics of automotive control systems showing the vehicle's software architecture (in dashed box) and the remote diagnostics center (RDC) communicating over a network link. The RDC communicates via the onboard "supervisor" with the vehicle control system to observe its state and update its software in the event of an unexpected fault. C_0, C_{f1}, C_{f2} = software-based controllers in the vehicle (e.g., for stability, traction, antilock braking, and cruise control). Using dynamic diagnostic trouble codes (DyDTCs), the RDC observes the state of the vehicle software for postmarket analysis of unanticipated faults.

In-Vehicle Systems: Remote Diagnostics, Testing, and Reprogramming

More than 20.3 million vehicles were recalled in 2010, many because of software issues related to electronic systems such as cruise control, antilock braking, traction control, and stability control. New and scalable methods are necessary to evaluate such controls in a realistic and open setting.

The increasing complexity of software in automotive systems has resulted in the rise of firmware-related vehicle recalls due to undetected bugs and software faults.[5] In 2009, Volvo recalled 17,614 vehicles because of a software error in the engine-cooling fan control module that could result in engine failure and possibly lead to a crash (NHTSA 2009). In August 2011, Jaguar recalled 17,678 vehicles because of concerns that the cruise control might not respond to normal inputs and once engaged could not be switched off.[6] In November 2011, Honda recalled 2.5 million vehicles to update the software that controls their automatic transmissions.[7]

Current automotive systems lack a systematic approach and infrastructure to support postmarket runtime diagnostics for control software (although at least one online source indicates that there is a significant effort to incorporate automotive software testing and verification at the design stage[8]). Once a vehicle leaves the dealership lot, its performance and operation safety are a "black box" to the manufacturers and the original equipment providers.

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[5] IEEE Spectrum. 2011. Honda Recalls 936,000 More Vehicles for Electrical and Software Fixes, September 7. Available online at http://spectrum.ieee.org.

[6] IEEE Spectrum. 2011. Jaguar Software Issue May Cause Cruise Control to Stay On, October 25. Available online at http://spectrum.ieee.org.

[7] Reuters. 2011. Honda recalls 2.5 million vehicles on software issue, August 25. Available online at www.reuters.com.

[8] AUTOSAR (Automotive Open System Architecture); www.autosar.org.

Furthermore, for the more than 100 million lines of code and 60-plus electronic controller units (ECUs) in a vehicle (Schäuffele and Zurawka 2005), there are only about eight standard diagnostic trouble codes (DTCs) for software and they are extremely general (e.g., "memory corruption"). Of the DTCs for software, none target the ECU software even though systems such as stability, cruise, and traction control are critical for safety.

In-Vehicle Diagnostics and Recall Management

The current approach to vehicle recalls is reactive: the manufacturer recalls all vehicles of a particular year/make/model only after a problem occurs in a significant number of them. For a software-related recall, the vehicle is taken to service center and a technician either manually replaces the ECU that has the faulty code or reprograms the ECU code with the new version provided by the manufacturer.

The wait-and-see approach to recalls has a significant cost in both time and money and may have a negative impact on the vehicle manufacturer's reputation. Furthermore, the current recall method relies on word of mouth or the transmission of manually logged information from the service centers to the manufacturer, which takes time—during which a safety-critical system may malfunction.

Consequently, there is an urgent need for systematic postmarket in-vehicle diagnostics for control system software so that issues can be detected early. An in-vehicle system would log sensor values and perform runtime evaluation of the states of the system controls. A remote diagnostic center (RDC) would receive the data (over a network link) to prepare a fault detection and isolation response (Figure 1), in the form of a proposed dynamic diagnostic trouble code (DyDTC) that "observes" the ECUs and system control tasks in question. Once sufficient data are captured, the RDC, using a gray-box model of the vehicle (i.e., with sensor and control system observation logs), executes system identification to build a model of the vehicle. It then develops a fault-tolerant controller to address the problem and the vehicle is remotely reprogrammed by a code update.

We have developed an early design of such a system, AutoPlug, although we recognize that the approach will be difficult in practice as it would require extensive runtime verification of the updated controller.

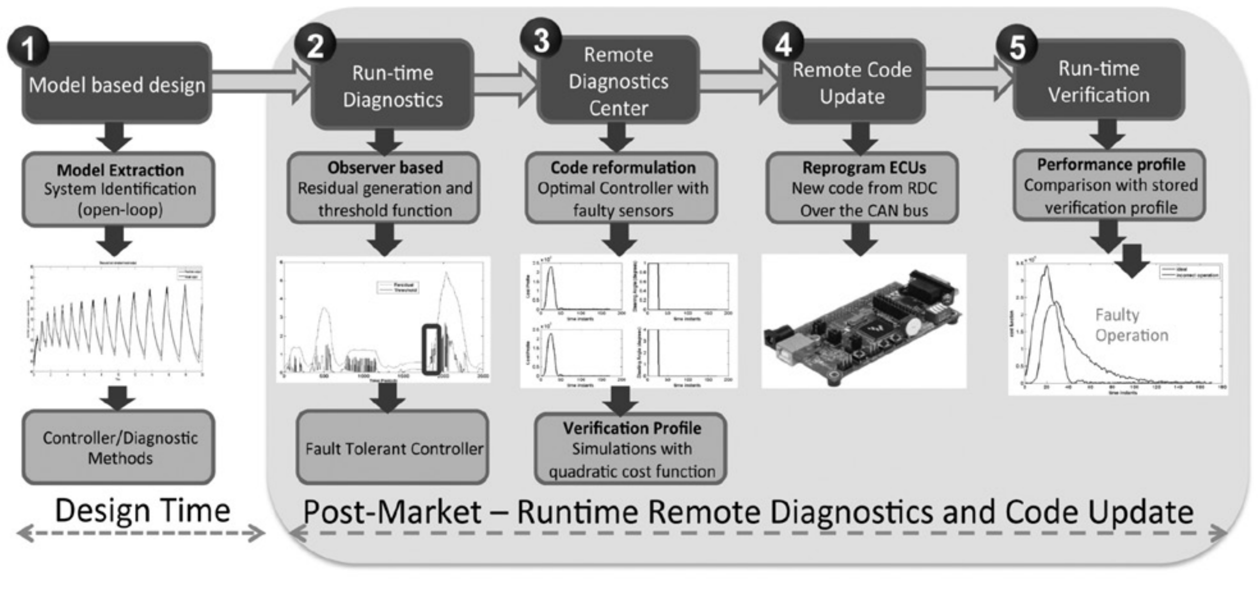


FIGURE 2 End-to-end stages of the AutoPlug automotive architecture. (1) When an unexpected fault is reported, the remote diagnostic center (RDC) sends custom diagnostic code to the vehicle to observe its performance. Using vehicle models developed during the design phase, the RDC safely observes the operation of the software on the vehicle while it is running. Using this information it extracts a new model for the vehicle (perhaps with changes due to wear and tear, faulty sensors, changes in suspension). (2-3) With the updated vehicle model, the control system design is reformulated to correct the faults in the vehicle. (4-5) The RDC remotely updates and verifies the correctness and safety of the reformulated control software. CAN = controller area network; ECU = electronic controller unit.

Overview of AutoPlug

AutoPlug is an automotive ECU architecture between the vehicle and an RDC to diagnose, test, update, and verify control software. Within the vehicle, we evaluate observer-based runtime diagnostic schemes and introduce a framework for remote management of vehicle recalls. The diagnostic scheme deals with both real- and non-real-time faults, with a decision function to detect and isolate system faults with modeling uncertainties.

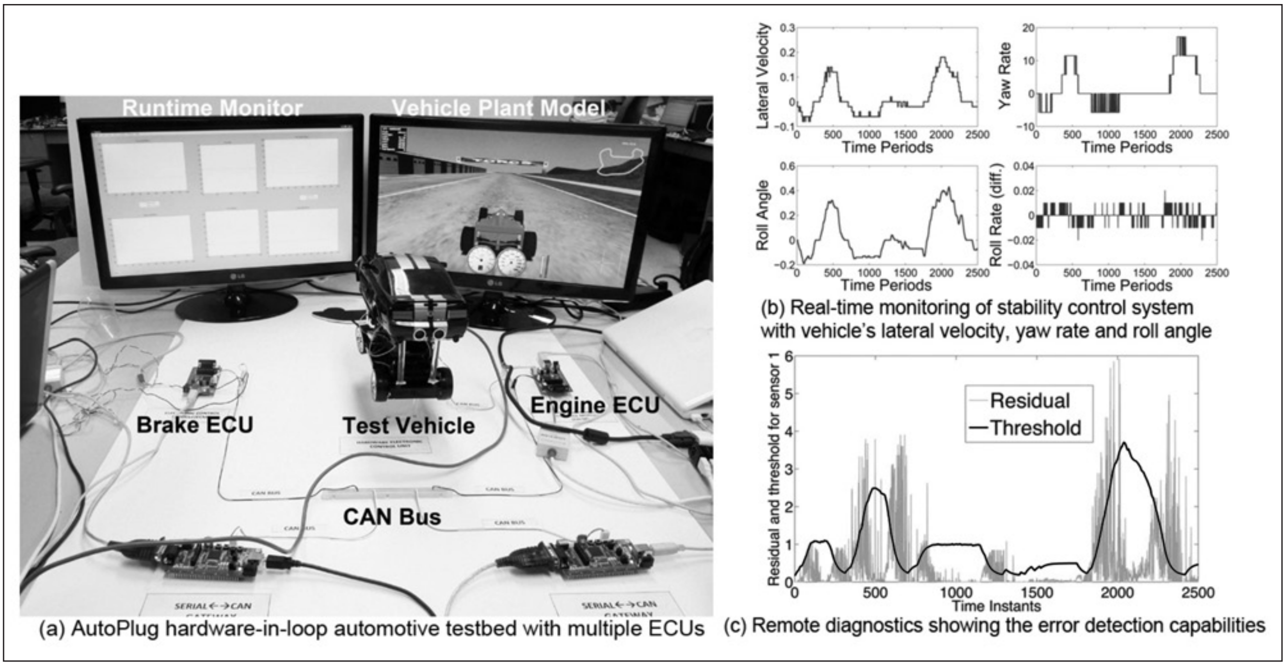
We also evaluate the applicability of "opportunistic diagnostics," where the observer-based diagnostics are scheduled in the ECU's real-time operating system (RTOS) only when there is slack available in the system (i.e., it can work with existing hardware in vehicles without interfering with current task sets). The performance of this aperiodic diagnostic scheme is similar to that of the standard, periodic scheme under reasonable assumptions. The framework integrates in-vehicle and remote diagnostics and makes vehicle warranty management more cost-effective.

The aim of the AutoPlug architecture, illustrated in Figure 2, is to make the vehicle recall process less reactive with a runtime system for diagnosis of automotive control systems and software. Our focus is on the online analysis of the control system and control software both in the vehicle ECU network and between the vehicle and the RDC. We assume the network link between the two is available.

The runtime system within the vehicle manages:

- **Fault detection and isolation.** Sensor, actuator, and control system states are logged for the specific ECU. The data are analyzed locally and a summary of the states is transmitted to the RDC.
- **Fault-tolerant controllers.** Once a fault is detected, the high-performance controller is automatically replaced with a backup controller.
- **ECU reprogramming for remote code updates.** Upon receipt of reformulated controller code from the RDC (which will guarantee the stability and safety of the vehicle), the runtime system reprograms the particular controller task(s) with the updated code. This can be done over a cellular or wireless communication link.
- **Patched controller runtime verification.** The updated code is monitored with continuous checks for safety and performance.

While the onboard system provides state updates of the specific controller, the RDC provides complementary support through:



(a) AutoPlug hardware-in-loop automotive testbed with multiple ECUs

(b) Real-time monitoring of stability control system with vehicle's lateral velocity, yaw rate and roll angle

(c) Remote diagnostics showing the error detection capabilities

FIGURE 3 (a) AutoPlug hardware-in-loop testbed with real-time monitoring and diagnostics. CAN = controller area network; ECU = electronic controller unit. (b) Real-time monitors for stability controller showing the sensor information of the vehicle dynamics. (c) Analysis of the error signal (i.e., residual) of a particular sensor and its expected values. A smart thresholding scheme is used at the remote diagnostics center to determine the extent of the fault based on the residual signal.

- **Data analysis and fault localization.** By observing sensor and control system operations locally, structured system identification is used to create a model of the vehicle and its control system is evaluated to isolate faulty behavior.
- **Reformulation of control and diagnostic code.** A new controller is formulated for the specific vehicle model and further diagnostic code dispatched.
- **Recall management.** Reformulated controller code is transmitted to the vehicle.
- **Generation of controller verification profiles.** The updated controller is probed for performance and safety.

The remote diagnostic system is capable of diagnosing and reformulating controllers with real-time faults (e.g., delay, jitter, incorrect sampling rates) and system faults (e.g., stuck-at faults, calibration faults, and noise in sensors/actuators).

AutoPlug Testbed

To design and validate the proposed architecture we developed the AutoPlug testbed, which consists of a hardware-in-loop simulation platform for ECU development and testing (Figure 3). The hardware is in the form of a network of ECUs, interfaced by a controller area network (CAN) bus, on which we implement the control and diagnostic algorithms. Each ECU runs a nano-RK RTOS, a resource kernel (RK) with preemptive priority-based real-time scheduling.

Instead of a real vehicle, we use an open-source racecar simulator, which provides high-fidelity physics-based vehicle models and different road terrains, thus affording both the realism of an actual vehicle and the flexibility to implement our own code. In addition, we can introduce faults not covered by standard DTCs. We have tested basic control algorithms, running as real-time tasks on nano-RK, for antilock braking systems (ABS), traction control, cruise control, and stability control to see that the testbed does indeed perform as a real vehicle would.

The main contributions of our applied research and development are threefold:

- an architecture that uses both in-vehicle and remote diagnostics for remote recall management of deployed vehicles;
- modification of the traditional observer-based fault detection and isolation scheme for in-vehicle opportunistic diagnosis, as well as an experimental thresholding scheme in the presence of modeling uncertainties; and
- implementation and evaluation of these schemes on real ECUs for hardware-in-loop simulation.

These three features facilitate postmarket diagnostics, testing, and reconfiguration from a remote data center.

Vehicle-to-Vehicle/Infrastructure Networking for Enhanced Safety

Connected vehicles involve a special class of wireless networks where the maximum relative speeds are in excess of 80 meters per second, the node density can span more than 9,000 vehicles/mi^2, and, most importantly, the dynamics of the vehicle, the environment, driver reaction, and interaction with other vehicles are considered in every communication and control decision. Vehicles enabled with programmable short-range wireless networking can communicate with each other and with the infrastructure to enhance the driver's

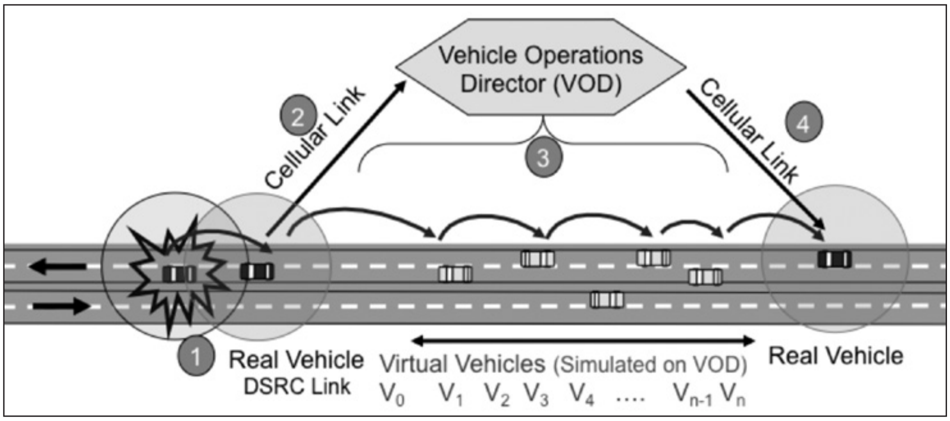
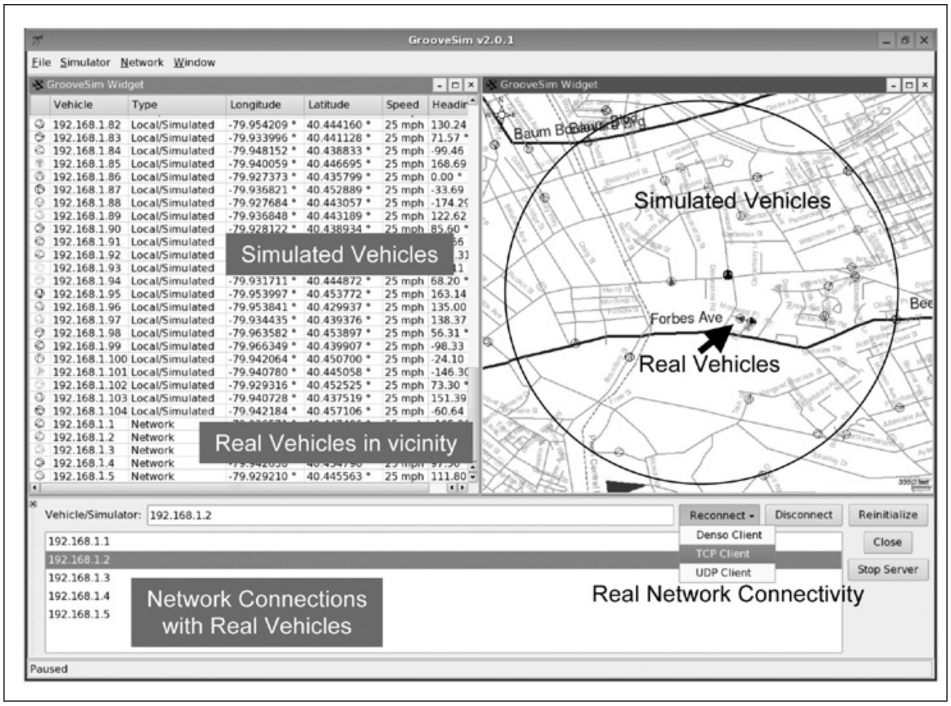


Figure 4 Mixed evaluation of real and virtual connected vehicles with the GrooveNet platform. The three vehicles in the circles are real vehicles communicating with short-range wireless communication (using the IEEE 802.11p/WAVE protocol) on the street. The remaining vehicles are simulated to facilitate communication between real and virtual vehicles. This platform allows for scalable and high-fidelity evaluation of vehicle-to-vehicle and vehicle-to-infrastructure network protocols. DSRC = dedicated short-range communication; V = virtual vehicle.



Vehicle	Type	Longitude	Latitude	Speed	Headir
192.168.1.82	Local/Simulated	-79.954209 °	40.444160 °	25 mph	130.24
192.168.1.83	Local/Simulated	-79.933996 °	40.441128 °	25 mph	71.57 °
192.168.1.84	Local/Simulated	-79.948152 °	40.438833 °	25 mph	-99.46
192.168.1.85	Local/Simulated	-79.940059 °	40.446695 °	25 mph	168.69
192.168.1.86	Local/Simulated	-79.927373 °	40.435799 °	25 mph	0.00 °
192.168.1.87	Local/Simulated	-79.936821 °	40.452889 °	25 mph	-33.69
192.168.1.88	Local/Simulated	-79.927684 °	40.443057 °	25 mph	-174.2
192.168.1.89	Local/Simulated	-79.936848 °	40.443189 °	25 mph	122.62
192.168.1.90	Local/Simulated	-79.928122 °	40.438934 °	25 mph	85.60 °
192.168.1.91	Local/Simulated				
192.168.1.92	Local/Simulated				
192.168.1.93	Local/Simulated				
192.168.1.94	Local/Simulated	-79.931711 °	40.444872 °	25 mph	68.20 °
192.168.1.95	Local/Simulated	-79.953997 °	40.453772 °	25 mph	163.14
192.168.1.96	Local/Simulated	-79.953841 °	40.429937 °	25 mph	135.00
192.168.1.97	Local/Simulated	-79.934435 °	40.439376 °	25 mph	138.37
192.168.1.98	Local/Simulated	-79.963582 °	40.453897 °	25 mph	56.31 °
192.168.1.99	Local/Simulated	-79.966349 °	40.439907 °	25 mph	-98.33
192.168.1.100	Local/Simulated	-79.942064 °	40.450700 °	25 mph	-24.10
192.168.1.101	Local/Simulated	-79.940780 °	40.445058 °	25 mph	-146.3
192.168.1.102	Local/Simulated	-79.929316 °	40.452525 °	25 mph	73.30 °
192.168.1.103	Local/Simulated	-79.940728 °	40.437519 °	25 mph	151.39
192.168.1.104	Local/Simulated	-79.942184 °	40.457106 °	25 mph	-60.64
192.168.1.1	Network				
192.168.1.2	Network				
192.168.1.3	Network				
192.168.1.4	Network				
192.168.1.5	Network	-79.929210 °	40.445563 °	25 mph	111.80

Vehicle/Simulator: 192.168.1.2

192.168.1.1
192.168.1.2
192.168.1.3
192.168.1.4
192.168.1.5

Figure 5 GrooveNet hybrid simulation demonstrating hundreds of virtual vehicles communicating with five real vehicles in the city of Pittsburgh, Pennsylvania. See text for discussion.

perception of oncoming danger within hundreds of milliseconds and, within seconds or minutes, route the vehicle based on real-time traffic congestion.

With connected vehicles, it is necessary to analyze and validate the effect of incremental deployment of V2V technologies on message delay, coverage, and persistence in the region of interest. Because it is expensive to develop and test experimental protocols on a large fleet of vehicles, there is a need for vehicular network simulators that faithfully model first-order effects of the street topology, vehicle congestion, speed limits, communication channels, and spatiotemporal trends in traffic intensity on the performance and reliability of V2V networking. Once protocols are designed and evaluated through simulation, their performance must be tested with real vehicles and realistic traffic densities. Although it may be possible to deploy a small fleet of vehicles (e.g., a dozen), it is not yet possible to assess the scalability of such protocols in rush-hour bumper-to-bumper vehicle densities.

GrooveNet Connected Vehicle Virtualization Platform

We have developed the GrooveNet vehicular network virtualization platform to simulate thousands of vehicles on any street map and communicate between real and simulated vehicles. GrooveNet supports a variety of models, network and vehicular system interfaces, message types, and operating modes and, by using the same protocols, algorithms, and software implementation in both real and virtual vehicles, facilitates model-based design, model validation, graceful deployment, and rapid prototyping. It works as both a simulator and in-vehicle network platform with connections to the CAN bus and radios using the recently standardized dedicated worldwide spectrum for vehicular communications (IEEE 802.11p/WAVE standard), a GPS unit, and a cellular interface.

Our tests of GrooveNet with a fleet of five vehicles over 400 miles across urban, rural, and suburban terrain show that it has realistic models for car following, communication, mobility, driver types, traffic lights, roadside communication nodes (e.g., wireless stations that transmit updates about traffic lights to enable drivers to adjust their speed accordingly), and other interactive features of real-time driving. Each GrooveNet-enabled vehicle is capable of tight time synchronization via the GPS pulse-per-second signal for time-critical multi-hop communication. Using this platform we will develop a suite of V2V and V2I safety communication protocols to relay traffic incident alerts and warnings of unsafe road conditions in the Philadelphia and Pittsburgh areas.

Simulated and Actual Use of GrooveNet

Figure 4 shows three real vehicles (in the circles), which I refer to here as *R1*, *R2*, and *R3* (from left to right). The first two vehicles are within communication range; *R3*, over a mile away, is not. Thus if a safety alert is triggered by an airbag deployment in *R1*, only *R2* receives the message. To illustrate the progression of the message to approaching vehicles, we simulate virtual vehicles on the same road, each of which will enable a "hop" for the data transmission. *R2* sends the message over a cellular link to the vehicle operations director, which simulates the progression of the message from one to another of the virtual vehicles (V_1, V_2,…) until another real vehicle is in the vicinity of the virtual vehicles. The message thus travels across multiple hops to be received by *R3* over the cellular link as if it were from *R1*. We mask the cellular link's latency by speeding up the simulated communication across the virtual vehicles.

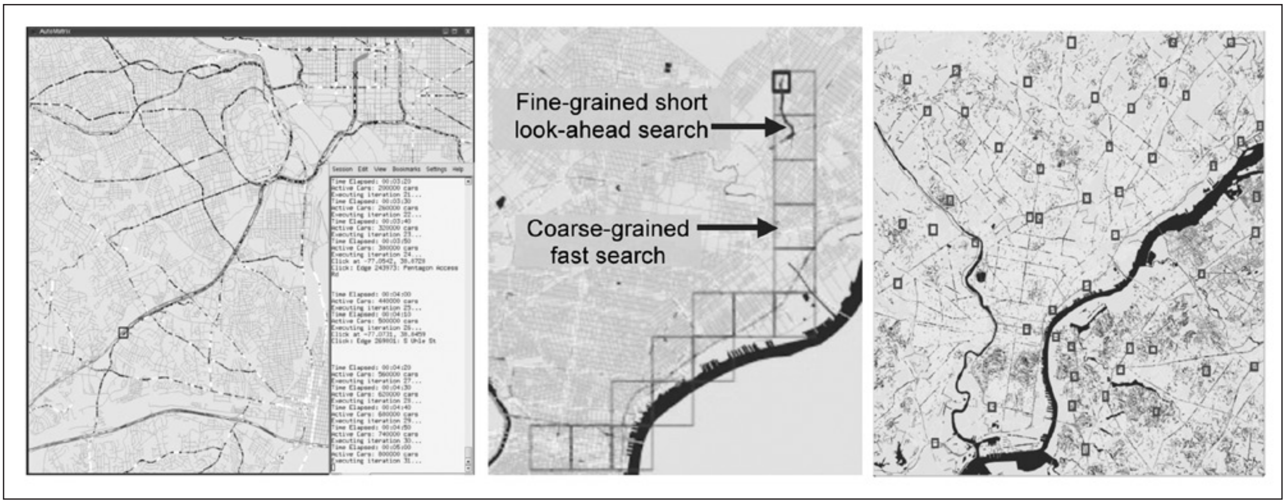
All vehicles follow the same rebroadcast policy, observe the posted speed limit, and obey car following standards. Vehicle density can be increased arbitrarily and its effects observed by a driver in a real vehicle on the road. Varying the number of virtual vehicles enables us to study the performance of the protocols and network algorithms under various densities, driving conditions, and street topologies. As more experimental vehicles become available, we can increase the realism and validation of our models. In the meantime, network virtualization provides the best of both model-based design and real-world validation with rapid prototyping, with only a few real vehicles needed to operate as mobile gateways.

Figure 5 presents a screen shot of GrooveNet implemented in Linux. In the top left panel is the list of simulated and real vehicles with their current position, street speed, and heading (i.e., direction). The top right panel provides a visualization of the current position and heading of vehicles in Pittsburgh, Pennsylvania. Small circles designate vehicles; circles around a dark arrow represent vehicles that rebroadcast an alert message. The bottom panel shows network connectivity between real vehicles via a wireless communication using the 802.11p/WAVE radio interface and between real and virtual vehicles over the cellular network. For this test we drove five real vehicles along Forbes Avenue in Pittsburgh and conducted experiments with more than 4,000 virtual vehicles.

Such hybrid simulation provides application users with an intuitive feel of the impact of communicating vehicle density on packet delivery ratio and event response time, and provides the developer with feedback about accuracy and details needed in the simulation models. This network virtualization will make it possible to answer questions such as: Under what driving conditions and market penetration of networked vehicles will application A achieve the desired performance? How does the probability distribution of model M compare with the real world? Is the resultant powertrain response safe and under what conditions is it unsafe?

Traffic Congestion Analysis

To better understand empirical models of traffic congestion in different street topologies across the nation, and to develop sound traffic prediction and congestion-aware fastest-path routing algorithms, it is necessary to analyze large-scale traffic mechanisms. We have developed a traffic analysis tool, AutoMatrix, that simulates and routes over 16 million vehicles on any US street map and provides real-time traffic routing services with hierarchical and synthetic traffic matrices (Figure 6). Using this tool, we are able to investigate the design of



```
Time Elapsed: 00:03:20
Active Cars: 200000 cars
Executing iteration 21...
Time Elapsed: 00:03:30
Active Cars: 260000 cars
Executing iteration 22...
Time Elapsed: 00:03:40
Active Cars: 320000 cars
Executing iteration 23...
Time Elapsed: 00:03:50
Active Cars: 380000 cars
Executing iteration 24...
Click at -77.0542, 38.8729
Click: Edge 243973: Pentagon Access
Rd


Time Elapsed: 00:04:00
Active Cars: 440000 cars
Executing iteration 25...
Time Elapsed: 00:04:10
Active Cars: 500000 cars
Executing iteration 26...
Click at -77.0731, 38.8459
Click: Edge 269001: S Uhle St


Time Elapsed: 00:04:20
Active Cars: 560000 cars
Executing iteration 27...
Time Elapsed: 00:04:30
Active Cars: 620000 cars
Executing iteration 28...
Time Elapsed: 00:04:40
Active Cars: 680000 cars
Executing iteration 29...
Time Elapsed: 00:04:50
Active Cars: 740000 cars
Executing iteration 30...
Time Elapsed: 00:05:00
Active Cars: 800000 cars
Executing iteration 31...
```

FIGURE 6 AutoMatrix real-time traffic congestion modeling and congestion-aware traffic prediction and routing algorithm design. (Left) Traffic congestion simulation showing more than 800,000 vehicles in Washington, DC. (Center) Hierarchical routing showing one vehicle's coarse-grained route (in large boxes), which is determined at the beginning of the trip. The real-time congestion-aware fine-grained fastest route shows the ¾-mile route ahead of the vehicle. (Right) Thousands of vehicles (each small box represents a vehicle), each with unique origins and destinations, routed with real-time congestion-aware fastest-path routes around Philadelphia.

adaptive routing strategies, methods to mitigate congestion, and ways to better use traffic network resources. Vehicles are modeled to be car following, have speed variations, communicate periodically, and be capable of multiple distributed and centralized routing algorithms.

AutoMatrix operates on a graphics processing unit (GPU) and so is capable of very large-scale microsimulation and traffic analytics. We have implemented A* routing, which executes each vehicle's search for a fastest path between its origin and destination in a parallel processing manner on the GPU. AutoMatrix is capable of hierarchical routing so routes with different levels of details are possible. Vehicles can be guided with adaptive routing—the assigned route "responds" to changes in congestion patterns and reroutes the vehicle to the updated fastest path. By modeling point-based congestion, such as blocked lanes due to vehicle breakdowns or accidents, we can model queuing effects as vehicles back up and congestion spreads through the region.

Using these approaches, AutoMatrix has the potential to improve response time to traffic incidents by advising drivers to take the updated fastest path to their destination. We are working to use live traffic congestion data to support the needs of urban transportation operation centers.

Conclusion

The future of the automobile lies in the design and development of new vehicles that are programmable, connected vehicles, and networked traffic centers. These efforts are a step toward safer, more efficient, and more enjoyable commuting with automobiles.

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Gaming techniques can save money, time, and resources while making departments and organizations more agile.

Playing to Win

Serious Games for Business

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Phaedra Boinodiris

Gordian Knots

Thousands of years ago in ancient Phrygia, there was a massive mound of tangled ropes that was so impressive, it had a name: the Gordian knot. Legend was that whoever could untangle the great knot would become king of all of Asia.

One can imagine a stream of men arriving on horseback, strolling up to the ropes, cursing loudly as they pulled here and pushed there, inadvertently making the mound even bigger and more tangled.

According to the legend, one day Alexander the Great came into town, jumped off his horse, and with his supernaturally sharp blade sliced through the Gordian knot in one stroke, effectively ending the knot's persistent challenge.

If only today's intractable problems could be solved so simply. As the world has become smaller and more interconnected, people and businesses rely on systems that produce huge quantities of data. Executives face enormous challenges in analyzing these quantities as they seek to transform their business to be more responsive to the global economy. According to a recent MIT report (Hopkins et al. 2010), company executives are seeking ways to not only visualize data but also run simulations and scenario development in order to learn how their organizations might be more agile. Agile businesses achieve 10–15% higher margins, up to 5% faster revenue growth, and up to 38% higher capital efficiency.[1] Agility requires enterprise visibility, operational dexterity, and process integrity. Visualization, motivation, and collaboration are the components of the solution—the blade that can cut through the massive mounds of data to enable businesses to adapt quickly and compete.

Transformation is not optional but it doesn't come easily to companies. Organizations that wish to be agile must transform their processes and decisions, embrace rapid, adaptable integration, and have a flexible and efficient infrastructure. For example, in a recent report, Gartner states that by 2015 more than 50% of organizations that manage innovation processes will "gamify" those processes—make them more accessible for adoption by engaging and teaching executives, managers, and employees through game techniques.[2]

In this article I explain how organizations can incorporate "serious games" to add value and agility in an increasingly complex environment.

Serious Games and Serious Solutions

Play is a universal language characterized by enjoyment, established rules, and tangible, clear goals. Digital games can create deep, immersive experiences or quick bursts of excitement. Serious games, designed for a primary purpose other than entertainment, focus on clarifying goals, excising irrelevant information, and developing tangible, measurable improvements in a particular activity or task. They create realistic environments for testing strategies, tactics, theories, and ideas, leveraging the best aspects of games to make modeling, prototyping, experimenting, training, and skill acquisition faster, cheaper, more enjoyable, and more visible.

Whether for a training exercise, supply chain, or cyber defense scenario, smart games techniques can help participants visualize and understand complex systems through video and online gaming, engaging them through competition, teamwork, intrigue, curiosity, and problem solving. These features attract participation, encourage creativity, and help establish a path to collaborative work and analysis.

Although technology has changed the appearance and interactions associated with games, the experience associated with the best games has not changed: the challenge of any game or simulation should match the skills—and test the limits—of the players and the surrounding system in a meaningful, enjoyable way. What better test of game and gamer limits than the most serious challenges facing the world today?

Visualization, motivation, and collaboration are the components of the solution to enable businesses to adapt quickly and compete.

Game Playing to Enhance Business Processes

Business simulations have been around for many years. They allow inputs and, given a set of business rules, produce new outputs. What they lack is the collaborative environment that motivates people to optimize. Keeping a business process locked up in a castle turret with fortified walls does no one any good. Business processes need to be vetted, stressed, and prioritized by the entire value chain to yield a meaningful return on investment.

Today's 24/7 world is filled with large streams of data in previously unimaginable volumes. Approaches such as serious games techniques allow data to be viewed in different ways that nonexperts can understand, contribute to, and act on. In the summer of 2011, thousands of people helped map the structure of an enzyme that could fight HIV and AIDS by playing a downloadable game called Foldit. Researchers were able to crunch data from players' moves to quickly gain valuable insights into protein folding, critical to the development of treatment options. This project shows the power of collective intelligence when big data are harnessed and analyzed through games.

Serious games are increasingly used to test business scenarios and conduct training in both public- and private-sector organizations and corporations around the world. Business gaming techniques are used to motivate and lead large global, virtual teams and to encourage creative problem solving, load balancing, and complex system (e.g., supply chain) optimization. Cross-genre games and games with natural language

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[1] BTM Business Agility, BTM Corporation 2010 (www.btmcorporation.com).

[2] "Gartner Says By 2015, More Than 50 Percent of Organizations That Manage Innovation Processes Will Gamify Those Processes." Press Release, April 12, 2011; www.gartner.com/it/page.jsp?id=1629214.

interpretation[3] are also growing popular as a means to aid critical thinking in the military. These new techniques can save money, time, and resources while making departments and organizations more agile.

One of the key differentiators of a serious games approach to problem solving is a concentration on process optimization. This focus involves examining the most efficient and effective ways to improve procedures via iterative collaborative gameplay, applying Six Sigma principles. Business process improvement can reduce cost and cycle time by as much as 90% while improving quality by more than 60% (Harrington 1991). Results can also include improvements in margin, capacity, and capital reductions.

> *Real-time strategy games enable players to examine how unforeseen events might affect real-world components and thus make their supply chains work better.*

In a serious games approach, participants sort and understand real data, analyze real issues, and test real potential solutions, applying variables that can be adjusted and readjusted for different approaches. Game play preserves engagement while focusing players on important concerns and helping transform their assumptions, skills, and behaviors.

With cloud computing infrastructure, organizations can use serious games to improve business processes by solving complex problems collaboratively through predictive modeling and real-time visualization of methods to, for example, reduce costs and cycle times. Gaming systems tap employee and citizen insights and promote collaboration with partners for greater organizational agility.

Game Playing to Enhance National Security

Military, security, and emergency services organizations were early adopters of serious games to help test interagency disaster response scenarios or scale skills training beyond the platoon level to tackle complex strategy and operational use. The coordinated and cooperative nature of defense work requires team building and prepares for specific and highly synchronized missions. Potentially hazardous work benefits from simulations in which mistakes can be made without causing actual damage or endangerment and then evaluated for future learning.

Serious games techniques can also help optimize military supply chains. By creating real-time strategy games that enable players to examine how unforeseen events might affect real-world components, departments can help make their supply chains work more reliably and efficiently. Business or industry partners can also be included to tap insights from a wider network. The end-product becomes a new, executable supply chain process that has been prevetted by the broader value chain.

In a cyber defense scenario, players benefit from competing in opposing roles on offense, defense, and network exploitation, playing as different entities such as countries and organizations. Strategic-level serious games should mimic the mundane and repetitive aspects of a scenario as well as information technology (IT) tasks, business processes, and attacks.

Direct representation of the decision process can be an instructive way to introduce new leaders to their roles and to allow key decision makers to focus on anomalous incidents by automating the common. A cyber security game that includes the possibilities of organizational policy, politics, operating costs, and social engineering will better prepare players for real-world complexities.

With current advances in process optimization, cloud, analytics, and artificial intelligence capabilities, the defense industry has the tools it needs to conduct strategy-level and process optimization gaming. These approaches teach the kinds of abilities needed to solve complex problems, including leading and managing, handling logistics and resources, prioritizing tasks, making sense of rapidly changing data, and learning from mistakes.

Five Steps to Serious Gaming

Game design and development are constantly underestimated. Many people assume that all they need to develop a serious game is interns with "game skills." The assumption that someone who plays games would be able to design a good game is completely erroneous.

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[3] This term refers to the means for artificial intelligence to interpret natural (i.e., human) language and respond accordingly.

From the development side, there are countless game engines on the market that require highly specialized coding skills.

Development of a serious game requires determination of the measures of its effectiveness, an architecture, specifically designed puzzles and/or experiences, a genre, and a platform.[4] Below are five steps for determining how to approach a serious games project.

Step 1: Determine the measures that will prove the game was worth the investment.

The very first question to answer concerns the purpose of the game. Is it to sell things? Is it to teach something? Is it to solve a problem? The game must then be designed in such a way that its effectiveness can be quantifiably measured. It is critical to start here. It may be tempting to do this last, but the answer to this can affect the entire architecture of the game so it is essential to start here.

If the game is to be used to improve sales skills, then the design must include measurements to prove that salespeople who played the game measurably understood their trade better than those who did not participate.

If the game is meant to optimize strategy among a group of participants, the results report must be able to substantiate that the model created by the players is better than one that has been Six Sigma–certified by a consultant.

If the game is meant to teach physics to 6th graders, results must show that they learned at least as well as from traditional methods.

How an organization measures success may directly affect the design of the game and the architecture of the system. It may be helpful to do an "after-action" review (i.e., to assess what players actually did during the gameplay) in an automated fashion to facilitate real-time insight.

Step 2: What is to be taught or conveyed?

Learning points should be documented in as much detail as possible, as in the following examples:

- The car salesman's 7 steps to a sale are . . .
- The best practice business model associated with a disaster response scenario is . . .

Step 3: What kinds of puzzles or experiences are best suited to the information or lesson to be conveyed?

Simpler puzzles can also be used to explain complex systems such as molecular structures, as in the Foldit example cited earlier.

This is the hardest step of the five, and unfortunately few people realize just how hard it is. Most think they could design a great game. But matching the right puzzle/experience(s) to the learning points documented in Step 2 is difficult. Someone who knows games intimately and across genres should help with this step.

How an organization measures success may directly affect the design of the game and the architecture of the system.

Step 4: Based on the puzzles/experiences, what is the right genre for the game?

Now that the basic design of the game has been determined, what genre does it fall into? Is it a city simulation, first-person adventure, strategy game, simulation-style game, pattern-matching game? Careful study of "flow" (a mental state of operation in which the person performing the activity is fully immersed in a feeling of energized focus; Csikszentmihalyi 1996) in games for entertainment in that genre can yield tips about how to proceed.

City sims, turn-based, and real-time strategy games have proven to be enormously powerful as genres to help explain complex systems. City-building games (city sims) are a genre of strategy computer game where players act as the overall planner and leader of a city, with responsibility for its growth and management. In a turn-based strategy (TBS) game (usually a war game, especially a strategic-level war game), players take turns, as distinct from a real-time strategy game, in which all players participate simultaneously.

Step 5: Knowing the genre and audience, what is the right platform for the game?

It is essential to know the intended audience well if the game is to be effective. How long are participants

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[4] Definitions of terms relevant to serious games are provided in a glossary at the end of this article.

likely to play? What will motivate them to play? Can the game be standalone or does it need to be integrated with other applications? Does the game need to be Web playable? Mobile? Single or multiplayer? How often does the game's content need to be refreshed?

Once these questions are answered it is time to shop around for the right platform and the right vendor to help with development, if in-house expertise is not available. It will be key to know whether the platform is proprietary to the selected vendor. If it is, then future updates will have to come from this vendor unless it offers a "mod kit," which allows noncoders to access and modify surface components of the game (e.g., prices and product descriptions in a sales game).

Choosing the Right Game Studio to Partner With to Make a Serious Game

It is important at the outset to get to know games and know them well. The ability to speak the language of games is essential to work with and gauge the efficacy of the studio that will make the game.

The best way to learn about games is by playing them across genres. The Game Developer's Conference in San Francisco, E3 (Electronic Entertainment Expo), and the East Coast Game Conference in Raleigh, North Carolina, are fantastic venues to learn about innovation in entertainment games. Why start there instead of a serious games summit? Because entertainment features the newest and most innovative ideas and is most likely to showcase examples of game play and techniques that can be adapted for a serious gaming purpose.

> *Entertainment features the most innovative ideas that can be adapted for serious gaming.*

Younger employees tend to be enthusiastic volunteers for help in this area. Their aptitude can be assessed by asking them what their favorite games are and why, especially if they play across genres and can critique their favorite games well. Such employees can be very useful resources in a new serious games program.

When trying to find the right game studio partner, I recommend considering the following questions:

1. Do they "get" games?

Get the bios of the staff members who would work on your serious games project. Are they full of e-learning and instructional designers and no one else? What game engines do the staff have expertise with? Take a look at the games they have developed. Do they look engaging? Did the staff correctly match the right kind of game experience to what they are trying to teach, or did they instead create chocolate-covered broccoli—merely creating an attractive cover (gaming) for the necessary "nutrients" (the material to be learned)? Make sure the people on your project have an understanding of good game design. If they come from the entertainment gaming industry, why did they leave? If they think a great game is a multiple choice questionnaire, *run* toward the exit sign.

2. Do they get serious games?

The team members will need to have enough breadth to take a complex idea and make it accessible and engaging to the participants. If all they know is entertainment games, they may not have the skill set needed to work with serious content. The team's bios should reveal whether the members have what it takes to understand, for example, molecular biology well enough to design an effective protein folding game.

3. What about the proximity of the vendor?

The Internet makes working virtually a lot easier, but there will be times when it will be most helpful to look over the designer's shoulder—literally—during the design process. The selected team *must* be able to understand your vision for the game throughout the entire development process.

4. What types of game genre does the vendor specialize in?

Does the game studio specialize in the genre that makes the most sense for your game? If you are making a next-generation city sim game to explain water management, it doesn't make sense to choose a studio that specializes in first-person shooters.

Conclusion

Sophisticated information technology, abundant human capabilities, a growing appreciation of engagement, and the desire for discovery have created a foundation for utilizing games to tackle intractable problems and achieve big changes. But gaming requires more than business leaders interested in adding experience points and digital merit badges to individuals who answer the most emails. It requires an investment of time and resources from a panoply of contributors—scientists, researchers, visionaries, futurists, game designers, game developers, game testers, gamers themselves, citizens, media, political leaders, informed business leaders, artists, science fiction writers, popular science writers, universities, academia, lobbyists, and educators. The gaming community has a responsibility to advocate for games and provide educational opportunities; likewise, business leaders have a responsibility to look beyond stereotypes and learn what games have become—a valuable tool for learning, communicating, and collaborating around important goals.

When well designed, games can not only be extremely adept at explaining complex systems but also motivate people to play using a wide variety of game design tricks. These same tricks can also be used to motivate and reward employees and partners who optimize the core components of the underlying business.

It's up to each organization to grasp just how powerful serious games are—and make the most of them. Game on!

Glossary

architecture: how a game is designed

experience: the flow of the game, what the user encounters through gameplay

genre: a category of game (e.g., puzzle, role play, strategy)

platform: web-based, mobile, console, downloadable executable

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The successful regeneration of tissue-to-tissue interfaces through a bioinspired approach may enable the translation of tissue engineering technologies from bench to bedside.

Engineering Tissue-to-Tissue Interfaces and the Formation of Complex Tissues

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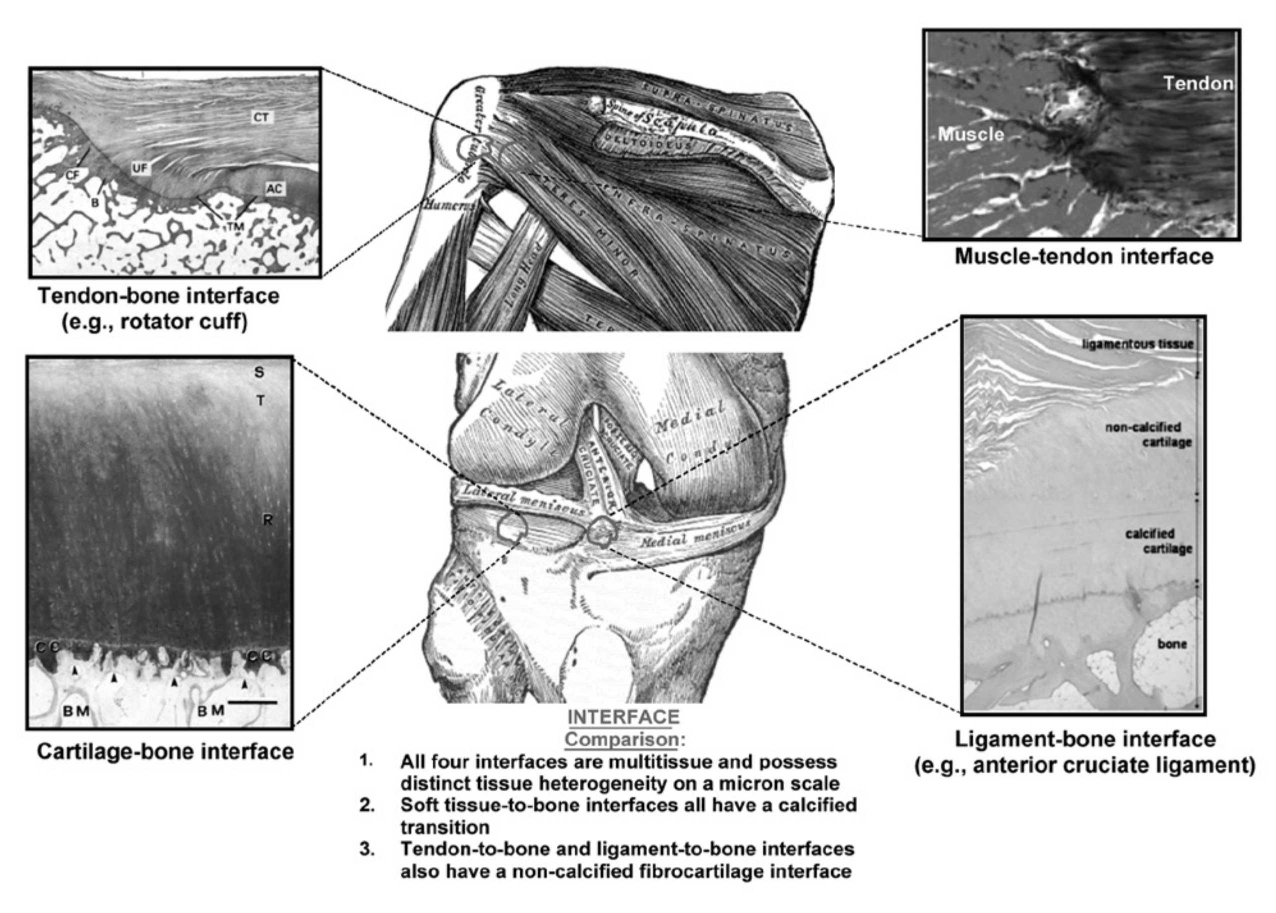
Helen H. Lu

Two significant challenges in the field of tissue engineering are the simultaneous formation of multiple types of tissues and the functional assembly of these tissues into complex organ systems (e.g., the skeletal, muscular, or circulatory systems). These challenges are particularly important for orthopedic regenerative medicine, as musculoskeletal motion requires synchronized interactions among many types of tissue and the seamless integration of bone with soft tissues such as tendons, ligaments, or cartilage. These tissue-to-tissue interfaces are ubiquitous in the body and exhibit a gradient of structural and mechanical properties that serve a number of functions, from mediating load transfer between two distinct types of tissue to sustaining the heterotypic cellular communications required for interface function and homeostasis (Benjamin et al. 1986; Lu and Jiang 2006; Woo et al. 1988). But these critical junctions are prone to injury (from trauma or even exercise and daily activity) and unfortunately do not regenerate after standard surgical repair, thus compromising graft stability and long-term clinical outcome (Friedman et al. 1985; Lu and Jiang 2006; Robertson et al. 1986). Consequently, there is a need for grafting systems that support *biological fixation* or *integrative repair* of soft tissues.

Background

Through a combination of cells, growth factors, and/or biomaterials, the principles of tissue engineering (Langer and Vacanti 1993; Skalak 1988)



INTERFACE
Comparison:

1. **All four interfaces are multitissue and possess distinct tissue heterogeneity on a micron scale**
2. **Soft tissue-to-bone interfaces all have a calcified transition**
3. **Tendon-to-bone and ligament-to-bone interfaces also have a non-calcified fibrocartilage interface**

FIGURE 1 Common orthopedic tissue-to-tissue interfaces. Significant structural and compositional homology exists in the orthopedic tissue-to-tissue interfaces of the tendon-bone (Benjamin and Ralphs 1998), muscle-tendon (Larkin et al. 2006), cartilage-bone (Hunziker et al. 2002), and ligament-bone junctions (Iwahashi et al. 2010). Regeneration of these complex junctions is essential for integrative soft tissue repair and treatment of massive, multitissue injuries. Tendon-to-bone interface: AC = articular cartilage, B = bone, CF = calcified fibrocartilage, CT = connective tissue, TM = tidemark, UF = uncalcified fibrocartilage. Cartilage-to-bone interface: BM = bone marrow space, CC = calcified cartilage, R = radial zone, S = superficial zone, T = transitional zone.

have been readily applied to the formation of a variety of connective tissues such as bone, cartilage, ligament, and tendon both *in vitro* and *in vivo*. More recently, emphasis has shifted from tissue formation to tissue function (Butler et al. 2000), with a focus on imparting biomimetic functionality to orthopedic grafts and enabling their translation to the clinic.

But clinical translation remains elusive as researchers seek to understand how to achieve biological fixation or functional integration of tissue-engineered orthopedic grafts—of bone, ligaments, or cartilage—with each other and/or with the host environment. The challenge is rooted in the complexity of the musculoskeletal system and the structural intricacy of both hard and soft tissues. These tissues, each with a distinct cellular population, must operate in unison to facilitate physiologic function and maintain tissue homeostasis. It is thus not surprising that the transition between various tissue types is characterized by a high level of heterogeneous structural organization that is crucial for joint function.

As shown in Figure 1, ligaments and tendons with direct insertions into bone exhibit a multitissue transition consisting of three distinct but continuous regions of ligament, fibrocartilage, and bone (Benjamin et al. 1986; Cooper and Misol 1970; Wang et al. 2006). The fibrocartilage interface is further divided into noncalcified and calcified regions. In light of this complexity, effective tissue engineering must incorporate *strategic biomimicry* or the prioritization of design parameters in order to regenerate the intricate tissue-to-tissue interface and ultimately enable seamless graft integration and functional repair.

Mechanisms of Interface Regeneration

The mechanisms underlying the formation, repair, and maintenance of tissue-to-tissue boundaries are not well understood. In particular, it is not known how distinct boundaries between different types of connective tissues are reestablished after injury. It is likely that mechanical loading (Killian et al. 2012) as well as chemical and biological factors play a role in this complex process.

It has long been observed that when tendon is resutured to its original attachment site, cellular organization resembling that of the native insertion occurs *in vivo* (Fujioka et al. 1998). Investigators have also reported that, although healing after ligament reconstruction does not lead to the reestablishment of the native insertion, a layer of interface-like tissue forms in the bone tunnel (Blickenstaff et al. 1997; Grana et al. 1994; Rodeo et al. 1993). These observations suggest that when trauma or surgical intervention results in nonphysiologic exposure of normally segregated tissue types (e.g., bone or ligament), interactions between the resident cell populations (e.g., osteoblasts in bone, fibroblasts in tendon, stem cells/progenitor cells in both tissues) are critical for initiating and directing the repair response that leads to reestablishment of a fibrocartilage interface between soft tissue and bone.

> *Effective tissue engineering must incorporate strategic biomimicry to enable seamless graft integration and functional repair.*

Specifically, it has been hypothesized that osteoblast-fibroblast interactions mediate interface regeneration through heterotypic cellular interactions that can lead to phenotypic changes or transdifferentiation of osteoblasts and/or fibroblasts (Lu and Jiang 2006). Moreover, these interactions may induce the differentiation of stem cells or resident progenitor cells into fibrochondrocytes and thereby promote the regeneration of the fibrocartilage interface. This hypothesis has been validated using coculture and triculture models of interface-relevant cell populations (Jiang et al. 2005; Wang et al. 2007), models that offer simple and elegant methods to systematically investigate cell-cell interactions (Bhatia et al. 1999; Hammoudi et al. 2010).

When ligament fibroblasts and osteoblasts were cocultured using a model permitting both physical contact and cellular interactions, it was observed that these controlled interactions altered cell growth and upregulated the expression of interface-related matrix markers. These cellular interactions have a downstream effect, either inducing cell transdifferentiation or causing the recruitment and differentiation of progenitor or stem cells for fibrocartilage formation. When this hypothesis was tested in triculture, it was noted that under the influence of osteoblast-fibroblast interactions, stem cells from the bone marrow began to differentiate toward a chondrocyte-like phenotype, producing a matrix similar in composition to that of the interface.

These intriguing findings suggest that heterotypic cellular communications play a regulatory role in the induction of interface-specific markers in progenitor or stem cells, and demonstrate the effects of these interactions in regulating the maintenance of soft tissue-to-bone junctions. The nature of the regulatory cytokines secreted and the mechanisms underlying these interactions are not known, but cell communication is likely to be significant for interface regeneration as well as homeostasis. Therefore the optimal interface scaffold must promote interactions between the relevant cell populations residing in each interface region.

Interface Structure-Function Relationship and Design Inspiration

From a structure-function perspective, the complex multitissue organization of the soft tissue-to-bone junction is optimized to sustain both tensile and compressive stresses experienced at the ligament-to-bone junction. Numerous characterization studies (Benjamin et al. 1986; Bullough and Jagannath 1983; Matyas et al. 1995; Moffat et al. 2008; Oegema and Thompson 1992; Ralphs et al. 1998; Spalazzi et al. 2004; Thomopoulos et al. 2003; Woo et al. 1988) have revealed remarkable organizational similarities among many tissue-to-tissue interfaces (Figure 1). They often consist of a multitissue, multicell transition and exhibit a controlled distribution of mineral content that, along with other structural parameters such as collagen fiber organization, results in a gradient of mechanical properties progressing from soft tissue to bone.

Direct measurement of interface mechanical properties has been difficult due to the complexity and relatively small scale of the interface, generally ranging from 100 μm to 1 mm in length. Instead, knowledge of insertion material properties has been largely derived from theoretical models.

Moffat and colleagues (2008) recently performed the first experimental determination of the compressive mechanical properties of the anterior cruciate ligament (ACL)-bone interface in a neonatal bovine model. They evaluated the incremental displacement field of the fibrocartilage tissue under the applied uniaxial strain by coupling microcompression with optimized digital image correlation analysis of pre- and postloading images. Deformation decreased gradually from the fibrocartilage interface to bone, and these changes were accompanied by a gradual increase in compressive modulus. The interface also exhibited a region-dependent decrease in strain, and a significantly higher elastic modulus was found for the mineralized fibrocartilage compared to the nonmineralized region. These region-specific mechanical properties enable a gradual transition rather than a sudden increase in tissue strain across the insertion, thereby minimizing the formation of stress concentrations and enabling load transfer from soft to hard tissues.

Given the structure-function dependence inherent in the biological system, these regional changes in mechanical properties are likely correlated to matrix organization and composition across the interface. Partition of the fibrocartilage interface into nonmineralized and mineralized regions likely has a functional significance, as increases in matrix mineral content have been associated with higher mechanical properties in connective tissues.

Evaluation of the insertion site using Fourier transform infrared imaging (Spalazzi et al. 2007) and X-ray analysis revealed an increase in calcium and phosphorous content progressing from ligament to interface and then to bone. A narrow exponential transition in mineral content, instead of a linear gradient of mineral distribution, was detected progressing from the nonmineralized to the mineralized interface regions. Moreover, the increase in elastic modulus progressing from the mineralized to the nonmineralized fibrocartilage interface region was shown to be positively correlated (Moffat et al. 2008) with the presence of calcium phosphate.

These observations have yielded invaluable clues for the design of biomimetic scaffolds for engineering tissue-to-tissue interface. Specifically, a stratified or multiphased scaffold will be essential for recapturing the multitissue organization observed at the soft tissue-to-bone interface. To minimize the formation

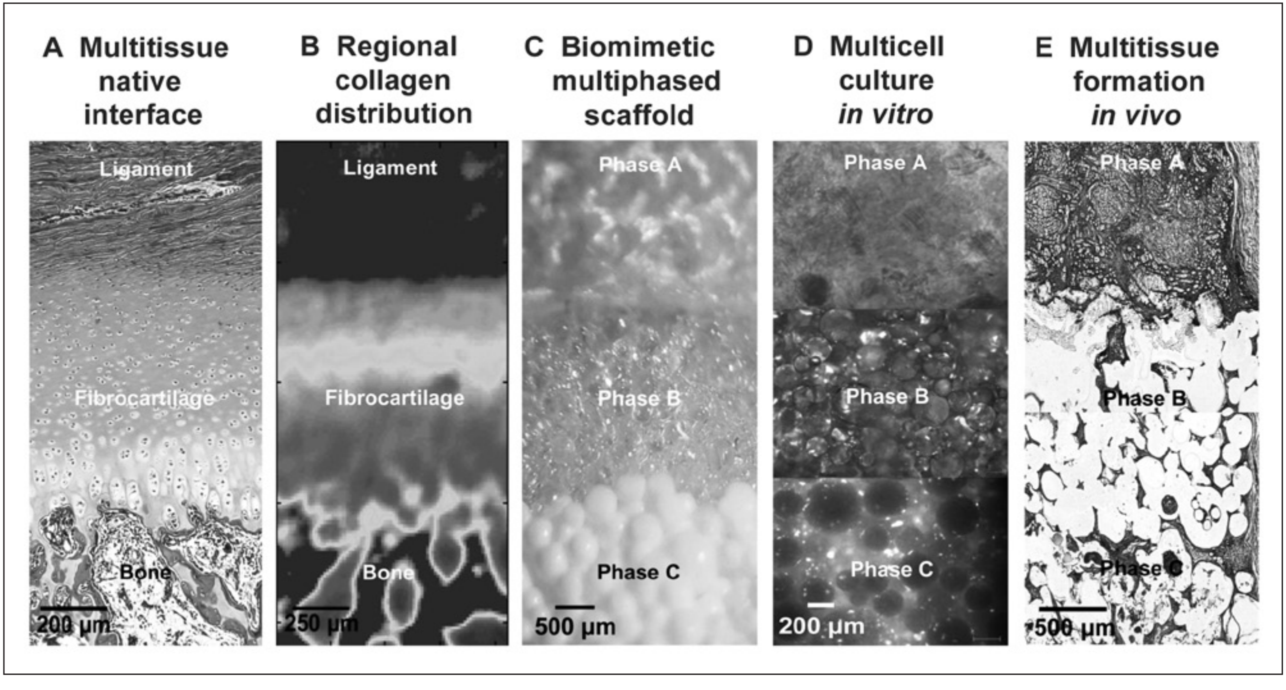


FIGURE 2 Bioinspired stratified scaffold design for interface tissue engineering and integrative soft tissue repair. This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

of stress concentrations, the scaffold should exhibit phase-specific structural and mechanical properties, with a gradual increase in the latter across the scaffold phases. Spatial control of mineral distribution on a stratified scaffold can impart controlled mechanical heterogeneity similar to that of the native interface. Compared to a homogeneous structure, a scaffold with predesigned, tissue-specific matrix inhomogeneity can better sustain and transmit the distribution of complex loads inherent at the multitissue interface.

It is important to bear in mind that the phases of a stratified scaffold must be interconnected and preintegrated with each other, to ensure the formation of *compositionally distinct* yet *structurally contiguous* multitissue regions. Furthermore, interactions between interface-relevant cells serve important functions in the formation, maintenance, and repair of interfacial tissue. Therefore, precise control over the spatial distribution of these cell populations is also critical for multitissue formation and interface regeneration. Consideration of these biomimetic parameters should guide and optimize the design of stratified scaffolds for promoting the formation and maintenance of controlled matrix heterogeneity and interface regeneration.

Functional and integrative repair may be achieved by coupling both cell- and scaffold-based approaches.

Bioinspired Scaffold Design for Interface Tissue Engineering

Inspired by the native ACL-to-bone interface, Spalazzi and colleagues (2006, 2008) pioneered the design of a triphasic scaffold (Figure 2C) for the regeneration of this challenging interface. The scaffold's three continuous phases are each engineered for a specific tissue region of the interface: Phase A is a polymer fiber mesh for fibroblast culture and soft tissue formation, Phase B consists of polymer microspheres and is designed for fibrochondrocyte culture, and Phase C is composed of sintered polymer-ceramic composite microspheres for bone formation (Lu et al. 2003). The innovative design is in essence a single scaffold system with three compositionally distinct yet structurally continuous phases, all designed to support the formation of multitissue regions across the ligament-bone junction.

To form the ligament, interface, and bone regions, fibroblasts, chondrocytes, and osteoblasts were seeded onto Phases A, B, and C, respectively. Interactions between these cell types on the stratified scaffold were evaluated both *in vitro* (Spalazzi et al. 2008) and *in vivo* (Spalazzi et al. 2006). Extensive tissue infiltration and abundant matrix deposition were observed, with tissue continuity maintained across scaffold phases. Interestingly, matrix production compensated for the decrease in mechanical properties that accompanied scaffold degradation, and three continuous regions of ligament, interface, and bone-like matrix were formed *in vivo* (Figure 2E).

In addition to stratified scaffolds, there is tremendous interest in designing scaffolds with a gradient of properties—that is, with a relatively gradual and continuous transition in either composition or structural organization, resulting in a linear gradient in mechanical properties (Chatterjee et al. 2011; Harris et al. 2006; Seidi et al. 2011; Singh et al. 2008). These novel scaffolds with either a compositional (Erisken et al. 2008; Li et al. 2009) or chemical factor (Phillips et al. 2008; Singh et al. 2010) gradient offer direct regional control and allow for scaffold heterogeneity that mimics the complex native interface. They may thus address the need to recapitulate the complex transition of mechanical and chemical properties that are characteristic of tissue-to-tissue junctions.

Design challenges in engineering biomimetic gradients revolve around scale—how best to recapitulate the micro- to nanoscale gradients that have been reported at the tissue-to-tissue interface. The stratified scaffold approach may represent a simpler strategy, whereby a *gradation* of key compositional and functional properties is preestablished by focusing on forming specific tissue regions of interest and preintegrating them through stratified design. In any case, it is necessary to adopt strategic biomimicry in functional interface scaffold design and to prioritize design parameters for interface regeneration based on the type of interface to be regenerated, the type and severity of injury, and the patient's age and overall health.

In addition to scaffold design, it is expected that cellular contributions will play a pivotal role in mediating the regeneration and homeostasis of the gradation of compositional and mechanical properties at the interface. For example, Ma and colleagues (2009) used cell self-assembly to form bone-ligament-bone constructs by culturing engineered bone segments to ligament monolayers. Paxton and colleagues (2009) also reported promising results when evaluating the use of a polymer ceramic composite and RGD peptide to engineer functional ligament-to-bone attachments.

Summary and Future Directions

The biomimetic interface tissue engineering approach described in this paper is rooted in an in-depth understanding of the inherent structure-function relationship at the tissue-to-tissue interface. The studies discussed indicate that controlling cellular response via coculture, triculture, or growth factor distribution on multiphased scaffolds is a critical emerging strategy to enable the development of local gradients on a physiologically relevant scale.

Many soft tissues connect to bone through a multitissue interface populated by multiple cell types that minimize the formation of stress concentrations while enabling load transfer between soft and hard tissues. In the event of injury or other disruption, reestablishment of tissue-to-tissue interfaces is critical for the formation of multitissue systems and the promotion of integrative tissue repair.

Investigations into the mechanism of interface regeneration have revealed the role of mechanical loading as well as heterotypic cellular interactions in directing the formation, repair, and maintenance of the tissue-to-tissue interface. Moreover, functional and integrative repair may be achieved by coupling both cell- and scaffold-based approaches. The vast potential of stratified scaffold systems is evident as (1) they are designed to support multitissue regeneration by mediating heterotypic cellular interactions and (2) they can be further refined by incorporating well-controlled compositional and growth factor gradients as well as the use of biochemical and biomechanical stimulation to encourage tissue growth and maturation.

Interface tissue engineering will be instrumental for the *ex vivo* development and *in vivo* regeneration of integrated musculoskeletal tissue systems with biomimetic functionality. Yet there remain a number of challenges in this exciting area. These include the need for a better understanding of the structure-function relationship at the native tissue-to-tissue interface and of the mechanisms that govern interface development and regeneration. Furthermore, the *in vivo* host environment and the precise effects of biological, chemical, and physical stimulation on interface regeneration must be thoroughly evaluated to enable the formation and homeostasis of the new interface. Physiologically relevant *in vivo* models are needed to determine the clinical potential of designed scaffolds.

The successful regeneration of tissue-to-tissue interfaces through a bioinspired approach may promote integrative and functional tissue repair and enable the clinical translation of tissue engineering technologies from bench to bedside. Moreover, by bridging distinct types of tissue, interface tissue engineering will be instrumental for the development of integrated musculoskeletal organ systems with biomimetic complexity and functionality.

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Engineered 3D tissue systems can better mimic human biology and thus meet the growing need for more effective in vitro models.

Engineering 3D Tissue Systems to Better Mimic Human Biology

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Matthew Gevaert

The scientific method—hypothesis-driven design and execution of an experiment—is great . . . except when it could kill you (or me). That's why, for example, there are extensive legal requirements to investigate new pharmaceutical agents using proxies before testing drug toxicity in a human clinical trial. The US Food and Drug Administration requires a combination of nonliving techniques (biochemical assays and *in silico* analysis), *in vitro* models (i.e., cell culture), and animal studies before new compounds may be administered to humans.

Although pharmaceutical and regulatory industries are doing the best they can in the current paradigm, to be blunt it's not going very well. According to recent publications, of all drugs that enter clinical trials, only 12% are eventually approved for use in humans (Paul et al. 2010). In other words, despite best efforts to predict those drug candidates' efficacy and toxicity during preclinical testing, 88% of them fail—usually in terms of their lack of efficacy or unacceptable toxicity—when put to the test in humans.

A new paradigm is needed! And the biggest opportunity lies in cell culture, which typically is still done in a Petri dish (or its derivative, the multiwell plate). This ubiquitous scientific container, first described well over a hundred years ago in the late 19th century (Petri 1887), was already commonplace when cells were first widely cultured in the mid-20th century and remains the standard of cell culture today.

The vast majority of human cell types are adhesion dependent, and after fluid transfer to a Petri dish or well plate they attach to the bottom. Once attached, they normally proliferate and cover the entire bottom surface without stacking, forming a confluent, flat monolayer (shorthanded as "2D" cell culture). As evidenced by usage patterns, normal limitations of this experimental mode (the environment is static, diffusion is passive, constant evaporation alters solute concentrations, frequent media changes are necessary, cell numbers plateau at confluence, the cell experiences stimuli largely unrelated to those it experiences *in vivo*) are viewed as less important than benefits (cells grow well, the approach is cost effective, 2D planes are easily imaged with inexpensive microscopes, existing body of data is 2D, granting agencies still fund it, and the method enables high throughput).

Yet, as I put it in a recent talk to a group of high school STEM whiz kids, "Your Petri Dish Is So 1887."

Significance

Few people ask (and fewer answer) these basic questions: Do the results of Petri dish–type cell culture experimentation mean anything? Are they at all relevant to the intent of the experiment, which in most cases is to model a process that occurs in the human body? Although the assumption is "yes," in an increasing number of demonstrated cases the answer to these important questions is actually "*no*."

A quantitative way to measure the "behavior" of a cell in culture is its gene expression. In a beautiful demonstration that answers the questions above, a comparison was made of key gene expression profiles of primary human cancers with comparative immortalized epithelial cells in 2D (Ridky et al. 2010). Tellingly, the correlation coefficient between the two datasets was 0.0. But there are much easier and cheaper ways to obtain datasets with exactly zero correlation to the behavior one is trying to characterize than to conduct 2D cell culture experiments!

The tremendous opportunity for improvement lies in the fact that cells are living organisms and can respond dynamically to local stimuli provided by and in their environment. *The solution is to provide a different environment with more of the "right" physical, mechanical, and biochemical stimuli.* Developments that address this challenge will affect much more than *in vitro* modeling of *in vivo* physiology. Aside from the desire to model human beings and the need to minimize the very serious consequences of the scientific method for certain kinds of questions, better *in vitro* systems have enormous implications as both manufacturing methods for implants (e.g., in tissue engineering and regenerative medicine) and as process steps for cell therapy.

Better in vitro *systems have enormous implications as manufacturing methods for tissue-engineered implants and as process steps for cell therapy.*

Engineering Cell Shape Through Material Interaction

As a living entity, each cell has the potential to sense and respond to physical stimulus at each point in all its transecting planes—i.e., its entire surface in three dimensions.

When an adhesion-dependent cell is presented with a flat surface to which it can favorably attach, it tends to maximize its adhesion and adopts a primarily flat morphology. Cells in a 2D paradigm tie up approximately 50% of this interaction capacity with the bottom surface of the well plate, approximately 50% with the liquid environment above the flat cell, and a very small amount in lateral cell-cell interactions.

The fundamental value proposition of "3D" cell culture is to provide a microenvironment in which the potential for physical interaction is distributed in a biologically relevant fashion across the entire surface of the cell. This is normally achieved by culturing cells in a scaffold or matrix material, which can span gels, fibers, or porous solids, among others. Cells in a 3D culture matrix adopt a more complex morphology (e.g., roughly ellipsoid) that is typically much closer to their morphology in their native state—that of a cell in tissue in a living organism.

Does this matter? Again relying on gene expression as a way to measure cell behavior, researchers have documented significant changes in gene expression profiles

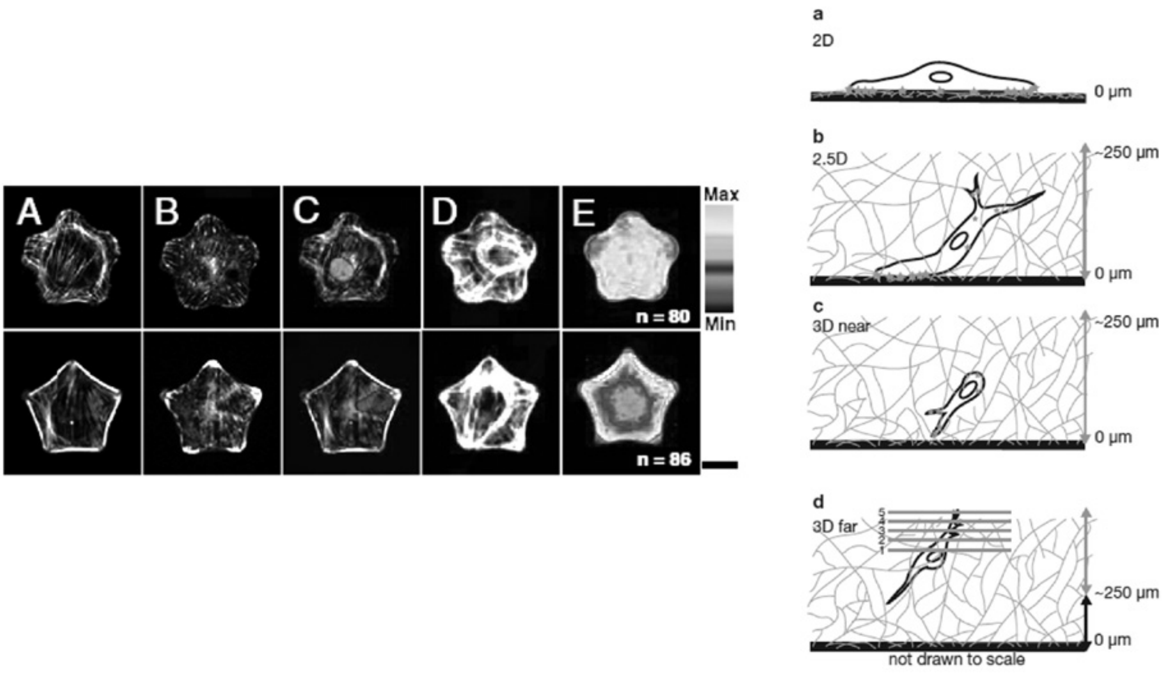

FIGURE 1 (Left) Immunofluorescent images and fluorescent heatmaps of cells in flower (top) and star (bottom) shapes, demonstrating differential cell response to nuanced physical constraints that influence the differentiation pathway. Reprinted with permission from Kilian et al. (2010). (Right) Schematic representation of focal adhesion visualization (stars on cell surface) in live HT-1080 cells cultured at increasing distances (a-d) from the dish bottom, characterizing edge effect in 3D matrix. Reprinted with permission from Fraley et al. (2011). This figure appears in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

(recently genomewide) of multiple cell types as a result of 3D relative to 2D cell culture conditions. These changes have been shown to be associated with key biological processes such as tissue development, cell adhesion, immune system activation, and defense response (e.g., Zschenker et al. 2012). Thus, cell morphology is fundamentally deterministic of some important aspects such as cell behavior, signal transduction, protein-protein interaction, and responsiveness to external stimuli. Gene expression profiles in 3D are also shown to have much more relevance to those measured *in vivo* (Birgersdotter et al. 2005; Martin et al. 2008).

In addition to the value of a 3D microenvironment that more effectively models *in vivo* realities, this form-function relationship is also subject to manipulation toward less "natural" ends. Stem cells' differentiation pathway has historically been controlled by soluble factor interactions, either from a second "feeder" layer cell type or as a result of soluble factors added to the cells' media. Surprisingly, forcing a cell into a particular shape (e.g., the stars and flowers shown in Figure 1) by physical confinement can also affect its differentiation pathway even in the absence of soluble factor manipulation (Kilian et al. 2010).

Unfortunately, effectively engineering the 3D microenvironment is not as simple as providing physical interactions in three dimensions. Topography and mechanical stiffness are among biophysical cues in a 3D context that affect cell function. This is proven via either the addition of 3D topography (e.g., grooves, pillars, posts, pyramids, pits) to an otherwise flat surface via microfabrication techniques (wherein the cell is cultured *on* the material) or the incorporation of controlled topography internally and culturing of the cell *in* the material (Nikkhah et al. 2012). Topography can also induce effects that determine stem cell differentiation pathways (Kumar et al. 2012).

Mechanical stiffness affects cell behavior and function, as exemplified by the presence of an "edge effect" in 3D gel scaffolds. Fraley and colleagues (2011) characterized focal adhesions of cells embedded in a 3D collagen gel and reported that tension in the gel decreased with increasing distance from the container surface. Cellular focal adhesions, associated with each cell's cytoskeletal structure, decreased as well. As shown in Figure 1, the authors were able to loosely qualify 2D (cell on surface), 2.5D (cell partially on surface), "3D near" (cell within 250 µm of surface), and

"3D far" regions based on the number of focal adhesions per cell.

Just how "3D" an environment is has very important implications for applications other than modeling. In a recent paper with profound ramifications for cell therapy, investigators demonstrated that a complex response (immunomodulation, e.g., the recruitment of monocytes to an inflamed endothelial monolayer) of cells in 3D was reduced fivefold compared to the same cells on 2D surfaces (Indolfi et al. 2012). The authors observed that the 3D cells had markedly altered cytoskeletal structure with rearranged focal adhesion proteins.

Engineering the Soluble Environment

In addition to the interaction of a given cell with the materials and other cells surrounding it, the soluble environment has a considerable effect on cell behavior. At the most basic level, it is through the soluble environment that cells receive nutrients and perform basic functions such as respiration and waste elimination. Interference with these basic needs over time compromises the viability of the cell culture. Cells cultured on a 2D surface have nearly 50% of their surface area interacting with the soluble environment and simple, passive diffusion is usually more than sufficient to enable these processes. With frequent media changes to compensate for evaporation, depletion of nutrients, and generation of wastes, compromised viability of 2D cell cultures due to insufficient soluble environment interaction is rarely a concern.

However, inherent in soluble environment interactions and the frequent replacement of cell media is a cyclic change in the media pH and a "feast to famine" dynamic with respect to nutrient access. Media pH in typical 2D cell culture decreases over time (Wu and Kuo 2011) and differing pH levels have been shown to affect cell function (Wu et al. 2007). The removal of "spent" media, containing relatively fewer nutrients and more waste, also removes nonwaste excretions (e.g., proteins), an environmental change that may be directly related to the observable phenomenon that confluent cells in 2D culture do not typically stack but occur as monolayers. In one experiment, researchers began with cells in a typical 2D culture environment and, using a specialized bioreactor that allowed nutrient and waste exchange but preserved insoluble extracellular matrix secretions, created mineralizing, collagenous tissue up to 150 μm thick with as many as 6 cell layers (Dhurjati et al. 2006).

Depending on the density of both the 3D matrix and other cells, a particular cell's soluble environment interactions can be severely compromised and result in muted function or eventually cell necrosis, particularly in the middle of the construct. The window for effective density management is significantly smaller if the *in vitro* model relies only on the passive diffusion that occurs with use of 3D scaffolds in static multiwell plates. The use of perfusion culture systems or bioreactors can minimize or alleviate the deleterious effects and stabilize the soluble environment by avoiding feast-to-famine changes in nutrient availability and maintaining pH. Compared with static conditions, perfusion cell culture has been shown to affect culture morphology and organization (Tomei et al. 2009), increase key enzyme activity (Goldstein et al. 2001), increase mineral deposition and production of protein and cytokines (Gomes et al. 2003; Mercille and Massie 1999), increase cell penetration into and distribution throughout the scaffold (Cimetta et al. 2007; Goldstein et al. 2001; Gomes et al. 2003), increase cell viability especially at the center of cell-scaffold constructs (Cimetta et al. 2007; Mercille et al. 1999), and thus extend the effective duration of the culture experiment.

Gene expression profiles in 3D are shown to have much more relevance to those measured in vivo.

Incorporating Biological Systems Effects with Multiple Cell Types

Consideration of a particular cell's interactions with other cells is essential to increasing the correlation of its *in vitro* functions and behavior to an *in vivo* organism. These interactions can take the form of direct cell-to-cell contact or of soluble factor interactions mediated by the environment. Human biology relies on both modes of interaction. Culture-based intercellular interactions among cells of the same type (monocultures) in 3D have been implicitly included in the discussions above, and are at least partially responsible for the morphological changes and functional benefits described.

A second type of intercellular interaction can be modeled via coculture of different types of cells, which can occur in the same culture chamber and create direct cell-to-cell contacts (a mixed coculture) or in multiple, separate chambers with a connected soluble environment through the exchange of soluble factors (a segregated coculture). A coculture and the multicellular biological feedback loop it represents are necessary to reproduce many complex *in vivo* effects, which is not surprising given the many interacting physiological systems that combine to result in complex human biology.

Coculture provides yet another opportunity to engineer greater relevance into an *in vitro* model. As previously described, stem cell differentiation pathways are one of the best known multiple cell type interactions, whereby the differentiation of stem cell "A" is directed (or suppressed) by the presence of soluble factors from cell "B." Rivaling and perhaps surpassing stem cell cocultures for scientific activity are cancer cocultures, particularly cancer-stroma cocultures: it is increasingly being demonstrated that the incorporation of a second cell type materially affects cancer cells in culture (Khodarev et al. 2003) and boosts their relevance to the *in vivo* pathology (Chung et al. 2005; Mahadevan and Von Hoff 2007).

Layering Complexity

Incorporation of any of these themes—3D matrix microenvironment, actively stabilized soluble environment, mixed and segregated cocultures—in an *in vitro* system represents an increase in complexity compared to standard 2D cell culture. Increased complexity is often associated with increased cost and time and decreased efficiency (often measured by throughput). These negative consequences are perhaps the largest reason these promising innovations have not achieved the wide use and rapid commercial uptake initially expected. Yet, in the absence of their purposed integration into drug delivery processes, correlation of *in vitro* models to *in vivo* results is poor, 88% of drug candidates fail in clinical trials, and each successful drug costs approximately $1 billion to develop and launch (Deloitte 2011).

There are nonetheless strong indications of progress toward a new era of *in vitro* models. With biologically derived gel matrices having led the way, there are now many commercially available scaffolds specifically marketed for 3D cell culture. Commonly used in multiwell plates to maintain throughput (but simultaneously limited by their static format), these scaffolds are primed for layering the additional complexities of a stabilized, actively perfused soluble environment and for the clever use of coculture, potentially with multiple matrices matched to cell type.

Basic segregated coculture has become widespread through the use of inserts fitted into the wells of multiwell plates and more recently through mixed but spatially controlled cocultures made possible by 2D microfabrication techniques. Limitations of the first iterations of these innovations include the static nature of multiwell plate culture and (for inserts) a limited range of materials suitable as membranes, but they have established important baselines that will be expanded with the integration of more and better 3D physical and soluble microenvironments.

Finally, early bioreactor systems have demonstrated the clear benefits of perfusion, but their adoption is hampered by high costs per experiment, a requirement for atypical cell culture equipment, and low throughput.

FIGURE 2 Examples of microfluidics (left, printed with permission from the Wyss Institute) and mesofluidics (right, KIYATEC Inc.) "layered complexity" in vitro systems. Both are perfusion based and incorporate 3D microenvironments and coculture interactions, but they differ in scale, manufacturing techniques, potential applications for cell-scaffold constructs, cost, and throughput. These images appear in color in the online posting of this article at www.nae.edu/publications/bridge.aspx.

Microfluidic and Mesofluidic Approaches

These first examples of successfully integrating a single innovation theme that acceptably increases complexity (i.e., is worth the tradeoff) have laid the foundation for "layered complexity" approaches that may break new ground in adoption and use. In the United States, recent National Institutes of Health (NIH) and Defense Advanced Research Projects Agency (DARPA) grant solicitations themed around modeling three and ten (respectively) interacting physiological systems were awarded to microfluidics "lab-on-a-chip" submissions (Figure 2, left).

The microfluidics approach embraces perfusion systems at a micrometer scale (the scale of the cells themselves), while layering the complexity of cocultures at various points in the fluidic channels. Benefits include a smaller footprint for the culture chamber device, reduced flow circuit volumes, and the use of micromanufacturing techniques for device manufacturing. This approach has most effectively been demonstrated when modeling flat biological barrier models (e.g., gut, lung luminal interfaces) where perfusion takes the form of laminar-type flow over a dense, flat, cell-membrane construct. Technical challenges can include the inability to load and recover scaffolds, "edge effects" of soft matrices, management of cell/matrix density over time in gel matrices, and successful maintenance of constant flow in channels with small dimensions.

Another approach that successfully achieves the desired layered complexity may be thought of as "mesofluidic," with culture chamber dimensions on the scale of millimeters rather than micrometers (Figure 2, right). In contrast to microfluidics, this approach has focused on modeling tissues rather than barriers, and perfusion can take the form of interstitial-type flow through a 3D cell-scaffold construct.

The mesofluidic approach inherits the benefits of more traditional bioreactors, including the highest cell viability over time, best potential to model complexity, and broadest incorporation and recovery of diverse 3D scaffold materials, the latter being an important bridge to biomanufacturing applications such as regenerative medicine, tissue engineering, and some forms of cell therapy. Layered complexity is achieved through inherent accommodation of both mixed and segregated cocultures and more controlled management of the soluble environment through active perfusion. Although cost may be mitigated to the extent that these smaller bioreactor systems can leverage the existing cost structure for 2D cell culture processes,[1] lower throughput in mesofluidic systems remains a tradeoff.

Impacts of Economic and Social Factors

Nontechnical factors are aligning with the emergence of layered-complexity technological approaches. The economic and political environments have changed such that there is an increased focus on the societal value derived from the expenditure of granting agencies' (and ultimately the public's) research monies. It is becoming less acceptable to fund or conduct research that can be demonstrated to have a low, or zero, correlation to the biology being modeled when alternatives with higher correlation exist, even though they are more complex. Funding agencies are increasingly supportive of initiatives that mandate the incorporation of layered complexities.

Funding agencies increasingly support initiatives that mandate the incorporation of layered complexities.

Contractions in the global pharmaceutical industry have resulted in emphasis on new approaches that both drive down development costs and point toward new understanding of complex biology (and new targets, mechanisms, and pathways). Successful regenerative medicine and cell therapy business models have emerged, heightening the demand for improved *in vitro* manufacturing and quality control processes compliant with Current Good Manufacturing Processes (cGMP). And finally, increasing societal interest (particularly in the European Union) is also driving broader and faster adoption of more complex *in vitro* models and techniques that show promise for refining, reducing, and replacing the use of animals.

Conclusions

Perception of the value of *in vitro* models is slowly changing to both embrace the need for more relevance

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[1] This cost structure encompasses the costs of commoditized supplies, equipment, instruments, and general infrastructure of traditional cell culture methods.

TABLE 1 Evolving Paradigm Through which the Value of *In Vitro* Models Is Perceived

Traditional Paradigm		New Paradigm	
2D static monolayer cell culture	More complex cell culture: 3D or perfusion or coculture	2D static monolayer cell culture	Layered complexity cell culture (e.g., 3D perfused coculture)
• High throughput	• Lower throughput	• Higher throughput but lower relevance	• Higher relevance but lower throughput
• Acute cost minimization	• Costs more than 2D	• Cost and value of data both matter	• Overall cost reduction potential
• Synch with past data	• Past data disconnect	• Oversimplified	• Managed complexity
• Convenience	• Interesting but impractical	• Use when can get away with	• Use when value justifies cost
NET EFFECT: Very heavy reliance on 2D static monolayer methods with emphasis on throughput and acute cost minimization.		NET EFFECT: Balanced approach that recognizes throughput/relevance tradeoffs and integrates both options. Ultimately reduces overall costs by decreasing late-stage failures (drugs) and/or increasing performance (cell therapy, regenerative medicine).	

and accept the tradeoffs of lower throughput and increased complexity (Table 1). This change is driven by multiple, related dynamics: (1) scientific literature demonstrating the increased relevance of more complex (e.g., 3D, perfused, coculture) cell cultures to *in vivo* biology, especially that of humans, compared to the low relevance of 2D monolayer cultures; (2) the increasing adoption of approaches incorporating single-factor complexity (e.g., 3D environment only), albeit for a limited number of applications; (3) the emergence of "layered complexity"–type approaches whose combined dynamics have begun to enable the modeling of organism-level interactions, with potentially broad application; (4) the unfavorable failure rate and high costs of clinical trials for the pharmaceutical industry, especially given the dearth of new blockbuster drugs; (5) the emergence of viable business models in related industries (regenerative medicine, cell therapy) that require and can coopt cell culture innovation for cell maturation and processing; and (6) aligned nontechnical trends, including increased emphasis on funding clearly relevant research and on further refining, reducing, and replacing the use of animals.

The combination of these factors results in unprecedented opportunity and provides the required foundation to usher in a new era of better *in vitro* models. As they are implemented, these models will significantly advance understanding of human physiology while simultaneously translating to substantial health and cost benefits.

Financial Disclosure

Dr. Gevaert is the CEO of, and owns stock in, KIYATEC Inc., a company focused on *in vitro* models with higher correlation to *in vivo* results via convenient and cost-effective perfused 3D cell-based assays.

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NAE News and Notes

NAE Newsmakers

B. Jayant Baliga, director, Power Semiconductor Research Center, North Carolina State University, has received the **2012 North Carolina Award for Science**, the state's highest civilian honor, sometimes called the "Nobel Prize of North Carolina." The award was presented on October 30 at the North Carolina Museum of History in Raleigh. Dr. Baliga is recognized for his groundbreaking work in electronics engineering and is included among the "Eight Heroes of the Semiconductor Revolution" by *Scientific American*. While working for General Electric he invented, developed, and commercialized the insulated gate bipolar transistor (IGBT), a device used in consumer, electrical, medical, renewable, and other products. His work has saved consumers more than $15 trillion and now helps form the basis for the emerging smart grid.

Pradman P. Kaul, president and CEO, Hughes Communications Inc., has been honored with the first-ever **Lifetime Achievement Award** at the COMSYS VSAT2012 Annual Global Industry Conference, presented on September 12, 2012, at the Lancaster London Hotel, UK. The award recognizes Mr. Kaul's significant contributions and dedication to the industry over a career spanning four decades.

Cato T. Laurencin, University Professor, Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery, Professor of Chemical, Materials, and Biomolecular Engineering, and CEO, Connecticut Institute for Clinical and Translational Science, and director, Institute for Regenerative Engineering, University of Connecticut, was recently **recognized by the Connecticut General Assembly**. An official citation signed by legislative leaders and Secretary of the State Denise Merrill thanks Dr. Laurencin for his many contributions to the state during his time as University of Connecticut Health Center vice president for health affairs and dean of the University of Connecticut and for his enduring leadership in bioscience innovations and research.

Asad M. Madni, retired president, chief operating officer, and CTO of BEI Technologies Inc., and independent consultant, has been selected to receive the **2012 IEEE Aerospace and Electronic Systems Society's Pioneer Award** for his groundbreaking contributions and accomplishments that have stood the test of time. Dr. Madni's award citation reads "for seminal and pioneering contributions to the development and commercialization of aerospace and electronic systems." The Pioneer Award has been given annually since 1949 to an individual or team for "contributions significant to bringing into being systems that are still in existence today."

Kaushik Rajashekara, Distinguished Professor of Electrical Engineering and Endowed Chair, Erik Jonsson School of Engineering and Computer Science, University of Texas at Dallas, was elected a **Foreign Fellow of the Indian National Academy of Engineering** on October 19, 2012. The Academy confers fellowship on Indian and foreign nationals who have demonstrated their eminence and achieved outstanding accomplishments in engineering and technology.

The Institute of Electrical and Electronics Engineers (IEEE) has awarded **Terrence J. Sejnowski**, Francis Crick Professor and head, Computational Neurobiology Laboratory, Salk Institute for Biological Studies, and professor and head of the Salk Institute's Computational Neurobiology Laboratory, the **2013 IEEE Frank Rosenblatt Award**. Dr. Sejnowski was selected in recognition of his outstanding contributions to computational neuroscience. A leader in the field, his trail-blazing work helped spark the neural networks revolution in computing in the 1980s. He is also recognized for his important contributions to artificial and real neural network algorithms and applying signal processing models to neuroscience.

Ponisseril Somasundaran, director, NSF/IUCR Center for Surfactants, and La Von Duddleson Krumb Professor, School of Engineering and Applied Science, Columbia University, was elected a **Foreign Fellow of the Royal Society of Canada**. Out of a class of 73 fellows, Dr. Somasundaran was the only foreign fellow named this year. He was recognized for his "groundbreaking contributions towards unraveling complex nanoscale structures and energetics of surfactant self-assemblies and polymer-surfactant hybrid at interfaces."

Gregory Stephanopoulos, Willard Henry Dow Professor of Biotechnology and Chemical Engineering, Massachusetts Institute of Technology, was awarded the **Siegfried Medal** by Siegfried AG. The award, presented on October 5 during the 5th Siegfried Symposium in Zurich, Switzerland, cites Dr. Stephanopoulos' contributions to efficient biotechnological processes for pharmaceutical API production. He is renowned for his work in metabolic engineering and the development of microbes for the production of specific essential biological molecules like amino acids or secondary metabolites like terpenes. His work has been implemented toward the "on scale" synthesis of the AIDS drug Crixivan and the anticancer drug Taxol.

Esther S. Takeuchi, SUNY Distinguished Professor, Materials Science and Engineering Chemistry, Stony Brook University, has been selected as the 2013 recipient of the **E.V. Murphree Award in Industrial and Engineering Chemistry** from the American Chemical Society. Professor Takeuchi, known for developing the technology for the power source used in implantable cardiac defibrillators and for holding 153 patents—more than any woman in the United States—will receive this prestigious award at the 245th American Chemical Society National Meeting and Exposition in New Orleans, Louisiana, April 7–11, 2013. Sponsored by the Exxon Mobil Research and Engineering Co., the E.V. Murphree Award is designed to stimulate research in industrial and engineering chemistry, the development of chemical engineering principles, and their application to industrial processes.

Charles H. Thornton, chairman, Charles H. Thornton & Company LLC, and Richard L. Tomasetti have received the Council on Tall Buildings and Urban Habitat's (CTBUH) **2012 Fazlur R. Khan Lifetime Achievement Medal** for their collective contribution to the advancement of tall buildings. This is the first time the CTBUH Board of Trustees has awarded the prize to two individuals jointly. The medal recognizes demonstrated excellence in technical design and/or research that has made a significant contribution to a discipline for the design of tall buildings and the built urban environment. The award was presented at CTBUH's 11th Annual Awards Dinner at the Illinois Institute of Technology in Chicago on October 18.

Vijay Vittal, Ira Fulton Chair, Department of Electrical Engineering, Ira A. Fulton School of Engineering, Arizona State University, has been selected to receive the **IEEE Herman Halperin Electric Transmission and Distribution Award** for his accomplishments in power systems engineering. The award specifically recognizes his contribution to "development of power system stability assessment methods leading to the maximum utilization and increased reliability of transmission lines."

David C. Wisler, GE Aviation, retired, received the **2012 R. Tom Sawyer Award** given by the International Gas Turbine Institute (IGTI) of ASME (founded as the American Society of Mechanical Engineers). He is being recognized for his career-long innovative technical contributions to advance the performance of gas turbine engines, for national and international initiatives to encourage research collaboration between universities and industry, and for providing exemplary leadership and service to the IGTI. The award was presented during the ASME Turbo Expo 2012 held in Copenhagen, Denmark, in June. Dr. Wisler retired from GE Aviation after a career spanning 38 years, during which he held positions of increasing responsibility for conducting and managing advanced technology programs. His work to improve airfoil shapes and understand complex flow fields in the rotating components of gas turbine engines has been instrumental in reducing losses (reducing fuel burn) and improving performance.

On October 4, 2012, University of Houston president Renu Khator and Joseph Tedesco, dean of Cullen College of Engineering, hosted a **National Academy of Engineering Wall of Fame** dedication ceremony for those associated with the university either by education or professorship. NAE members were celebrated for their significant impact on engineering research, education, and the profession. Each is recognized as a role model for the next generation of engineering students and faculty, challenging, encouraging, and enlightening newcomers to the dynamic world of 21st century engineering. Those honored were **Charles Cutler**, president, Cutler Technology Inc.; **Bonnie Dunbar**, Dunbar International LLC; and, from the University of Houston, **Neal R. Amundson**, Cullen Professor of Chemical Engineering and professor of mathematics (deceased); **Benton Baugh**, adjunct professor of mechanical engineering; **Abraham Dukler**, Distinguished University Professor of Chemical Engineering (deceased); **Fazle Hussain**, Cullen Distinguished Professor of Mechanical Engineering; **W. John Lee**, Cullen Distinguished University Chair; **John Lienhard**, M.D. Anderson Professor of Technology and Culture Emeritus; **Dan Luss**, Cullen Professor of Engineering; **Michael Pao**, Distinguished Research Professor of Engineering; **Allen F. Rhodes**, adjunct professor of mechanical engineering (deceased); **James Symons**, Cullen Distinguished Professor of Civil Engineering Emeritus; **Anestis S. Veletsos**, Distinguished Adjunct Professor; and **Kaspar Willam**, Cullen Professor of Engineering.

C.D. (Dan) Mote Jr. Nominated to Be Next National Academy of Engineering President

C.D. (Dan) Mote Jr.

The National Academy of Engineering (NAE) 2013 nominating committee[1] has unanimously recommended **C.D. (Dan) Mote Jr.**, past president and Regents Professor of the University of Maryland (UMD), to stand as the sole candidate[2] for the NAE presidency. NAE members will vote in March 2013 to elect a new NAE president to a six-year term beginning July 1. If elected, Mote will succeed **Charles M. Vest**, whose term ends June 30, 2013.

“I am thrilled that Dan has accepted the nomination for the NAE presidency,” said NAE council chair **Charles O. Holliday Jr.**, retired chairman of the board and CEO of DuPont. “His passion for engineering excellence and his experience advancing the profession make him the ideal person to build upon the leadership of Chuck Vest.”

The National Academy of Engineering is part of the National Academies, which also include the National Academy of Sciences, Institute of Medicine, and National Research Council. These independent, nonprofit institutions advise the government and the public on issues related to science, engineering, and medicine. NAE members are the nation’s premier engineers, elected by their peers for their distinguished achievements. Established in 1964, NAE operates under the congressional charter granted to the National Academy of Sciences in 1863. The NAE president is a full-time employee of the organization at its headquarters in Washington, DC, and also serves as vice chair of the National Research Council (NRC), the principal research arm of the National Academies.

From 1998 to 2010, Mote served as UMD president and Glenn L. Martin Institute Professor of Engineering. Under his leadership, UMD research funding increased by more than 150 percent and the university greatly expanded partnerships with corporate and federal laboratories. Mote also negotiated establishment of the University of Maryland–China Research Park, connecting Maryland and Chinese companies for joint ventures. Stressing the importance of closing the achievement gap, Mote helped UMD achieve in 2007 the fourth highest graduation rate for underrepresented minorities at public research universities. He has testified before Congress and been featured in the news media on issues ranging from education funding models to visa barriers for international students to deemed export control issues.

Internationally recognized for his research on the dynamics of gyroscopic systems, including high-speed translating and rotating systems, and the biomechanics of snow skiing, Mote has authored or coauthored more than 300 publications, holds patents in the United States, Norway, Finland, and Sweden, and has mentored 58 PhD students.

Mote was elected to the NAE in 1988 “for analysis of the mechanics of complex dynamic systems, providing results of great practical importance in vibrations and biomechanics,” and is the current NAE treasurer and a member of the NRC Governing Board Executive Committee. In addition, he cochairs the NRC Government-University-Industry Research Roundtable and Committee on Science, Technology, Engineering, and Mathematics Workforce Needs for the US Department of Defense and the US Defense Industrial Base. His past NRC service includes membership on the Committee on Science, Engineering, and Public Policy and chairmanship of the Committee on Global Science and Technology Strategies and Their Effect on US National Security.

Mote received his BS, MS, and PhD in mechanical engineering from the University of California, Berkeley, where he served on the faculty for 31 years and held positions as chair of the Department of Mechanical Engineering, president of the UC Berkeley Foundation, and vice chancellor. He has received three honorary doctorates and the Berkeley Citation, an award from the university similar to an honorary doctorate.

Notes

1. The members of the NAE nominating committee represent each of the 12 sections of the Academy and are elected by the members of each section. The three largest sections place two members on the committee, resulting in an elected membership of 15. The chair of the nominating committee is selected from among these 15 members by the NAE Council, the governing body of the NAE. In addition, one member of the council serves as its representative on the nominating committee, the NAE vice president and home secretary serve ex officio, and the chair of the previous year's nominating committee also serves. No member may be elected to serve on the nominating committee more than once in six years. The members of the committee were as follows:

John L. Anderson (chair)
Illinois Institute of Technology

Rudolph Bonaparte
Geosyntec Consultants

James A. Brierley
Brierley Consultancy, LLC

Bruce R. Ellingwood
Georgia Institute of Technology

Zvi Galil
Georgia Institute of Technology

Arthur H. Heuer
Case Western Reserve University

Fazle Hussain
University of Houston

Karl G. Kempf
Intel Corp.

Frances S. Ligler
Naval Research Laboratory

Kuo-Nan Liou
University of California,
Los Angeles

Debasis Mitra
Bell Labs, Alcatel-Lucent

Arogyaswami J. Paulraj
Stanford University

Arun G. Phadke
Virginia Polytechnic Institute and
State University

Prabhakar Raghavan
Google Inc.

David A. Whelan
The Boeing Company

Julia Phillips
NAE Council representative;
Sandia National Laboratories

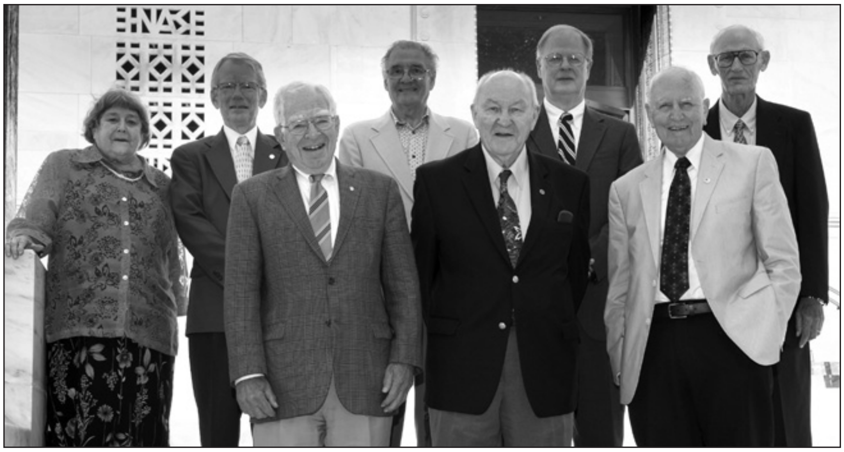
Thomas Budinger (ex officio)
NAE home secretary; Lawrence
Berkeley Laboratory and University
of California, Berkeley

Maxine Savitz (ex officio)
NAE vice president;
Honeywell Inc. (ret.)

Ann L. Lee (immediate past chair)
Genentech Inc.

2. According to the NAE bylaws, a candidate may be added to the ballot for any position by petition. Such petition must be signed by 5 percent of the active members of the Academy, representing at least 10 different institutions, and must be submitted by January 15 of the election year.

Highlights of the 2012 NAE Annual Meeting



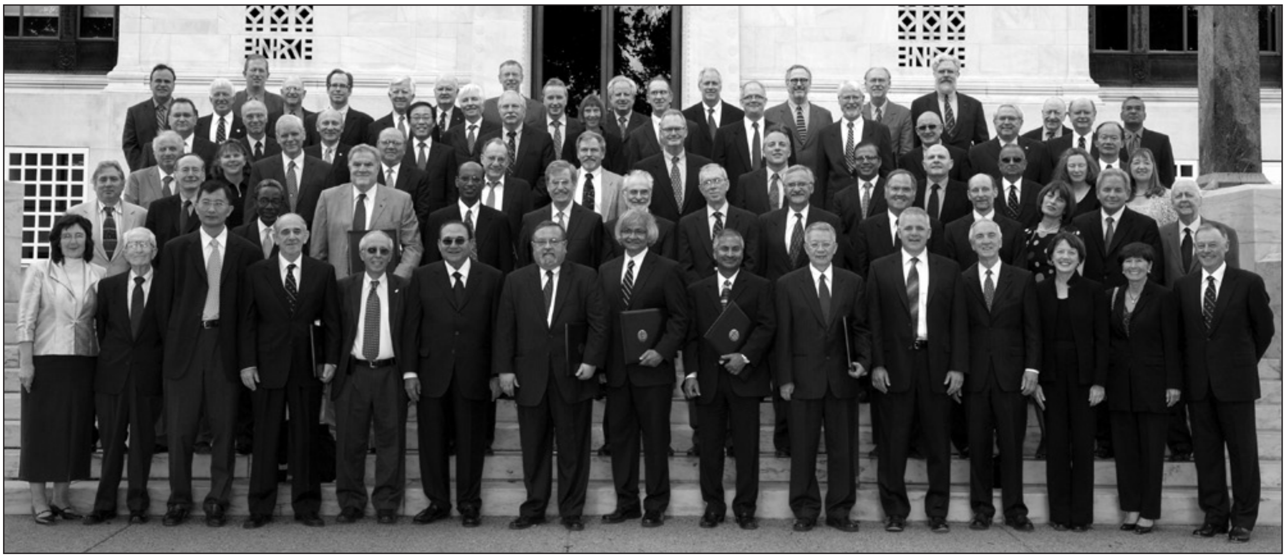
Anniversary members (l to r): Front row: Ronald F. Probstein, Melvin F. Kanninen, William D. Nix; Back row: Yvonne Brill, Arthur W. Westerberg, Raymond Viskanta, James J. Duderstadt, Richard M. Christensen.

NAE members, foreign associates, and guests gathered in Washington, DC, in September for the 2012 NAE Annual Meeting, which was held in the newly restored National Academy of Sciences (NAS) Building on Constitution Avenue. The meeting began on Saturday afternoon, September 29, with an orientation session for new members. That evening 66 new members and 10 new foreign associates were honored at the NAE Council dinner in the Great Hall of the NAS Building.

NAE chair **Charles O. Holliday Jr.** opened the public session on Sunday, September 30, with remarks congratulating new members and calling on them, as they consider a new realm of choices now before them, to practice the highest ethical standards. He illustrated the value of his own experiences when faced with ethical challenges, and offered "three simple tests" to guide ethical decisions (see p 63).

President **Charles M. Vest** then delivered his annual address to the members and guests. In his speech "What Are We Waiting For? Sputnik? An Explanation of Today's World? New Ways of Working? National Strategy?" he cited the need for bold vision and leadership as the United States confronts a new era of national and global challenges. (The speech is printed in this issue [see p 65] and posted online at www.nae.edu.) The induction of the NAE Class of 2012 followed President Vest's address, with introductions by NAE Executive Officer **Lance Davis**.

The program continued with the presentation of the 2012 Founders and Bueche Awards. The 2012 Founders Award was presented to **Nicholas A. Peppas**, Fletcher Pratt Chair of Chemical Engineering, Biomedical Engineering, and Pharmacy at the University of Texas at Austin, for "contributions to biomedical and



NAE Class of 2012.

drug delivery applications of polymer networks and hydrogels and for leadership in the bioengineering community" (see p 69). **James Duderstadt**, president emeritus and university professor of science and engineering at the University of Michigan, was presented the Arthur M. Bueche Award for "leadership in academe and national service to support innovative science and technology policies" (see p 72).

The Bernard M. Gordon Prize Lecture featured the three 2012 winners: Clive L. Dym, Fletcher Jones Professor of Engineering Design and Director of the Center for Engineering Design Education; M. Mack Gilkeson, Professor of Engineering Emeritus; and J. Richard Phillips, Professor of Engineering Emeritus, all from Harvey Mudd College. The speakers described engagement and innovation in the college's engineering curriculum, with a focus on engineering design, hands-on experience, and workshops.

After a break, Dr. Vest introduced the Armstrong Endowment for Young Engineers—Gilbreth Lecturers, outstanding young engineers who have made presentations at the NAE's Frontiers of Engineering symposia. John Ochsendorf, Associate Professor of Civil and Environmental Engineering, Massachusetts Institute of Technology, spoke on "Challenges and Opportunities for Low-Carbon Buildings." Hod Lipson, Associate Professor of Mechanical and Aerospace Engineering and of Computing and Information Sciences, Cornell University, spoke on "The Shape of Things to Come: Frontiers in Additive Manufacturing."

Subra Suresh, director of the National Science Foundation, delivering keynote address.

Dr. **Subra Suresh**, Director, National Science Foundation, delivered the Distinguished Guest Lecture on a "New Era of Global Science and Engineering." The day ended with a reception for members and their guests.

At the annual business session for members on Monday morning, Dr. Vest provided a quick summary of the organization of the NAE, its relationship with the NAS, IOM, and NRC, and its finances. He discussed the need for independent funds and thanked the members for their personal philanthropy of giving to the NAE. He highlighted recent NAE program activities, including newly emerging joint activities with the IOM, the ongoing Grand Challenges project, the Frontiers of Engineering symposia series, and the upcoming Frontiers of Engineering Education Symposium.

The business session was followed by a forum on "Educating Engineers: Preparing 21st Century Leaders in the Context of New Modes of Learning." Ali Velshi, Anchor and Chief Business Correspondent, CNN, moderated a discussion exploring many facets of contemporary engineering education. Speakers addressed opportunities and responsibilities made available by advances in educational modalities, including new institutional structures, new IT-based capabilities, and new approaches to team-based, hands-on learning. The panelists were Anant Agarwal, President, edX, and Professor, Massachusetts Institute of Technology; **Linda P. Katehi**, Chancellor, University of California, Davis; Salman Khan, Founder, Khan Academy; **Richard K. Miller**, President, Olin College; Richard D. Stephens, Senior Vice President for Human Resources and Administration, the Boeing Company; and Tuula Teeri, President, Aalto University, Finland. The video of the forum is available on the NAE website (www.nae.edu) and a summary of the forum will be published early in 2013.

On Monday afternoon, members and foreign associates participated in NAE section meetings at the

Forum panelists and moderator.

NAS Building and Keck Center. The meeting concluded with the annual reception and dinner dance, held at the JW Marriott with music by the Odyssey Band.

The next annual meeting is scheduled for October 6–7, 2013, in Washington, DC. Please save the date!

Special Events

NAE Hosts Estate Planning Brunch During Annual Meeting

This year's estate planning seminar was well received by over 30 NAE members and guests. Held annually, this session gives members a chance to learn about tax-savvy financial strategies and to hear about incorporating philanthropy into their long-term plans. Cindy Sterling, an independent financial expert, discussed how the presidential election, the expiration of the Bush administration tax cuts, and other political changes might affect people's taxes in 2013. As of September 30 Congress had not determined whether tax cuts would be extended, and Ms. Sterling warned that there will likely be sweeping changes to the tax code. She shared creative ideas for bundling philanthropy into financial planning—including, for example, setting up charitable gift annuities and charitable remainder unitrusts—while urging members to consult their financial advisors to see whether taking advantage of the current tax code may be beneficial for their unique financial situation. If you were not able to attend the brunch and would like the materials from the session, please contact Radka Nebesky, NAE's Director of Development, at *RNebesky@nae.edu* or 202.334.3417.

New Einstein Society members with their statuettes.

Estate Planning Brunch

2012 Golden Bridge Society Dinner Honoring NAE's Most Generous Donors

NAE President Dr. **Charles M. Vest** and his wife Becky hosted 70 of NAE's most generous members and friends at this year's Golden Bridge Society Dinner held at the United States Institute of Peace. The Sunday evening event in honor and appreciation of NAE's best donors drew members participating in the NAE Annual Meeting and friends who partake in what has become an annual tradition.

Donors are recognized in several categories for their level of giving. An unprecedented five new donors were welcomed into the Einstein Society, which celebrates members and friends who have given over $100,000 in their lifetime, and presented with an Einstein statuette as a token of NAE's gratitude for their contributions. Dr. Vest also welcomed new members of the Golden Bridge Society, celebrating donors who have given between $20,000 and $99,999 over their lifetime, and of the Heritage Society, celebrating donors who have made provisions for future gifts to NAE through their estates or other planned giving vehicles.

New Einstein Society members recognized at this year's dinner were NAE Chairman **Chad Holliday** and his wife Ann, NAE member **Robin McGuire** and his wife Rose, NAE member **Erich Bloch**, NAE member **George Bugliarello**'s widow

Virginia, and Lawrence Finegold. NAE Council member **Arnold Stancell** and his wife Connie, and NAE member **Asad Madni**, his wife Taj, and their son Jamal were recognized for making commitments to reach the Einstein Society level of giving. NAE's Foreign Secretary **Venkatesh "Venky" Narayanamurti** and his wife Jaya were welcomed into the Golden Bridge Society, and Einstein Society member Tobie Fink, widow of deceased NAE member **Dan Fink**, was welcomed into the Heritage Society.

Several donors were eligible for NAE's cumulative giving societies as of September 30, 2012, but were not able to make it to the dinner. NAE member **Gary Tooker**, NAE member **Robert Wertheim**, NAE member **Lewis Branscomb**, and John McDonnell are all new members of the Einstein Society. NAE Council member **Alice Agogino**, NAE member **Linda Sanford**, NAE member **Narayana Murthy** and his wife Sudha, NAE member **David Shaw**, and Yoon-Woo Lee are all new members of the Golden Bridge Society. NAE member **Joseph Goodman** is a new member of the Heritage Society.

Many of these donors were spurred to increase their giving in anticipation of NAE's 50th Anniversary in 2014. Increased membership in all three cumulative giving societies is a key goal of the 50th Anniversary fundraising effort, and Dr. Vest expressed his appreciation and enthusiasm for the positive response from members and friends who are excited to help NAE celebrate this milestone.

Remarks by NAE Chair Charles O. Holliday Jr.

Charles O. Holliday Jr.

Thank you, and let me offer my congratulations to all the new members.

I have a few brief comments this morning, directed to the new members, but the rest of you can listen if you want to.

Yesterday you had a set of choices. You had a long menu—because of what you have done in your life and what you have accomplished—of how you could spend your time, your talents, and your resources. After today, that menu is going to be a bit longer. Now, as a member of the National Academy of Engineering, you serve the nation, you advance our profession, you help society understand what we do for the world. I hope, as you make your selections going forward, you will find that time and time again you will want to pick some new things off the menu. I think you'll find they taste pretty good.

But today I'm not talking about those choices. I'm talking about just one choice that I sincerely and personally hope you will make, and that is to be a standard bearer for the highest ethical standards.

As you enter any new organization, you look around and say, What are the standards of this place? I have never seen an organization that didn't say they had ethical standards.

What about high ethical standards? Well, Enron had high ethical standards until they suspended their code of conduct to do what they wanted to do. How many times do people with high ethical standards do a mathematical calculation on the cost, that being a factor in their standards?

What we must have are the highest ethical standards. As you read the Professional Engineering code of conduct, that's exactly what it says. That's the standard I believe you operate to or you wouldn't be here today. But that's the standard I'm asking you to make the choice to advance considerably as a lifetime member of the National Academy of Engineering.

Let me share a couple of experiences from my career at DuPont that help me stay calibrated about how to do that. I was serving DuPont in Southeast Asia. I was taking a team to potentially build a plant in a country I won't name, a medium-size country in Southeast Asia. We were leaning toward doing this venture. As part of our normal due diligence, we went to see the US ambassador. I went in with two of my colleagues, he had two of his staff. We were sitting in his office. They were very happy because this would be the biggest plant DuPont had built in that country.

But partway into the conversation, the ambassador leans over and says, "Chad, I understand you like roses. I want to show you my rose garden."

I've been accused of liking a lot of things, but never roses before, as my wife can attest.

So we walk down the hall, and I'm a little bit suspicious about what this is really about. We look out the window at the three scrawniest rose bushes I have ever seen in my life. That took away any doubt—we weren't there to talk about roses.

He said, "That company you're talking to—yes, it's one of the five largest companies here locally. But, as I understand their standards, here is what they're going to ask you to do within weeks." Then he listed both the local and US laws the company's requests would violate.

I looked at him and said, "Well, thank you very much. That's very helpful. But why couldn't you tell me down the hall?"

He said, "Because I can't prove it. My ability to serve as ambassador here would be gone if I put out rumors about companies that I couldn't back up."

I said, "Why did you tell me now? Why did you suddenly tell me here?"

He said, "Because I understand DuPont operates to the highest ethical standards, and you would use this information appropriately."

I had never met this ambassador before. But the reputation of the company I worked for went before me and set that standard and allowed me to move up.

As you join the National Academy of Engineering, you are joining an organization with the highest ethical standards. Perhaps you are moving up a bit. But the message in this is, any time you are thinking about who else you might want to associate yourself with, always have the highest ethical standards.

The second story is a little farther north from where we were in Southeast Asia. This was in Hong Kong, before it rejoined the mainland. DuPont had its operating headquarters in Hong Kong, and we had a plant across the border in Shenzhen, if you are familiar with the geography. We would send a courier back and forth several times a week to transport various things. The government of China and the government of Hong Kong had gotten together and had special license plates you could get so you didn't have to wait in line—sometimes the lines could be an hour or two long. You had to apply for this license plate and you had to have good reasons for it. We thought we fit; we applied. About two months after we applied, we realized we hadn't heard anything from them. So we went in to check and we found out that our application was in order and we met all the requirements—but we hadn't paid the $50 bribe. They called it something much nicer, but a bribe is a bribe.

Our folks came back, and we said, "Okay, we'll just wait our turn in line." We do not pay bribes, no matter what the case might be.

This dragged on for 14 months, with our drivers waiting in line. And people would kid them—"What a dumb company you have. Look at the economics of just paying the bribe. Your time in one month would just pay for the $50." It got so much talk that a reporter for the *South China Morning Post*, the Hong Kong newspaper, heard about it and printed on the front page of the paper a list of all the companies that had gotten their license plates after we had applied. We got our license plate about three days later.

But what we got so much more of was the feeling our employees had about ethics. We could have had 100 ethics lessons, and it never would have communicated what that article did. We had so many people—because people remembered it for a year or two—who wanted to work for DuPont because of that standard.

What I share by this story is that, in the short term, you may be able to make a calculation that shows it's a good business decision. But I would dare you to show me a point in the long term where it ever turns out to be a good business decision. Sometimes you won't get the payback in 14 months, but I'm confident your ethical decision will pay off in financial terms to what you are doing, as well as in ethical terms.

If you look at the Professional Engineering code of conduct, it is long. There is a lot of detail. It's very useful. But sometimes you are going to be out and you'll have to make an ethical decision. You can't get online, you can't see the code, and you can't study it. Let me share with you the three things that I use all the time, and have for several decades, to help me when I can't get on the website.

If I'm making a decision and I'm proud to tell one of the colleagues I work with that this is my decision, that passes the first test.

If I'm proud to go home and tell my family of this decision, it passes the second test.

If I'm okay if you print it in the newspaper accurately—I don't have to like it, but okay—it passes the third test.

I would challenge you to use those three simple tests. In my experience, if a decision passed all three of those tests, it also passed the code of conduct of the organization I was a part of.

In closing, you have a lot of choices to make in your work with the National Academies. You will get out of this organization exactly what you put in. We are an organization of members.

I really hope you will make a lot of choices from the new items on your menu. And one of your choices should be to practice the highest ethical standards and seize every opportunity you have to move other members of our profession to do the same thing.

Thank you very much.

What Are We Waiting For? Sputnik? An Explanation of Today's World? New Ways of Working? National Strategy?
Annual Address by NAE President Charles M. Vest

Charles M. Vest

What Are We Waiting For?

I want to begin my remarks today by expressing my appreciation for the honor and privilege of serving as your president. It has been a very rewarding experience, and I hope that I have added some value to the NAE and to the greater causes that we serve.

There is one thing that the outgoing leader of an important organization values above all else…that is that he or she will be succeeded by a new leader whom he or she deeply respects. Although I appropriately played no role whatsoever in the work of the Nominating Committee, I could not be more pleased than to have Dan Mote nominated to be our next president. We could not possibly do better.

But there are areas in which we could do better. For example, the embarrassing silliness of this political season has reinforced something that has bothered me for some time: For many years now, as a nation and as a body politic, we have been *waiting*. Waiting when we should have been acting and leading. I don't get it. What are we waiting for?

If I hear one more person say that our educational, scientific, and technological enterprises are waiting for another "Sputnik moment" I fear that I will react in some bizarre, illogical manner unbefitting this office.

But there *are* some things that I am waiting for, and I suspect that I am waiting for them in the good company of all or most of you. I am waiting for our political and corporate leaders to honestly explain today's world…clearly and continually in their public dialogue and through their strategies and actions.

I also think that far too much of our nation is waiting for new ways of working to arrive. We hear lots of rhetoric about how the nature of work will change, as if it relates to some unknown distant future. The fact is that it is happening now, and we need a broader recognition of this fact and policies and education that reflect it.

Finally, I am waiting for national strategies around the fundamental issues of our time. By "national strategy" I generally mean "rules of the road." One of the great lessons of the second half of the 20th century is that central planning does not work. The private sector and especially entrepreneurial communities will beat central government planning every time. But, having said that, in my view many of the great national and global challenges we face today require the government and society to establish and sustain goals, directions, and policies that describe "rules of the road" according to which the private sector can find optimum solutions.

Waiting for Sputnik

When I was a high school student, America woke up one day and learned that the Soviet Union had placed a satellite named Sputnik into orbit about the Earth. This injured our national pride, raised national security and geopolitical concerns, and led fairly quickly to a focus on the importance and quality of our science and mathematics education. It inspired many young people, including me, and in due course provided us with better teaching materials and with major increases in financial aid, from both corporations and government, for advanced studies in engineering and science, and new career opportunities. Like Pearl Harbor, it was a single, crystallizing moment of the kind to which our nation is good at responding.

But waiting for a new Sputnik moment in 2012 is folly. This generation already has its challenges, and they are far more fundamental and far more important than was a Soviet satellite. And most—perhaps all—of this generation's challenges are *global*. They are global because our world is straining to support 7 billion people who share a single environment, finite natural resources, knowledge, economy and commerce, and, above all, a common humanity.

As you know, the NAE commissioned a committee of 18 superbly creative and innovative men and women to establish a set of Engineering Grand Challenges that, if met, would improve life on earth and that they believed could be accomplished if we set our minds and resources to them. These Grand Challenges fall into four large buckets: Sustainability, Security, Health, and Joy of Living. Mostly through the voluntary efforts of many leaders of higher education, these NAE Engineering Grand Challenges have led to numerous education and outreach programs and have entered the national dialogue among business, government, and academia.

What I have observed through our Grand Challenges work, and through many campus visits and gatherings of entrepreneurs, is that this generation of young people is eager to engage. They aren't waiting for Sputnik. So let's all work together to provide them with the opportunities and resources to start meeting these Grand Challenges. Let's stop dampening their well-informed enthusiasm and efforts by choking back funding of higher education, stalling research support, blocking immigration, and glorifying and rewarding careers that add no value.

Waiting for Leaders to Explain Our New World

Virtually everyone in this room is engaged in industry and commerce, in higher education, in research and development, or in national security. Each of us lives, works, and learns in a highly integrated, networked world.

Do you recognize this world in our political rhetoric? Do you hear our corporate leaders working explicitly and in a sustained manner to help our people understand this? Maybe you do, but I don't.

The world has changed. We need to get on with it.

R&D investments by both the private and public sectors are increasingly spread around the globe. Currently they are approximately one-third in North America, one-third in Europe, and one-third in Asia. And the level of education is rising all around the world, especially in the STEM disciplines. These new global distributions are good things. But we can't sit on our thumbs and watch much of the rest of the world approach and then surpass us in these important investments. In my view, our most important national comparative advantages are democracy, free enterprise, diversity, and excellence and inventiveness in higher education and research.

I think our leaders owe us more straight talk about the nature of today's world. In particular, we all must understand that, now and in the future, we must compete but also cooperate with others all over the world—other countries, other companies, other universities,… other colleagues. Cooperation and competition are the yin and yang of the modern world.

And sharing is the enabling mechanism—sharing of knowledge, sharing of talents, sharing of education. This is the new world of open innovation and of new ways of working.

During our 2011 NAE National Meeting, we held a forum on Manufacturing, Design, and Innovation. Our colleague **Rod Brooks** was one of the panelists. Suggesting that we concentrate too much on the most sophisticated technologies and environments, he laid out a case for focusing on small, easily programmable robots to help humans perform fundamental manufacturing operations. Such devices could "democratize low-end manufacturing." Fast forward to last month, and note these words in Tom Friedman's August 26, 2012, *NYT* column describing Rod's newest venture, a company called Rethink Robotics:

> The Rethink design team includes Bruce Blumberg, the product manager of the Apple LaserWriter, as well as 75 other experts from Russia, Georgia, Venezuela, Egypt, Australia, India, Israel, Portugal, Sri Lanka, the United States and China.
>
> "It is all made in America," says Brooks, but by "the best talent" gathered "from around the world."

So here, in one package, are competition, cooperation, and new ways of working.

Waiting for New Ways of Working

Yet I keep reading about new ways of working that are going to happen in some distant future. In fact, they are happening now, and we need to be preparing more people for them.

A few decades ago, we talked about *brain drain*. This generally referred to the movement of highly talented young people, especially scientists and engineers, to the United States to study and subsequently contribute richly to our nation as faculty members, entrepreneurs, and business leaders. But "drain," of course has a negative connotation because to some extent America's gain was a loss to these individuals' home countries.

Today, especially for young people, we are more in an age of *brain circulation*, with students, entrepreneurs, and corporate personnel living and working in multiple countries during their careers.

But I believe we are rapidly entering the age of *brain integration*. By this I mean integrating people's minds with each others' and with computers. Here is a simple example of what I mean:

Think about the game of chess. A well-programmed computer can consistently defeat a human chess opponent. This was most famously demonstrated several years ago when IBM's Deep Blue defeated Gary Kasparov. But it turns out that a *team* of humans and a computer can be expected to beat any other human or any computer.

One of the most exciting examples of brain integration is by the website Foldit. Foldit is basically a computer game developed by faculty at the University of Washington. It not only chains together many personal computers around the world, it also chains together many minds, because the thousands of people playing this game are in fact cooperating to solve complex protein-folding problems. Although, to the individual players, this is a new way of playing, in fact it is a new, cooperative way of working.

Douglas Thomas and John Seeley Brown explore the same concept of harnessing massively multiplayer online games for purposes of learning in the interesting book *A New Culture of Learning*. But in this case, my use of the word "harnessing" shortchanges the concept of brain integration because the players and communities themselves develop the culture of learning; it is not a new way of doing traditional teaching and learning.

Finally I should note that developing such new ways of working and problem solving is the object of intense research at places such as the MIT Center for Collective Intelligence, which is devoted to answering a core research question: *How can people and computers be connected so that—collectively—they act more intelligently than any person, group, or computer has ever done before?*

Now let me turn briefly to the manufacturing sector. Our nation is perplexed about the future of manufacturing in the US and about what manufacturing jobs have changed or will change. Too frequently, discussions about manufacturing revolve around a nostalgic view that the old jobs may return. In fact, we need to understand what the *new* jobs will be and how to prepare young people for them.

During the last several months, the NAE, with the guidance of an informal advisory committee headed by the visionary former General Motors executive **Larry Burns**, has helped us begin developing a new framework for thinking about the nexus of manufacturing, design, and innovation. We have held one major workshop of leaders from business, academia, and government, and are developing a fast-track set of research and analysis projects that we hope will be useful to the nation.

There is an exciting world out there involving additive manufacturing, biologically based manufacturing, design for sustainability, and advanced robotics. There is plenty of great and important R&D to be done in these fields, but the overall picture, and especially the issue of jobs, is much broader than just advances in these individual technologies.

Things are stirring. Our committee observed that, "While overall US manufacturing employment has decreased by 5 million jobs since 1980, manufacturing employment requiring at least a college degree has *increased* by approximately 1 million jobs." That should make us sit up and pay attention.

The framework we are working toward is centered on *making value*. By this, we imply that it is not just about making things, nor is it just about creating services. It certainly is not just about making money in ways that add little value to customers or society, and it is not just about making anything confined solely to US geographic boundaries.

In our developing framework, making value requires an integrated system of activities—including understanding customers, research, development, design, manufacturing, and services—necessary to deliver value to customers. Making value requires a holistic system of these activities that must be developed and optimized in the national interest.

If all of this sounds suspiciously like gobbledygook, just stop and think about what the iPhone and its progeny have done. For sure, they integrated innovation, design, and manufacturing. But they also created an entire new industrial ecosystem, especially the “app” industry. For sure, they made money—but they also created opportunity for basement software developers, provided new platforms for business and for education, and either harnessed or unleashed creativity and innovation all over the world. They created and enabled a new ecosystem of people and activities. We believe this general framework of making value will extend far beyond the IT device industry.

I hope that in the coming months our NAE work will meet three basic objectives:

1. Analyze existing best practices in holistic enterprises that make value;
2. Learn all we can about the likely ecosystem that will support future work, including the skills, education, infrastructure, and government policies to enable and support new work; and
3. Determine the necessary and sufficient conditions to make the United States the ideal place to make value.

Waiting for National Strategy

I worry a lot about the seeming inability of the nation to set strategy, in the broad sense of establishing and sustaining “rules of the road.” In fact, in the dark recesses of the night, I sometimes become afraid that this could be an Achilles’ heel of democracy itself. I know that this is overly pessimistic, but let me give you an example of why I worry.

A few years ago, I visited a sprawling facility of one of our largest companies. It had invested huge amounts of money and engineering in several forms of alternate or renewable energy production—wind, solar, biomass, and the like. These had been carried to the large-scale demonstration level.

But the machines were just sitting there. When I asked what their plans were for bringing these huge devices to market, the answer was “We have no plans for commercialization. Our investment is ending because the government has set no energy policy and they have set no carbon policy. Until that happens, we have no idea what the markets will be.”

Government is not going to do the things that are required for us to have a vibrant economy, health, security, and quality of life.

Business is not going to address the things that are required for us to have a vibrant economy, health, security, and quality of life.

Academia is not going to address the things that are required for us to have a vibrant economy, health, security, and quality of life.

The fact is that we have to have all hands on deck. Each of these sectors must play its proper role and forge an alliance to meet today’s challenges.

What we are missing is bold vision and leadership.

“Well,” you might ask, “don’t you know that we have a big financial problem?”

“Don’t you know that we have been fighting wars in the Middle East?”

“How can we summon bold vision and leadership in such a time?”

Here is a thought: 150 years ago, in the midst of the utter devastation of the American Civil War, our leaders conceived and passed the Morrill Act. The Morrill Act established our great system of land-grant universities to invest in the education of young people from all social strata. I would guess that most of us in this room were educated in land-grant universities.

And 150 years ago, in the midst of the utter devastation of the American Civil War, our leaders conceived and created the National Academy of Sciences because they understood that “science and art” were fundamental to the development and expansion of our nation.

Until or unless such bold vision comes again, we must unleash our innovation system as best we can. This is a nonlinear, loosely organized system that is still the *best in the world*.

And we need to be at the forefront of other emerging models of innovation: inducement prizes; new, reorganized universities; virtual communities.…

But we must remember that it all begins with education.

And something big is about to happen in education. We will explore this tomorrow in our Forum on the Future of Engineering Education.

Thank you.

2012 Founders Award Acceptance Remarks by Nicholas A. Peppas

Left to right, NAE chairman Charles O. Holliday Jr., Founders Award recipient Nicholas A. Peppas, NAE President Charles M. Vest, and Matthew O'Donnell, 2012 NAE Awards Committee chair.

It is a great honor for me to receive the Founders Award of the National Academy of Engineering today. The Founders Award is not only recognition of an individual's achievements but also an acknowledgement of the hard work and contributions of all the collaborators who contributed to this work. I am touched by the generosity of the Academy and its Awards Committee and I am humbled to be included among the giants of engineering who have received this award before.

My contributions over the past 42 years have been in the fields of biomaterials science, polymer science, drug delivery, and biomedical engineering. But when I arrived in the United States, in Boston, on a hot and humid late afternoon of July 1971, I could not imagine what a turn my life would take. Indeed, my aspirations in the early years were quite different.

I was born in Athens, Greece, in August 1948. My father, Athanassios Peppas, was an economist and playwright, my mother, Alice Rousopoulos, a teacher of French literature. I was brought up in a loving home in the suburbs of Athens and in the early days I was taught to read and admire the classics. Classics in our household did not mean only a love for Greek and Latin history and literature, but also an appreciation for European traditions and the work of German, French, British, Italian, and Russian authors. A loving circle of relatives had a major influence on me and I was sure I wanted to study archaeology like my great-grandfather Athanassios Rousopoulos, who was a professor of archaeology at the University of Athens. But I also loved chemistry and I had inherited all the books of my grandfather Peter Rousopoulos, a chemistry professor at the Commercial Academy of Athens, who did his doctorate at the University of Göttingen under the supervision of Otto Wallach, a 1910 Nobel laureate in chemistry.

History, archaeology, and Italian opera kept me busy as I was growing up in the sixties. But the educational environment was fertile and eventually chemistry prevailed. Upon taking national examinations, as was the norm, I entered the Chemical Engineering Department of the National Technical University of Athens, at that time the most prestigious department in Greece. As students at NTU in the middle and late sixties in Athens, we were all fascinated by novel mathematical techniques, advanced transport phenomena, and chemical reaction engineering, courses taught by a group of young faculty members who had arrived from the United States.

When the time came for me to continue my studies toward a PhD degree, I had the fortitude—audacity would be a more appropriate word—to deviate from the mathematical norm and study biomedicine, something that was unheard of in European engineering circles at that time. So, I arrived in Cambridge, MA, in August 1971 and I was enrolled in chemical engineering at MIT. At MIT, we all had the great fortune to be students of this great pioneer of biomedical engineering, one of the fathers of the field, Edward Wilson Merrill. Ed instilled in all of us the idea that the principles of engineering and physiology could be applied to the solution of important medical problems. Those were the days when medical scientists from the Harvard Medical School and the main hospitals of Boston would cross the Charles River to collaborate with MIT professors on medical problems requiring modeling, rheology, new materials, and innovative technical solutions. I was fortunate to be in the same class and laboratories with other ambitious young men, notably **Bob Langer** of MIT, who became a giant in the biomedical field and preceded me as an NAE Founders Award recipient in 2010; Michael Sefton, now of the University of Toronto and member of the Royal Society; and even a young undergraduate chemist, **David Tirrell**, who was helping us in the lab and is now a distinguished member of all three Academies.

Those were truly wonderful days for biomedical education. Along with many friends, we embarked upon the study of biomedical engineering, biomaterials science, and allied fields, with the enthusiasm and dedication that only the young innocent generation of the early seventies could exhibit. We worked on the development of new nonthrombogenic biomaterials for artificial organs, valves for artificial hearts, new membranes for artificial kidneys, contact lenses, and prostheses, but also on a fundamental understanding of the causes of diseases from thrombosis to arteriosclerosis. These were the wonderful days when NIH funding was plentiful. I will always be grateful to this country for allowing a young engineer like me to delve into important medical problems and make an impact in the field.

At MIT I had the opportunity to meet many giants of the field. Several made an impact on me, such as the late **Robert Reid** and **Elias Gyftopoulos**, both NAE members, who taught us to be responsible scientists and engineers. The legendary **Warren K. "Doc" Lewis** at the age of 91 taught us a short IAP course on anemometry in January 1973, the same year he received the NAE Founders Award. Paul Flory (Nobel Prize 1974) had been invited by Ed Merrill to MIT and was a Visiting Professor in ChE at the time we were all doing our PhDs. You can imagine the impact he had on our thinking about biopolymers and cross-linked structures. A year later I had the opportunity to work as a postdoctoral fellow at the Arteriosclerosis Center of MIT under the direction of Clark Colton and **Ken Smith**, another NAE member. They both taught me to appreciate engineering and science but also to strive for advanced modeling and biological understanding.

Soon thereafter, I joined the faculty of chemical engineering at Purdue University. As I was starting my independent career there in July 1976 I realized how "open" the biomedical engineering field was to new ideas. I recall a summer meeting in Boston when Bob Langer and I met at a delicatessen in Boylston Street and over a long dinner we decided that we could "save the world" with novel biomaterials and drug delivery systems. We decided to work on the solution of important biomedical and pharmaceutical problems. So in my laboratories at Purdue University I started working on hydrogels as biomaterials, first for artificial vocal cords, then for articular cartilage replacement, followed by work on contact and intraocular lenses, nonthrombogenic biomaterials, and new artificial kidney membranes.

These were also the early days of drug delivery, a subject we started pursuing in 1977. In the beginning there were some obstacles but funding came early, first with Research Corporation and NSF grants in 1977, and a PETC grant on three-dimensional cross-linked structures in 1978. NIH funding was not easy for engineers, but by 1981 I had secured my first R01 grant, one that I must admit with pride I continue having. (Acceptance of biomedicine into the chemical engineering field was equally questionable with other researchers making statements such as "this is not chemical engineering.")

But by 1978 we had started addressing important new areas of drug targeting, drug delivery, parenteral and oral delivery, mucosal targeting, cell transport, and so on. My students and I became passionate about providing solutions to significant medical problems. We believed that the treatment of diabetes, osteoporosis, asthma, cardiac problems, and cancer should not be based only on conventional pharmaceutical formulations. Indeed, I believe that a key problem of biology and medicine this century has been to reduce the problems of disease to problems of molecular science. Many of the associated methodological advances in biomedical sciences are the result of earlier investments in the basic sciences. I believe that breakthroughs in molecular science have led to new opportunities for curing disease. In the last few years, Phil Sharp of MIT has been promoting the idea of "convergence in biomedical sciences." Of course, this is a paramount idea in bioengineering and has been a standard in my laboratory in the last 30 years and especially at the University of Texas at Austin. These interactions have led to collaborations with biologists, pharmacists, and practicing physicians.

I was fortunate to have had some great doctoral students in all my years at Purdue and the University of Texas at Austin—close to 100 PhDs, 42 of them now professors in academia. Two of them were particularly instrumental in biomedical research in those days and they are both here today, as they were inducted to the National Academy of Engineering as new members about an hour ago. Dr. **Richard Korsmeyer**, a senior fellow of Pfizer and internationally known leader in development of new pharmaceutical formulations, was a PhD student in my laboratory with whom we applied transport theory to understand drug transport in controlled release systems and in tissues. Those pioneering studies of 1979–1982 have led to an equation and a theory (the Korsmeyer-Peppas theory) that is now the basis for the design of new drug delivery system. The other newly inducted NAE member is **Antonios Mikos** of Rice University, with whom we studied targeting to specific sites and developed advanced theories of bioadhesion in tissues. Dr. Mikos went on to become one of the brilliant engineers and scientists in tissue engineering and regenerative medicine.

My career in the 1980s, 1990s, and especially this past decade at the University of Texas at Austin has allowed me to design, study, and utilize advanced biomaterials and advanced drug delivery formulations. These formulations do not simply release the drug, peptide, or protein at some characteristic rate but do so in a way that we design them to do. [Thus] pulsatile swelling/deswelling of polymer carriers and the associated drug delivery are consequences of significant changes of the physiological environment. For example, in collaboration with my former PhD student Anthony Lowman, now Vice Provost at Temple University, we have developed new systems with which insulin may be delivered to diabetic patients only when the glucose concentration in the blood is above the normal level. Calcitonin may be directed to bypass the stomach and be delivered only in the upper small intestine of women suffering from osteoporosis, from which it will be absorbed and pass into the blood. Finally, large molecular–weight, genetically engineered molecules can be delivered across tissues at acceptable rates. For example, we have exciting new results on oral delivery of interferon beta-1a for treatment of multiple sclerosis.

These biomedical developments and inventions use intelligent, hydrophilic, biomedical polymers, often hydrogels or networks, as carriers. The structure of these materials plays a key role in their diffusional behavior and the molecular stability of the incorporated bioactive agents. In my scientific career we have also advanced fundamental aspects of materials science and polymer gel theory. Some of the major developments in the field of rapid photopolymerizations came from the PhD work of my former students Alec Scranton, now Dean of Engineering at the University of Iowa, and Christopher Bowman, Head of Chemical Engineering at the University of Colorado. Dr. Bowman and I had the fortune to meet and work with a brilliant young student at different stages of her career: **Kristi Anseth**, a member of both the NAE and IOM, has become a major contributor to the field of biomaterials and tissue engineering. She was the nominator for the NAE Founders Award that I am receiving today and I want to thank her for her support and collaboration over the years.

Among other hydrogel-based formulations, we have also studied new polymers that can respond to changes of the physiological environment, especially changes of the pH, temperature, ionic strength, and analyte concentration. The pioneer in this work was Lisa Brannon-Peppas, with whom we developed not only some of the early pH-sensitive hydrogels but also the associated theories for swelling behavior and diffusion through ionic networks. I thank her for being a wonderful and highly innovative scientist—and also for being a great partner in life.

As I close I want to say that for me this NAE Founders Award is not the end of a career. I was fortunate enough to have wonderful colleagues, great collaborators, and brilliant, innovative graduate students and postdoctoral fellows who shared my vision to do research based on the principles of my field but also with an immediate application and a concern for patients. I am glad the medical and pharmaceutical industry used these ideas for important medical products. I share the feelings of my friend and 2010 NAE Founders Award recipient Bob Langer that "by the end of the next century disease as we know it today will no longer pose a major threat to human life and that highly effective methods to diagnose disease, prolong life, and relieve suffering will have been created." I believe that the convergence in biomedical sciences, chemistry, biology, and engineering will allow us to understand how diseases and genetic defects occur; develop new chemicals, biomaterials, and drugs to treat these diseases; engineer delivery systems that will target drugs and genes to the correct tissues, cells, or cell components; noninvasively diagnose diseases; and create new replacement tissues and organs.

I thank you for this great honor you are bestowing to me today and I am grateful to all those who helped me pursue and achieve a dream.

Tilting at the Windmills of Public Policy: Some Lessons Learned from an Engineering Perspective

2012 Arthur M. Bueche Award Acceptance Remarks by James J. Duderstadt

Charles O. Holliday Jr., Bueche Award recipient James J. Duderstadt, Charles M. Vest, and Matthew O'Donnell.

The 2012 Arthur M. Bueche Award was presented to James J. Duderstadt, President Emeritus and University Professor of Science and Engineering, University of Michigan, for "leadership in academe and national service to support innovative science and technology policies."

It is indeed an honor to receive the 2012 Arthur M. Bueche Award of the National Academy of Engineering for "leadership in academe and national service to support innovative science and technology policies," particularly since I have long regarded the National Academies as setting the gold standard for expertise, integrity, and impact in science and technology policy. In fact, much of my own policy education and experience have been shaped by leaders of the National Academy complex. It is in this spirit of "lessons learned" from years of tilting at the windmills of public policy that I thought I would offer a few observations on this occasion.

First, a bit of personal background. As a nuclear engineer, I have spent almost 50 years in the nuclear power policy wars, usually losing more battles than winning them, although the war is still not lost. As a faculty member, dean, provost, and president of a major research university, there have also been many battles concerning higher education policy. Fortunately, most of these have been won—except for my total failure in making a dent in the rampant commercialization of big-time college sports!

My activities in federal policy have been more of a mixed bag—over a decade on the National Science Board (including as chair); the NRC Committee on Science, Technology, and Public Policy; the NAE Executive Council (two terms); currently chairing the Policy and Global Affairs Division of the NRC; and dozens of various studies, commissions, boards, and the like over the years, some successful, some frustrating, but all quite interesting. Perhaps of most importance to the National Academy of Engineering was my role in chairing the nomination committee that persuaded **Chuck Vest** to become your president! Most recently, I have enjoyed reporting to **Chad Holliday** in his role as chair of the National Academies committee on the future of the American research university.

So, what are the lessons learned from almost a half-century of these experiences as an engineer venturing into the thicket of public policy? Some of these lessons are obvious; others are worrisome:

- Lesson 1: There are two flavors of S&T policy. The first involves *science and technology for policy*—that is, how science and technology are used to develop public policies in a broad array of domains such as national security, public health, economic competitiveness, and environmental sustainability. The second involves *policy for science and technology*—how policies are developed to promote beneficial scientific and technological development at the international, national, state, and local levels, such as the allocation of research funding and the regulation of research and technology development.
- Lesson 2: There are two groups of participants involved in S&T

policy: The scientists and engineers serving on key advisory and executive committees who understand science and technology but not always the policy process, and the elected officials, staff, and academics who understand well the policy process but less so the scientific context for their actions. Here, part of the problem is the wide gap that usually exists between "those who know what to do but not how to get it done" and "those who know how to get things done but not what to do"!

- Lesson 3: There are many different approaches to both the substance and the objectives of science and technology policy activities. While those of us from technical backgrounds are most comfortable with scientific evidence and reasoning, policy discussions also involve other belief systems such as political pragmatism, faith-based belief, public misunderstanding, and occasionally more sinister agendas designed to thwart and confuse more rational policy efforts.
- Lesson 4: Largely because of the cacophony of backgrounds, beliefs, and agendas of those involved in policy activities, there is an unpredictable, indeed a mysterious character to policy development that requires great patience, an ability to listen carefully, an openness to not only other points of view but quite different thought and value systems, and a tolerance for frequent failure if one is to make progress in science and technology policy development.
- Lesson 5: This brings me to my last lesson learned: Engineers are different from scientists! Of course, they are quite different in perspective, in the sense that while scientists are focused on understanding nature and the way things are, engineers are involved in manipulating nature to create things that have never been. The more pragmatic approach engineers take to policy issues can be very valuable, since they tend to avoid endless debates and instead demand action.

But there is also one significant weakness that engineers sometimes bring to the table in policy discussions that arises as a consequence of our current approach to engineering education.

Ironically, although engineering is one of the professions most responsible for and responsive to the profound changes in our society driven by rapidly evolving technology, its characteristics in practice, research, and education have been remarkably constant—some might even suggest stagnant—relative to other professions. The current paradigm for engineering education—an undergraduate degree in a particular engineering discipline, occasionally augmented with workplace training through internships or co-op experiences—seems increasingly suspect in an era in which the shelf life of taught knowledge has declined to a few years and the challenges faced by engineers continue to grow in complexity and diversity. To be sure, the engineering curriculum has added more scientific content as well as emphasis on engineering activities such as design and systems integration, but this has been done within a four-year undergraduate curriculum increasingly overwhelmed by both the breadth and depth of knowledge required by professional practice. In a very real sense, we are continuing to educate 21st century engineers using a 20th century curriculum in 19th century institutions.

It has long been apparent that the education for practice in knowledge-intensive professions needs to be broadened considerably if students are to have the opportunity to adapt to the rapidly changing needs of a global society. Essentially all other learned professions (e.g., law, medicine, business, architecture) long ago moved in this direction, requiring a broad liberal arts baccalaureate education as a prerequisite for professional education at the graduate level. Yet engineering educators and employers continue to resist most efforts to elevate engineering education to the postgraduate practice-based programs that characterize other learned professions. In fact, looking through the University of Michigan catalogue, I find that the only two remaining professional degrees still taught at the undergraduate level are engineering and dental hygiene!

Ironically, most engineering education occurs in comprehensive universities spanning a broad range of academic disciplines and professions characterized by unusually broad learning communities of students and faculties. Hence, we certainly have the opportunity to augment engineering education with the exposure to the humanities, arts, and social sciences that are absolutely essential to building both the creative skills and cultural awareness necessary to relate to a globally integrated society. By embracing a paradigm for engineering education that takes full advantage of the comprehensive nature and unusually broad intellectual span of the American university, we can create a new breed of engineer, capable of adding much higher value in a global, knowledge-driven economy.

The key is to reaffirm the fundamental purposes of a college education and its foundation based on the concept of a liberal education. Our colleague **Bill Wulf** used to quote Thomas Jefferson's concept of a college education: "To develop the reasoning faculties of our youth, enlarge their minds, cultivate their morals, and instill in them the precepts of virtue and order." Note how appropriate this view of the purpose of liberal education seems today as preparation for the profession of engineering. Such breadth would also produce engineers more capable of shaping public policies in the diverse and challenging environment that characterizes most of today's policy issues.

The leadership of the National Academy of Engineering has demonstrated quite convincingly how influential engineers can be in shaping public policy if equipped with the appropriate breadth of experience, interests, and understanding necessary to relate to the great diversity of viewpoints and experiences of others involved in policy development. I have had the privilege of working closely with three such leaders: Bill Wulf, whose skill and determination united the membership of the National Academy in a common vision for the future; Chuck Vest, whose great ability to relate to the broad interests and experiences of both government leaders and the public they serve has reestablished engineering as a vital national priority; and **Dan Mote**, whose leadership in higher education, engineering, and Academy matters provides strong confidence in the future of this important institution.

Once again, let me express my deep gratitude for being honored with the 2012 Arthur Bueche Award. Let me also convey my great respect for and confidence in the unique role that the National Academy of Engineering will continue to play in addressing the challenges faced by our nation.

Charles M. Vest President's Opportunity Fund

Charles M. Vest

In June of 2013, Dr. Charles M. Vest will complete his term as NAE president. To honor his service, and to build a stronger and more proactive NAE, members and friends are establishing the **Charles M. Vest President's Opportunity Fund**, with a goal of raising $10 million by June 30, 2013.

Elected in 2007 as the 10th president of the National Academy of Engineering, Dr. Vest has promoted actions to secure American competitiveness and leadership in the world economy and fostered global collaboration to address 21st century engineering grand challenges. During his tenure NAE initiated Frontiers of Engineering Education, a program aimed at building collaboration and innovation in engineering education; conducted the definitive technical analysis of the Macondo Well–Deepwater Horizon explosion and oil spill and developed recommendations to improve the safety of offshore drilling; announced and promoted the Grand Challenges for Engineering as a way to engage young people in engineering; initiated steps, with Dr. Vest as committee cochair, to implement Changing the Conversation, an effort to change the way people perceive and talk about engineering; initiated a joint roundtable on technology and peacebuilding with the US Institute of Peace; and established a unique, forward-looking initiative on US manufacturing, design, and innovation. In addition, both before and during his presidency, Dr. Vest was an active proponent of two important Academies reports—*America's Energy Future* and *Rising Above the Gathering Storm*. He served on the committee that produced the latter, and also cochaired the cross-disciplinary committee that produced the report *Protecting Individual Privacy in the Struggle Against Terrorists: A Framework for Program Assessment*.

The new President's Opportunity Fund being established in Dr. Vest's name will support exploratory studies and seed new initiatives, as directed by future NAE presidents, and will thus empower NAE to be proactive in identifying and leading initiatives to benefit the nation and profession. NAE cannot afford to lose precious momentum, or simply be late to the table, because of the time required—as much as two or three years—to secure project funding.

To meet the ambitious $10 million goal, NAE needs help from members and friends who want to honor Dr. Vest and ensure a strong NAE. To learn more about how you can help, or to make a gift to the President's Opportunity Fund, contact Radka Nebesky, NAE's Director of Development, at 202.334.3417 or *RNebesky@nae.edu*.

Any gift you make to the President's Opportunity Fund will also help NAE celebrate its 50th Anniversary in 2014 and meet our fundraising goals to ensure that NAE is positioned for future success. To learn more about the 50th Anniversary campaign, please visit *www.nae.edu/50thgiving*.

2012 US Frontiers of Engineering Held at GM Technical Center

US FOE participants take rides in the urban electric concept car, EN-V. (Photo courtesy of GM.)

On September 13–15, 100 earlier-career engineers attended the 2012 US Frontiers of Engineering (US FOE) symposium hosted by General Motors at the GM Technical Center in Warren, Michigan. NAE member **Kristi S. Anseth**, Distinguished Professor and HHMI Investigator, Department of Chemical and Biological Engineering, University of Colorado Boulder, chaired the organizing committee and the symposium.

The presentation topics this year were climate engineering, vehicle electrification, serious games, and engineered materials for the biological interface. Talks in these areas described the removal of carbon dioxide from the atmosphere through mechanical or natural means; research in improved magnetic materials used in electric machine drives, including reduction of critical materials such as rare earth elements; the use of serious games such as Foldit to advance science; and identification and modulation of biophysical signals that control stem cell function and fate. In addition to the seven papers featured in this issue, a book with all of the featured presentations will be published in early 2013.

On the first afternoon of the meeting, participants gathered in small groups for "get-acquainted" sessions where they presented and answered questions about their research or technical work. This event gave them an opportunity to get to know more about each other relatively early in the program. On the second afternoon, GM hosted a "Ride-n-Drive" event where attendees could drive or ride in advanced vehicles such as the plug-in hybrid Volt and concept cars such as the two-seat EN-V that can operate autonomously. This was followed by dinner at the GM Heritage Center, where some 200 vehicles from GM's Heritage Collection are on display. NAE member **Alan I. Taub**, professor of materials science and engineering at the University of Michigan and retired vice president of global R&D at GM, gave the dinner address.

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

Dr. Anseth will continue as chair for the 2013 US FOE, which will be hosted by DuPont in Wilmington, Delaware, September 19–21. The 2013 topics are social media, flexible electronics, renewable energy, and smart manufacturing.

Funding for the 2012 US Frontiers of Engineering symposium was provided by General Motors, The Grainger Foundation, Air Force Office of Scientific Research, Department of Defense ASDR&E Research Directorate–STEM Development Office, National Science Foundation, Microsoft Research, Cummins Inc., and numerous individual donors.

NAE has been hosting an annual US Frontiers of Engineering symposium since 1995, and also has bilateral programs with Germany, Japan, India, China, and the European Union. A Frontiers of Science and Engineering meeting with Brazil will be held in 2014. The meetings bring together outstanding engineers from industry, academia, and government at a relatively early point in their careers (participants are 30–45 years old). Frontiers provides an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, an opportunity that is increasingly important as engineering has become more interdisciplinary. The meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series, visit the FOE website at *www.naefrontiers.org* or contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or *jhunziker@nae.edu*.

NAE Welcomes Mirzayan Science and Technology Policy Fellows

Gina Adam

Ryan Shelby

GINA ADAM is a Mirzayan S&T policy fellow at NAE, where she is working with Dr. Katie Whitefoot to develop a new approach for analyzing national statistics data about manufacturing and related sectors. In her spare time at NAE, Gina wrote four articles on career planning for the *EngineerGirl!* website and volunteered for the JobSquad. Through the Mirzayan Fellowship, she gained a hands-on understanding of US policymaking and connected with professionals around Washington.

Gina is pursuing a PhD in electrical and computer engineering and an MA in educational leadership at the University of California, Santa Barbara, with the financial support of the International Fulbright Science and Technology Award. Her PhD research is related to neuromorphic hybrid circuits, which could provide computer chips capable of ultrafast processing of information and advanced machine learning.

A native of Romania, Gina received her BS in applied electronics from Politehnica University of Bucharest. She has received several international awards: the General Electric Foundation Scholar-Leaders Award, NanoInitiative Munich International Student Research Award, and the Roberto Rocca Award for Student Excellence in Engineering.

Gina also received a BA in public administration in Romania and has contributed to a number of projects related to Romanian higher education and research policy. These experiences sparked her interest in the intersection of education, jobs, and policy. More particularly, she is interested in reforms of engineering education in cultural contexts, the transfer of engineering education research findings into classrooms, and academia-industry partnerships to improve education. Gina can be contacted at *adam.gina.cristina@gmail.com*.

RYAN SHELBY is working on the development of policy briefs related to the application of operational system engineering techniques for peacebuilding endeavors in Libya, Kenya, and Haiti. Additional focus areas of his fellowship include a preliminary review related to the alignment of US-based undergraduate and graduate programs with the recommendations in the NAE reports

The Engineer of 2020 and *Educating the Engineer of 2020*.

Ryan received his MS in mechanical engineering from the University of California, Berkeley, in 2008 and his BS in mechanical engineering from Alabama Agricultural and Mechanical University in 2006. His PhD in mechanical engineering from the University of California, Berkeley, will be completed in January 2013. His dissertation research lies at the intersection of engineering, policy, and society. The main outcome is a methodological framework that allows engineers and members of Native American nations to create a shared understanding of the social performance metrics in sustainability systems associated with the codesign and implementation of housing and renewable energy systems that meet the cultural sovereignty, economic, environmental, and tribal sovereignty needs and goals of Native American nations such as the Pinoleville Pomo Nation of Ukiah, California.

Ryan's research interests include sustainability, engineering education, renewable energy, energy science policy, public engagement with engineering, design theory, indigenous knowledge, coproduction of knowledge, and user needs assessment.

To learn more about Ryan Shelby, please visit *www.ryanlshelby.com*.

Calendar of Meetings and Events

December 28, 2012–January 30, 2013	Election of new NAE Members and Foreign Associates
January 2–April 1	Call for nominations for the 2014 Draper and Gordon Prizes and the 2013 Founders and Bueche Awards
January 15	Deadline for submission of petition candidates for NAE Officers and Councillors
January 29–30	Climate Change and America's Infrastructure: Engineering, Social, and Policy Challenges Arizona State University, Phoenix
January 31–February 1	Membership Policy Committee Meeting Irvine, California
February 6–7	NAE Council Meeting Irvine, California
February 7	NAE National Meeting Irvine, California
February 17–23	National Engineers Week
February 19	NAE Awards Forum and Award Dinner/Ceremony (by invitation only)
March 1	Deadline for submission to the EngineerGirl essay contest "Engineering: Essential to our Health" (*EngineerGirl.org*)
March 1–31	Election of NAE Officers and Councillors
March 5	NAE Regional Meeting Palo Alto, California
March 11–13	Grand Global Challenges Summit London, England
March 28	NAE Regional Meeting Georgia Institute of Technology, Atlanta
April 4	NAE Regional Meeting Carnegie Mellon University, Pittsburgh, Pennsylvania
April 7–13	National Institute for Energy Ethics and Society Arizona State University, Phoenix
April 22	NAE Convocation of the Professional Engineering Societies
April 26–28	German-American Frontiers of Engineering Irvine, California
April 29	NAE Regional Meeting University of Minnesota, Minneapolis

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

In Memoriam

NEIL A. ARMSTRONG, 82, Chairman of the Board Emeritus, EDO Corporation, died on August 25, 2012. Mr. Armstrong was elected to NAE in 1978 for "contributions to aerospace engineering, scientific knowledge, and exploration of the universe as an experimental test pilot and astronaut."

JACK E. CERMAK, 89, co-founder and retired president of Cermak Peterka Petersen, died on August 21, 2012. Dr. Cermak was elected to NAE in 1973 for "development of experimental facilities and research contributions concerning wind forces on structures."

RICHARD C. CHU, 79, IBM Fellow Emeritus, International Business Machines Corporation, died on September 8, 2012. Mr. Chu was elected to NAE in 1987 for "pathfinding contributions and creative technical leadership in the development of cooling technology and thermal systems for electronic equipment."

BENSON J. LAMP, 86, president, BJM Company Inc., died September 14, 2012. Dr. Lamp was elected to NAE in 1998 for "research and development of harvesting machinery and commercialization of agricultural equipment worldwide."

DAVID M. LEDERMAN, 68, managing director, Analytical LLC, died on August 8, 2012. Dr. Lederman was elected to NAE in 2002 for "designing, developing, and commercializing heart failure assist and heart replacement devices, and for leadership in engineering science education."

LAWRENCE M. MEAD JR., 94, retired senior vice president, Grumman Corporation, died on August 23, 2012. Mr. Mead was elected to NAE in 1988 for "outstanding technical accomplishment and leadership in the design and development of naval aircraft."

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street NW, Keck 360, Washington, DC 20001. For more information or to place an order, contact NAP online at *www.nap.edu* or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Making Value: Integrating Manufacturing, Design, and Innovation to Thrive in the Changing Global Economy. Manufacturing is in a period of dramatic transformation. But in the United States, public and political dialogue focuses almost entirely on the movement of some manufacturing jobs overseas to low-wage countries. Yet there has been a recent uptick in US manufacturing employment and output, and manufacturing is changing in ways that may favor American ingenuity. Rapid advances in biomanufacturing, robotics, smart sensors, cloud-based computing, and nanotechnology put a premium on continual innovation and highly skilled workers. In addition, smaller runs and custom-designed products favor agile and adaptable workplaces, business models, and employees, all of which have become a specialty in the United States. On June 11–12, 2012, the National Academy of Engineering hosted a workshop to discuss the new world of manufacturing and how to position the United States to thrive in it, with a focus not just on making *things* but on making *value*, the quality that will underlie high-paying jobs in America's future. This report summarizes the workshop and the topics discussed.

NAE members on the workshop steering committee were **Lawrence D. Burns** (chair), professor of engineering practice, University of Michigan; **Nicholas M. Donofrio**, IBM fellow emeritus and retired executive vice president, Innovation and Technology, IBM Corporation; and **Jonathan J. Rubinstein**, former executive chairman and CEO, Palm Inc. Paper, $28.00.

Community Colleges in the Evolving STEM Education Landscape: Summary of a Summit. This report, based on a national summit supported by the National Science Foundation and organized by the National Research Council and National Academy of Engineering, highlights the importance of community colleges, especially in emerging areas of STEM (science, technology, engineering, and mathematics) and in preparation of the STEM workforce. Community colleges are essential in accommodating growing numbers of students and retraining displaced workers in skills needed in the new economy. *Community Colleges in the Evolving STEM Education Landscape* focuses on partnerships and processes that can facilitate student success in STEM; efforts to expand participation of students from historically underrepresented populations in undergraduate STEM education; and the impacts of certain subjects, such as mathematics, as gateways or barriers to college completion.

NAE member **Karl S. Pister**, chancellor emeritus, University of California, Santa Cruz, and Dean & Roy W. Carlson Professor of Engineering, Emeritus, Department of Civil and Environmental Engineering, University of California, Berkeley, was a member of the study committee. Paper, $41.00.

Blueprint for the Future: Framing the Issues of Women in Science in a Global Context—Summary of a Workshop. Given the growing worldwide connectivity of scientific disciplines, it is important to recognize the impacts of social, political, and economic mechanisms on women's participation in the global scientific enterprise. Although sociocultural factors vary among countries and regions, studies within and across nations consistently show inverse correlations between levels in the scientific and technical career hierarchy and the number of women: the higher the positions, the fewer the women. Understanding these complex patterns requires interdisciplinary and international approaches. In April 2011, a committee overseen by the National Academies' standing Committee on Women in Science, Engineering, and Medicine (CWSEM) convened a workshop entitled "Blueprint for the Future: Framing the Issues of Women in Science in a Global Context" in Washington, DC. The workshop focused on women's participation in chemistry, computer science, mathematics, and statistics. Presenters were scholars and professionals active in documenting, analyzing, and interpreting the status of women in selected technical fields around the world. Lessons learned from this examination of selected disciplines may yield insights applicable to other fields.

NAE member **Johanna M.H. Levelt Sengers**, scientist emeritus, Material Measurement Laboratory, Thermophysical Properties Division, National Institute of Standards and Technology, was a member of the study committee. Paper, $39.00.

Lifelong Learning Imperative in Engineering: Sustaining American Competitiveness in the 21st Century. The United States is facing a crisis in its engineering workforce just as global competition is becoming very intense. As the pace of technological change accelerates, the United States has one of the lowest rates of graduation of bachelor-level engineers in the world—just 4.5 percent—and in coming years there will be massive retirements of skilled and experienced engineers. The Lifelong Learning Imperative (LLI) project brought together leaders in US industry, academia, government, and professional societies to assess the current state of lifelong learning for engineers; examine the need for, and nature of, lifelong learning going forward; and explore the responsibilities of and potential actions for primary stakeholders. A project-framing workshop was organized by the University of Illinois at Urbana-Champaign (UIUC) in partnership with the National Academy of Engineering in June 2009, after which a UIUC research team conducted a survey-based assessment of the issues identified at the workshop. This monograph reflects the opinions of the authors based on the UIUC team's survey analysis and learning from the workshop discussions.

NAE members on the advisory committee were **Nicholas M. Donofrio**, IBM fellow emeritus and retired executive vice president, Innovation and Technology, IBM Corporation; **James J. Duderstadt**, president emeritus and university professor of science and engineering, University of Michigan; and **C.D. (Dan) Mote Jr.**, regents professor and Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park. Free PDF.

A Review of the Manufacturing-Related Programs at the National Institute of Standards and Technology: Fiscal Year 2012. The mission of the National Institute of Standards and Technology (NIST) is to provide broad support for the advancement of US manufacturing. Research and services supporting manufacturing are intended to be an important component in all of the NIST laboratories. The director of NIST requested that the National Research Council (NRC) assess NIST's manufacturing-related programs in 2012. The NRC review panel considered manufacturing research at NIST broadly, with emphasis on the following areas: nanomanufacturing (including biomanufacturing and flexible electronics); smart manufacturing (including robotics); and next-generation materials measurements, modeling, and simulation (recognizing that the boundaries among these areas are not rigid and that there is some overlap among them). Based on its assessment, the panel formed the observations and recommendations detailed in this report.

NAE members on the study panel were **Kanti Jain** (chair), professor, Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign; **Hadi Abu-Akeel**, president, Amteng Corporation; **Thomas W. Eagar**, professor of materials engineering and engineering systems, Massachusetts Institute of Technology; **Barry C. Johnson**, retired dean, College of Engineering, Villanova University; **Lawrence L. Kazmerski**, executive director, Science and Technology Partnerships, National Renewable Energy Laboratory; **Lyle H. Schwartz**, senior research associate, Department of Materials Science and Engineering, University of Maryland, College Park, and retired director, Air Force Office of Scientific Research; and **F. Stan Settles**, professor and codirector, Systems Architecture and Engineering Program, University of Southern California. Free PDF.

From Science to Business: Preparing Female Scientists and Engineers for Successful Transitions into Entrepreneurship—Summary of a Workshop. Scientists, engineers, and medical professionals are vital to the 21st century science and technology enterprises that will create solutions and jobs critical to solving large, complex, and interdisciplinary problems in energy, sustainability, the environment, water, food, disease, and health care. And as a growing percentage of the scientific and technological workforce, women need to participate fully both in finding solutions to these problems and in building organizations that will create jobs and bring solutions to market. This report, the summary of an August 2009 workshop on the status of entrepreneurial women in technical fields, makes the case that women need experience and training to acquire the skills that will enable them to move from academia to entrepreneurship and to assume leadership roles in dynamic new business enterprises.

NAE member **Alice M. Agogino**, Roscoe and Elizabeth Hughes Professor of Mechanical Engineering, University of California, Berkeley, was a member of the study committee. Paper, $32.00.

Continuing Innovation in Information Technology. A 1995 report of the National Research Council's Computer Science and Telecommunications Board (CSTB), *Evolving the High-Performance Computing and Communications Initiative to Support the Nation's Information Infrastructure*, included a graphic (often called the "tire tracks" diagram because of its appearance) that linked government investments in academic and industry research to the creation of sizable new IT industries (i.e., with more than $1 billion in annual revenue). The figure dispelled the assumption that the commercially successful IT industry is self-sufficient. It has since been updated and is included in *Continuing Innovation in Information Technology* together with brief text based in large part on the 1995 and other prior CSTB reports.

NAE members on the study committee were **Mark E. Dean**, vice president, WW Strategy and Operations, IBM Thomas J. Watson Research Center; **Deborah L. Estrin**, professor, University of California, Los Angeles; **James T. Kajiya**, distinguished engineer, Microsoft Corporation; **Prabhakar Raghavan**, vice president of engineering, Google, Inc.; and **Andrew J. Viterbi**, president, Viterbi Group, LLC. Paper, $27.00.

Rising to the Challenge: US Innovation Policy for the Global Economy. America enjoyed economic vitality and military power in the postwar era and became the source of much of the world's innovation. But US preeminence is no longer assured as the rest of the world improves its capacity to generate new technologies and products, attract and grow industries, and build positions in the high-technology industries of tomorrow. *Rising to the Challenge: US Innovation Policy for the Global Economy* describes the rapid transformation of the global innovation landscape and the resulting challenges and opportunities for the United States. This report argues for more vigorous attention to capturing the outputs of innovation—commercial products, industries, and particularly high-quality jobs to restore full employment—to ensure America's economic and national security future.

NAE member **Mary L. Good**, dean emeritus, Special Advisor to the Chancellor for Economic Development, University of Arkansas at Little Rock, and former under secretary for technology, US Department of Commerce, was a member of the study committee. Paper, $72.00.

Water Reuse: Potential for Expanding the Nation's Water Supply through Reuse of Municipal Wastewater. Expanding the reuse of treated wastewater for beneficial purposes such as irrigation, industrial use, and drinking water augmentation could significantly increase the nation's total available water resources. *Water Reuse* describes treatment options to mitigate water quality issues in reclaimed water. The report also presents new analysis suggesting that the risk of exposure to certain microbial and chemical contaminants from the consumption of reclaimed water does not appear to be any higher than the risk experienced in some current drinking water treatment systems, and may be orders of magnitude lower. This report recommends adjustments to the federal regulatory framework to enhance public health protection for both planned and unplanned (or de facto) reuse and to increase public confidence in water reuse.

NAE member **R. Rhodes Trussell**, president, Trussell Technologies Inc., was chair of the study committee. Hardcover, $64.00.

International Science in the National Interest at the US Geological Survey. Science at the US Geological Survey (USGS) is intrinsically global, and the USGS has a history of successful international projects that serve US national interests and benefit the USGS domestic mission. Over the next 5–10 years opportunities abound for the USGS to strategically pursue international science that bears on growing worldwide problems that directly affect the United States—climate and ecosystem changes, natural disasters, the spread of invasive species, and diminishing natural resources, to name a few. A more coherent, proactive agency approach to international science would help the USGS participate in international science activities more effectively.

NAE member **Jean-Michel M. Rendu**, mining consultant, Santa Fe, New Mexico, was a member of the study committee. Paper, $29.75.

Research for a Future in Space: The Role of Life and Physical Sciences. During its more than 50-year history, NASA's success in human exploration has depended on the agency's ability to effectively address a wide range of challenges in the biomedical, engineering, and physical sciences and related areas. This success is rooted in NASA's strong and productive commitments to life and physical sciences research for human space exploration as well as its use of human space exploration infrastructures for scientific discovery. *Research for a Future in Space* explains how unique characteristics of the space environment can be used to address complex problems in the life and physical sciences. This booklet also presents both new knowledge and practical benefits for humankind as the agency embarks on a new era of space exploration.

NAE member **Vijay K. Dhir**, dean, Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles, was a member of the study committee. Paper, $1.00.

The Use and Storage of Methyl Isocyanate (MIC) at Bayer CropScience. In 2008, an explosion at the Bayer CropScience chemical production plant in Institute, West Virginia, resulted in the deaths of two employees, a fire in the production unit, and extensive damage to nearby structures. The facility manufactured and stores methyl isocyanate (MIC), a volatile, highly toxic chemical used in the production of carbamate pesticides and the agent responsible for thousands of deaths in Bhopal, India, in 1984. After the Institute accident, an investigation by the US Chemical Safety and Hazard Investigation Board found that flying debris could have struck a relief valve vent pipe and caused the release of MIC into the atmosphere. The Board's investigation also highlighted weaknesses in the Bayer facility's emergency response systems. In light of these concerns, the Board asked the National Research Council to convene a committee to examine the use and storage of MIC at the facility. This report evaluates analyses of alternative production methods for MIC and carbamate pesticides performed by Bayer and the previous owners of the facility. It also presents a framework to help plant managers choose alternative processing options—considering factors such as environmental impact and product yield as well as safety—to reduce risks associated with a chemical manufacturing system.

NAE members on the study committee were **Elsa Reichmanis**, professor, Department of Chemical and Biomolecular Engineering, Georgia Institute of Technology, and **Jeffrey J. Siirola**, retired technology fellow, Eastman Chemical Company. Paper, $55.00.

Earth Science and Applications from Space: A Midterm Assessment of NASA's Implementation of the Decadal Survey. Understanding human-induced changes in Earth's interior and their implications requires a foundation of integrated observations of land, sea, air, and space on which to build credible information products, forecast models, and other tools for making informed decisions. A 2007 National Research Council decadal survey called for a renewal of the national commitment to a program of Earth observations, and NASA embraced the survey's recommendations for Earth observations, missions, technology investments, and priorities for the underlying science. As a result, the science and applications communities have made significant progress over the past five years. However, the Committee on Assessment of NASA's Earth Science Program found that the survey vision is being realized at a far slower pace, for reasons ranging from budget shortfalls to launch failures and delays and substantial increases in mission costs. This report recommends steps to better manage existing programs and to implement future programs, and highlights the urgent need for the Executive Branch to develop and implement an overarching multiagency national strategy for Earth observations from space, a 2007 recommendation that remains unfulfilled.

NAE members on the study committee were **Lee-Lueng Fu**, JPL fellow, Jet Propulsion Laboratory; **Dennis P. Lettenmaier**, Robert and Irene Sylvester Professor of Civil and Environmental Engineering, University of Washington; and **Thomas H. Vonder Haar**, director emeritus, Cooperative Institute for Research in the Atmosphere, and university distinguished professor of atmospheric science, Colorado State University, Fort Collins. Paper, $45.00.

Challenges in Chemistry Graduate Education: A Workshop Summary. Graduate education in chemistry is under considerable pressure. Pharmaceutical companies, long a major employer of synthetic organic chemists, are drastically paring back their research divisions to reduce costs. Chemical companies are opening new research and development facilities in Asia to take advantage of growing markets and trained workforces there. Universities face fiscal constraints that threaten their ability to hire new faculty members. Future funding of chemical research may decrease as the federal budget tightens. The Board on Chemical Sciences and Technology held a workshop on Graduate Education in Chemistry in the Context of a Changing Environment, in January 2012, bringing together leaders and future leaders of academia, industry, and government across the chemical enterprise. Participants discussed critical issues affecting chemistry graduate education, such as the attraction and retention of students, financial stressors and their implications, competencies needed in the changing job market for PhD chemists, and competencies needed to address societal problems such as energy and sustainability.

NAE member **Charles T. Kresge**, vice president, research and development, The Dow Chemical Company, was a member of the study committee. Paper, $38.00.

Remediation of Buried Chemical Warfare Materiel. Approximately 250 sites in 40 states, the District of Columbia, and 3 US territories are known or suspected to have buried chemical warfare materiel (CWM). Of greatest concern are sites in residential areas and large sites on legacy military installations. The Army asked the National Research Council to examine its mission for the remediation of recovered chemical warfare materiel (RCWM), which is turning into a program much larger than the existing munition and hazardous substance cleanup programs. One focus of this report is the current and future status of the Non-Stockpile Chemical Material Project, which now plays a central role in RCWM remediation. In addition, the report reviews both supporting technologies for cleanup of CWM sites and organizations involved in remediation of suspected CWM sites to determine current practices and coordination. The report identifies potential deficiencies in operational areas and options for research and development to mitigate potential problems.

NAE member **Edward L. Cussler Jr.**, distinguished institute professor, Department of Chemical Engineering and Materials Science, University of Minnesota, Minneapolis, was a member of the study committee. Paper, $45.00.

Evaluation of the Updated Site-Specific Risk Assessment for the National Bio- and Agro-Defense Facility in Manhattan, Kansas. Safeguarding US agriculture from foreign animal diseases and protecting the food system require cutting-edge research and diagnostic capabilities. The Department of Homeland Security (DHS) and the US Department of Agriculture (USDA) have embarked on an important mission to replace the aging Plum Island Animal Disease Center with a new National Bio- and Agro-Defense Facility (NBAF), which would serve as a world reference laboratory for identifying emerging and unknown disease threats and would thus be a critical asset in securing the health and security of the nation. DHS selected Manhattan, Kansas, as the site for the new NBAF after an extensive site-selection process. But after the Government Accountability Office (GAO) raised concerns about DHS's analysis of the potential spread of foot-and-mouth disease virus, Congress directed DHS to conduct a site-specific risk assessment (SSRA) for the NBAF, instructed the National Research Council to evaluate the SSRA, and prohibited obligation of NBAF construction funds until the NRC review was complete. Congress then mandated that DHS address shortcomings of the 2010 SSRA, directed the NRC to evaluate the updated SSRA (uSSRA), and again prohibited obligation of construction funds until the completion of the second review. The scope for both SSRA reports concerned accidental release of pathogens from the proposed NBAF (excluding terrorist acts and malicious threats). This report is the evaluation of the final uSSRA.

NAE members on the study committee were **Gregory B. Baecher** (chair), Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park; **Ahsan Kareem**, Robert M. Moran Professor of Engineering, University of Notre Dame; and **Ali Mosleh**, Nicole J. Kim Professor of Engineering and director, Center for Risk and Reliability, University of Maryland, College Park. Paper, $40.00.

Evaluating the Effectiveness of Offshore Safety and Environmental Management Systems (Transportation Research Board Special Report 309). This report recommends that the Department of the Interior's Bureau of Safety and Environmental Enforcement (BSEE) take a holistic approach to evaluating the effectiveness of offshore oil and gas industry operators' Safety and Environmental

Management Systems (SEMS) programs. According to the report, such an approach should include inspections, audits by the operator and BSEE, key performance indicators, and a whistleblower program. SEMS promotes a proactive, risk-based, and goal-oriented approach to improve safety and reduce the likelihood of recurrence of events such as the April 2010 Macondo well blowout. According to this report, successful implementation of SEMS requires that its tenets be fully accepted and actively supported throughout the organization. The report also notes that BSEE can encourage and aid industry in the development of a culture of safety by the way it measures and enforces SEMS.

NAE members on the study committee were **Kenneth E. Arnold** (chair), senior technical advisor, WorleyParsons, and **Raja V. Ramani**, professor emeritus, George H. Jr. and Anne B. Deike Chair in Mining Engineering, Pennsylvania State University, and independent consultant. Free PDF.

Ranking Vaccines: A Prioritization Framework—Phase I: Demonstration of Concept and a Software Blueprint. As a number of diseases emerge or reemerge, stimulating new vaccine development opportunities, decision makers need tools that can assist and inform their vaccine prioritization efforts. In this report, the Institute of Medicine offers a framework and proof of concept to account for various factors that influence vaccine prioritization—demographic, economic, health, scientific, business, programmatic, social, and policy factors as well as public concerns. *Ranking Vaccines: A Prioritization Framework* describes a decision support model and the blueprint of a software called Strategic Multi-Attribute Ranking Tool for Vaccines, or SMART Vaccines. SMART Vaccines 1.0 is expected to be released at the end of the second phase of this study as a fully operational tool to guide discussions about prioritizing the development and introduction of new vaccines.

NAE members on the study committee were **Paul Citron**, retired vice president, Technology Policy and Academic Relations, Medtronic Inc., and **Vinod K. Sahney**, retired senior vice president and chief strategy officer, Blue Cross and Blue Shield of Massachusetts. Paper, $54.00.

Dam and Levee Safety and Community Resilience: A Vision for Future Practice. Advances in engineering can reduce but not completely eliminate the risk of dam and levee failures, which have impacts on social and physical infrastructure that extend far beyond the flood zone. Collaboration among dam and levee safety professionals at all levels, persons and property owners directly at risk, members of the wider economy, and the social and environmental networks in a community would allow all stakeholders to understand risks, shared needs, and opportunities, and make more informed decisions related to dam and levee infrastructure and community resilience. This report explains that fundamental shifts in safety culture are necessary to integrate the concepts of resilience into dam and levee safety programs.

NAE member **Ross B. Corotis**, Denver Business Challenge Professor, Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder, was a member of the study committee. Paper, $47.00.

Exposure Science in the 21st Century: A Vision and a Strategy. From the use of personal products to consumption of food, water, and air, people are exposed to a wide array of agents each day—many with the potential to affect health. Exposure science improves understanding of how stressors affect human and ecosystem health, contributes to efforts to prevent or reduce contact with harmful stressors, and can help inform environmental regulation, urban and ecosystem planning, and disaster management. Recent advances in tools and technologies (e.g., sensor systems, analytic methods, molecular technologies, computational tools, and bioinformatics) have provided the potential for more accurate and comprehensive exposure science data. This report investigates the implications of contact with chemical, physical, and biologic stressors and provides a roadmap to take advantage of technological innovations and strategic collaborations to move exposure science into the future.

NAE member **Leroy E. Hood**, president, Institute for Systems Biology, was a member of the study committee. Paper, $47.00.

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