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Erratum
In the table on p. 8 in the September issue, the names of the cities for Microsoft and Oracle should have been Beijing, Bangalore, and Hyderabad.

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Cutting-Edge Research in Engineering

The U.S. Frontiers of Engineering (FOE) Symposium, a yearly event sponsored by NAE, brings together some 100 outstanding young engineers (ages 30 to 45) from academia, industry, and government laboratories for three days of sharing ideas and learning about cutting-edge research on a broad range of engineering topics. The competitively selected emerging engineering leaders who attend FOE symposia represent a wide spectrum of backgrounds, interests, and talents, and the event offers them a unique opportunity to learn about the latest research in engineering areas other than their own. Six papers based on this year’s presentations are included in this issue of The Bridge.

The eleventh FOE Symposium, held on September 22–24, 2005, at the General Electric Global Research Center in Niskayuna, New York, encompassed four themes: ID and verification technologies, engineering for developing communities, engineering complex systems, and energy resources for the future.

The session on ID and verification technologies was chaired by Visvanathan Ramesh. The first speaker, Peter Belhumeur, addressed the challenge of face recognition as a computational pattern-recognition or machine-learning problem. He described the challenges that lie ahead, such as handling voluntary changes in facial expression and natural outdoor lighting. Jonathon Phillips focused on the design of objective biometrics for assessing face- and fingerprint-recognition problems and independent evaluations. Matthai Philipose, whose paper appears in this issue (p. 5), described the development of computing systems that can observe, understand, and act on physical human activity. As an example of the potential benefits of this technology, he described how it might be used in caring for the elderly. Rapid progress is being made in this field based on a family of sensors based on radio frequency identification.

Garrick Louis and Amy Smith organized the session on engineering for developing communities, which opened with a presentation by Kurt Kornbluth. He described the DISASCARE Wheelchair Center in Zambia, a project that makes use of locally available resources to address technological needs. Daniele Langagne highlighted engineering inputs to the Centers for Disease Control and Prevention Safe Water System (SWS) Program. This initiative provides safe drinking water to people with no access to infrastructure-treated water through point-of-use water chlorination, water storage in safe containers, and education to improve hygiene and water practices. Julie Beth Zimmerman explained how engineers could use the principles of green engineering as a design protocol for promoting sustainability. She argued that a design framework that incorporates sustainability factors as performance criteria could advance the goals of prosperity and a healthier environment. Daniel Kammen, who gave the last presentation in the session, focused on sustainability science. In his paper (p. 11), he argues for the development of a science and engineering research agenda in which the preservation of natural and social systems plays a central role.

Luis Amaral and Kelvin Lee organized the session on the engineering of complex systems. In a brief opening talk, Luis Amaral identified the distinguishing characteristic of complex systems as the emergence of behavior not foreseeable by the system designer. In Alessandro Vespignani’s presentation, he showed how the computational study of complex networks, such as the World Wide Web, can provide valuable insights into infrastructure design, epidemiology, and social science. Jay Keasling, whose paper is printed in this issue (p. 18), described synthetic biology, that is, the design and construction of new biological entities, such as cells, enzymes, and genetic circuits. The exciting possibilities in this emerging field include engineered bacteria for the production of anti-malaria drugs. The final presentation by Zoltán Toroczkai described modeling of agent-based systems, collectives of living entities, as distinguished from collectives of inanimate constituents, such as multiparticle systems. He illustrated how agent-based modeling can be used for planning urban transportation and for analyzing disease-spread scenarios. His paper appears on p. 22.
The subject of the fourth session, chaired by John Vohs, was energy resources for the future. John Reinker discussed the current and future electrical energy picture in the United States. He also addressed the challenges of satisfying world energy demand and the roles of fossil fuels, nuclear, wind, solar, hydroelectric, and biomass technologies in meeting those challenges. Sunita Satyapal provided an overview of research and development activities in the U.S. Department of Energy Hydrogen Program. She described how improved theoretical modeling, high-throughput screening techniques, and understanding at the nanoscale have impacted the discovery and optimization of materials to meet the targets for commercially viable vehicular hydrogen storage systems. Stuart Adler described the current status and future challenges of fuel cell technologies (p. 28). He compared polymer-electrolyte and solid-oxide fuel cells and described the significant technical challenges that must be overcome for these technologies to become commercially viable. Michael McGehee addressed the need for alternative technologies to meet worldwide energy demand while minimizing adverse environmental consequences. He described organic semiconductors, which can be dissolved in common solvents and sprayed or painted onto substrates, as promising candidates for the development of solar cells that would not only be environmentally benign, but would also be economically competitive (p. 33).

The technical talks were followed by extended, lively Q&A sessions with enthusiastic participation by the audience. The program this year also featured 90-minute get-acquainted sessions, during which attendees were divided into nine groups. Each person had been asked before the meeting to prepare a transparency describing his or her work and was given two minutes to introduce him/herself and explain his/her technical work. The balance of the time was devoted to discussions on research interests and activities. The get-acquainted sessions turned out to be highly interactive and very educational.

The dinner speaker, a traditional highlight of FOE programs, was Shirley Jackson, president of Rensselaer Polytechnic Institute. In the course of her distinguished career, Dr. Jackson has held leadership positions in government, industrial research, and academia. She is an NAE member and a fellow of the American Physical Society and American Academy of Arts and Sciences. Her truly inspirational speech, entitled “Engineering for a New World,” addressed the need for a larger, more diverse workforce in science and engineering, the challenges and opportunities involved in meeting world energy demand, and the emergence of new economic powers, such as China and India.

For the past three years, it has been my privilege to chair the FOE organizing committee, which selects the speakers and topics for the symposium. I thank all the session chairs, speakers, and participants of the 2003, 2004, and 2005 meetings for maintaining the high quality that has become the standard of FOE symposia. I am also grateful to Lance Davis, NAE Executive Officer, and Janet Hunziker, NAE Program Officer, for their invaluable contributions to the planning, organization, and successful implementation of these unique meetings. I wish the incoming chair of the organizing committee, Dr. Julia Phillips, Director of the Physical, Chemical and Nano Sciences Center at Sandia National Laboratories, every success.

I know of no meeting as interdisciplinary, diverse, and stimulating as FOE, and I hope that the six papers included in this issue convey some of the excitement we experienced in Niskayuna in September.
Building computing systems that can observe, understand, and act on day-to-day physical human activity has long been a goal of computing research. Such systems could have profound conceptual and practical implications. Because the ability to reason and act based on activity is a central aspect of human intelligence, from a conceptual point of view, such a system could improve computational models of intelligence. More tangibly, machines that can reason about human activity could be useful in aspects of life that are currently considered outside the domain of machines.

Monitoring human activity is a basic aspect of reasoning about activity. In fact, monitoring is something we all do—parents monitor children, adults monitor elderly parents, managers monitor teams, nurses monitor patients, and trainers monitor trainees; people following medication regimens, diets, recipes, or directions monitor themselves.

Besides being ubiquitous, however, monitoring can also be tedious and expensive. In some situations, such as caregiver-caretaker and manager-worker relationships, only dedicated, trained human monitors can make detailed observations of behavior. However, such extensive observation causes fatigue in observers and resentment in those being observed. The constant involvement of humans also makes monitoring expensive.

Tasks that are ubiquitous, tedious, and expensive are usually perfect candidates for automation. Machines do not mind doing tedious work, and...
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expensive problems motivate corporations to build machines. In fact, given the demographics of our society, systems that notify family members automatically when elderly relatives trigger simple alarms, such as falling, not turning off the stove, or not turning off hot water, are now commercially available. However, compared to a live-in family member who can monitor an elder's competence in thousands of day-to-day activities, these systems barely scratch the surface. In this paper, I describe a concrete application for a monitoring system with broad activity-recognition capabilities, identify a crucial missing ingredient in existing activity “recognizers,” and describe how a new class of sensors, combined with emerging work in statistical reasoning, promises to advance the state of the art by providing this ingredient.

The Caregiver’s Assistant

Caring for the elderly, either as a professional caregiver or as a family member, is a common burden in most societies. Gerontologists have developed a detailed list of activities, called the activities of daily living (ADLs), and metrics for scoring performance of crucial day-to-day tasks, such as cooking, dressing, toileting, and socializing, which are central to a person's well-being. An elder’s ADL score is accepted as an indicator of his or her cognitive health.

Professional caregivers in the United States are often required to fill in ADL forms each time they visit their patients. Unfortunately, although the data they collect are used as a basis for making resourcing decisions, such as Medicaid payments, the data are often inaccurate because (1) they are often based on interviews with elders who may have strong motives for misrepresenting the facts and (2) because the data-collection window is narrow relative to the period being evaluated. Given increasing constraints on caregivers' time, purely manual data collection seems unsustainable in the long run.

The Caregiver’s Assistant system is intended to fill out large parts of the ADL form automatically based on data collected from the elder's home on a 24/7 basis. The system would not just improve the quality of data collected, but (because it provides constant monitoring) might also be able to provide proactive intervention and other assistance. Figure 1 shows a prototype form of the Caregiver’s Assistant. Actual forms include activities in 23 categories, such as “housework” and “hygiene,” which instantiate to tens of thousands of activities, such as “cleaning a bathtub” and “brushing teeth.”

Thus, an activity-recognition system that could track thousands of activities in non-laboratory conditions would remove a substantial burden from human monitors. Professional caregivers could, at any time, be provided with a version of this form with potentially troublesome areas highlighted. If a nurse were given this form before a visit, for instance, he or she could make better preparations for the visit and could focus on the most important issues during the visit. A study of roughly one hundred professional caregivers around the country has shown that such a system would be useful, at least for caregivers.

Discriminating among Activities

The process of recognizing mundane physical activities can be understood as mapping from raw data gathered by sensors to a label denoting an activity. Figure 2 shows how traditional mapping systems are structured. Feature selection modules typically work on high-dimensional, high-frequency data coming directly from sensors (such as cameras, microphones, and accelerometers) to identify relatively small numbers of semantically higher level features, such as objects in images, phonemes in audio streams, and motions in accelerometer data. Symbolic inference modules reason about the relationship between these features and activities in a variety of ways. The reasoning may include identifying ongoing activities, detecting anomalies in the execution of activities, and performing actions to help achieve the goal of the activities.

Both feature selection and inference techniques have been investigated extensively, and depending on the feature, researchers can draw on large bodies of work. In the computer vision community alone, extensive work has been done on objects, faces, automobiles, gestures, and edges and motion flows, each of which has a dedicated sub-community of researchers. Thus, once features for an activity-recognition system have been selected, a very large number of model representations and inference techniques are available. These techniques differ in several ways, such as whether they...
support statistical, higher order, or temporal reasoning; the degree to which they learn and the amount of human intervention they require to learn; and the efficiency with which they process various kinds of features, especially higher dimensional features. In Figure 2, the variety of feature selections and inference algorithms is indicated by stacks of boxes.

Despite the profusion of options, no activity inferencing system capable of recognizing large numbers of day-to-day activities in natural environments has been developed. A key underlying problem is that no existing combination of sensors and feature selector has been shown to detect robustly the features necessary to distinguish between thousands of activities. For instance, objects used during activities have long been thought to be crucial discriminators. However, existing object-recognition and tracking systems tend not to work very well when applied to a large variety of objects in unstructured environments (Sanders et al., 2002). Activity-recognition systems based on tracking objects, therefore, tend to be customized for particular environments and objects, which limits their utility as general-purpose, day-to-day activity recognizers. Given that producing each customized detector is a research task, the goal of general-purpose recognition has, not surprisingly, not been reached.

A new class of small, wireless sensors seems likely to provide a practical means of detecting objects used in many day-to-day activities (Philipose et al., 2004; Tapia et al., 2004). Given a stream of objects, recent work has shown that even simple symbolic inference techniques are sufficient for tracking the progress of these activities.

**Detecting Object Use with Radio Frequency Identification Tag Sensors**

A passive radio frequency identification (RFID) tag (Figure 3a) is a postage-stamp-sized, wireless, battery-free transponder that, when interrogated (via radio) by an ambient reader, returns a unique identifier (Finkenzeller, 2003). Each tag consists of an antenna, some protocol logic, and optional nonvolatile memory. RFID tags use the energy of the interrogating signal to return a 64-bit to 128-bit identifier unique to each tag, and when applicable, data stored in on-tag memory. Short-range tags, which are inductively coupled, have a range of 2 to 30 cm; long-range backscatter-based tags have a range of 1 to 10 m. Tags are available off the shelf for less than

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**FIGURE 2** A typical activity-recognition system.

**FIGURE 3** a. RFID tags. b. Tagged toothbrush and toothpaste.
50 cents each. Short-range readers cost a few hundred dollars; long-range readers cost a few thousand dollars. If current trends continue, there will be a steep drop in the price of both tags and readers in the next few years.

If an RFID tag is attached to an object (Figure 3b) and the tag is detected in the vicinity of a reader, we can infer that the attached object is also present. Given their object-tracking abilities, RFID-based systems are currently being seriously considered for commercial applications, such as supply-chain management and asset tracking. Existing uses include livestock tracking, theft protection in the retail sector, and facilities management. The promise of a viable RFID system for tracking the presence of large numbers of objects suggests that it might be the basis of a system for tracking objects used by people whose activities we wish to monitor. Because a sensor can be attached to each object, we have, in principle at least, an “ultra-dense” deployment of sensors that could allow each tagged object to “report” when it is in use.

However, neither short-range nor long-range RFID systems, as conventionally designed, are quite up to the task of detecting object use in a way that would be useful for tracking activity. Short-range RFID readers are typically bulky hand-held units (similar to bar-code readers) that must be intentionally “swiped” on tags. Clearly, it is not practical to expect a person whose activities are being tracked (whether an elder or a medical student) to carry a scanner and swipe tagged objects in the middle of day-to-day tasks.

Long-range tags, however, do not require the explicit cooperation of those being monitored. Readers in the corner of a room can detect tags anywhere in that room. Unfortunately, because a conventional RFID tag simply reports the presence of tagged objects in the reader’s field, and not their use, long-range tags cannot tell us when objects are being used either. Long-range tags simply list all tagged objects in the room they are monitoring.

However, each of these modalities can be re-engineered to detect object use unobtrusively. Figure 4 shows how the short-range RFID reader can be adapted to become an unobtrusive sensor of object use (Figure 4a). Essentially, the RFID reader is a radio with built-in processor, nonvolatile memory, and a power supply integrated into a single bracelet called the iBracelet (Fishkin et al., forthcoming). The antenna of the RFID reader is built into the rim of the bracelet. When turned on, the bracelet scans for tags at 1 Hz at a range of 20–30 cm. Any object, such as the water pitcher in Figure 4b, that has a tag within 10 to 15 cm of its grasping surface, can therefore be identified as having been touched. The data can either be stored on board (for later offloading through a data port) or immediately radioed off board. The bracelet can currently read for 30 hours between charges when storing data locally, and roughly 10 hours when transmitting data.

Careful placement of tags on objects can reduce false negative rates (i.e., tags being missed). However, given the range of the bracelet, “accidental” swipes of objects are unavoidable. Therefore, the statistical framework
that processes the data must be able to cope with these false “hits.” Early studies indicate that an iBracelet equipped with inexpensive inductively coupled tags are a practical means of detecting object touch, and therefore object use.

Some people may consider wearing a bracelet an unacceptable requirement, however. In these cases, wireless identification and sensing platforms (WISPs) may be a useful way of detecting object use (Philipose et al., 2005). WISPs, essentially long-range RFID tags with integrated sensors, use incident energy from distant readers not only to return a unique identifier, but also to power the onboard sensor and communicate the current value of the sensor to the reader. For activity-inferencing applications, so-called α-WISPs, which have integrated accelerometers and are about the size of a large Band-Aid™, are attached to objects being tracked (Figure 5). When a tagged object is used, more often than not the accelerometer is triggered and the ambient reader notified.

A single room, which may contain hundreds of tagged objects (most of them inactive at any given time), can be monitored by a single RFID reader. A complication with WISPs is that the explicit correspondence between the person using the object and the object being used is lost. Thus, higher-level inference software may be necessary to track the correspondence implicitly.

Inference Systems

Given the sequence of objects detected by RFID-based sensors, the job of the inference system is to infer the type of activity. The inference system relies on a model that translates from observations (in this case, the objects seen) to the activity label. Recent work has shown that even very simple statistical models of activities are sufficient to distinguish between dozens of activities performed in a real home (Philipose et al., 2004).

Figure 6 shows a model for making tea, in which each activity is represented as a linear sequence of steps. Each step has a specified average duration, a set of objects likely to be seen in that step, and the probability that one of these objects will be seen in an observation window. In the figure, the first step (corresponding to boiling tea) takes five minutes on average; in each one-second window, there is a 40-, 20- and 30-percent chance respectively of a kettle, stove, or faucet being used. Experiments in a real home with 14 subjects, each performing a randomly selected subset of 66 different activities selected from ADL forms, and using activity models constructed by hand to classify the resulting data automatically, have yielded higher than 70 percent (and often close to 90 percent) accuracy in activity detection.

Although the models are simple, it is still impractical to model tens of thousands of activities by hand. However, because the features to be recognized are English words that represent objects and the label to be mapped to is an English phrase (such as “making tea”), the process of building a model is essentially translating...
probabilistically from English phrases to words. Recent work based on this observation has successfully, completely automatically, extracted translations using word co-occurrence statistics from text corpora, such as the Web (Wyatt et al., 2005). If one million Web pages mention “making tea” and 600,000 of them mention “faucet,” these systems accept 60 percent as the rough probability that a faucet is used when making tea. These crude “common-sense” models can be used as a basis for building customized models for each person by applying machine-learning techniques to data generated by that person. Experiments on the data set just described have shown that these completely automatically learned models can recognize activities correctly roughly 50 percent of the time. Analyses of these corpus-based techniques have also provided indirect evidence that object-based models should be sufficient to discriminate between thousands of activities.

Conclusions

Monitoring day-to-day physical activity is a tedious and expensive task now performed by human monitors. Automated monitoring has the potential of improving the lives of many people, both monitors and those being monitored. Traditional approaches to activity recognition have not been successful at monitoring large numbers of day-to-day activities in unstructured environments, partly because they were unable to identify reliably sufficiently discriminative high-level features. A new family of sensors, based on RFID, is able to identify most of the objects used in activities simply and accurately, and even simple statistical models can classify large numbers of activities with reasonable accuracy. In addition, these models are simple enough that they can extract automatically from massive text corpora, such as the Web, and can be customized for observed data.

Acknowledgments

This paper describes work done by the author jointly with the SHARP group at Intel Research Seattle and with researchers at the University of Washington. Specifically, work on the iBracelet was done with Adam Rea and Ken Fishkin. The work on WISPs was done with Joshua Smith and the WISP team. The work on mining models was done with Mike Perkowitz, Danny Wyatt, and Tanzeem Choudhury. Inference techniques were developed jointly with Dieter Fox, Henry Kautz, and Don Patterson.

References

The recognition that human activity is transforming the planet, both in intended and dramatically unintended ways, has led to the development of a new field of research—sustainability science. Widely discussed essays (e.g., Clarke, 2002; Kates et al., 2001; Kennedy, 2003; McMichael et al., 2003; Swart et al., 2002), special issues of premier journals (NAS, 2003), and extensive websites (FSTS, 2005) are now devoted to defining sustainability and identifying useful modes and topics for research. Building on this foundation, we now have a tremendous opportunity to advance a new global scientific research paradigm—the generation and implementation of sustainability science. One important lesson emerges very clearly from this body of work—only by posing the question of sustainability explicitly and, where necessary, repairing the damage humans have caused to the biosphere, can we begin to understand how humans can prosper without degrading the planet.

In a seminal treatise on science policy, Vannevar Bush (1945) wrote that, “applied research invariably drives out pure [research],” to the detriment, in his view, of the national capacity for innovation. The subsequent separation

Ecological stewardship will be the guiding scientific principle for new avenues of inquiry.

Science and Engineering Research That Values the Planet

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of basic and applied research shaped the evolution of science and engineering research for decades and was a point of departure for E.F. Schumacher (1973) and the “appropriate technology” movement, a precursor of sustainability science that involved identifying important but neglected issues for scientific study. This approach, dubbed “mundane science,” (Kammen and Dove, 1997), involves projects that combine pragmatic and goal-oriented applied research with potential advances in basic science (Stokes, 1997). The growing recognition of the value of supporting interdisciplinary research and the emergence of sustainability science are continuations of the intellectual evolution of the interaction between science and society.

The scientific recognition of the reality of global environmental change (Hansen et al., 2005), the political awareness of the need to act now to address greenhouse gas emissions (Kennedy, 2005), and the increasing disparities between the lives of the poor and the wealthy provide an opportunity for galvanizing global action to place sustainability science at the forefront of educational, research, and career-development agendas. The next step toward putting sustainable science into action is recognizing that, with ecological stewardship as a guiding scientific principle, entirely new avenues of inquiry are possible.

At this moment in history, this message has the potential to transform research careers and make sustainability a theme that researchers, public officials, and civil society can all embrace. The World Conference on Physics and Sustainable Development, held in Durban, South Africa, in October and November 2005, provided a forum for showcasing opportunities for the co-evolution of basic research and social advances (SAIP, 2005).

Currently attention, debate, and a trans-Atlantic division are focused on how to provide meaningful, long-term aid and assistance to Africa. To highlight a potential solution, we present two cases of sustainable science, engineering, and action in developing nations that advance both science and sustainable human and ecological communities.

**The Energy-Health-Ecology Nexus**

Household use of solid fuels is one of the leading causes of death and disease in developing countries throughout the world—particularly among women and children (Smith et al., 2004). Over the past decade, a series of studies has been conducted of programs to design and disseminate more efficient, safer household stoves and to develop and implement sustainable forestry and fuel (often charcoal) production practices in Africa. As Figure 1 shows, combined attention to both stove and forestry programs can lead to dramatic simultaneous improvements in human health, ecological sustainability, and local economic development (Kammen, 1995).

The Kenya study showed that transitions from wood and dung fuels burned in simple stoves to charcoal burned in improved stoves reduced the frequency of acute respiratory infections

![FIGURE 1](image-url)
(ARI) by a factor of two. This is a tremendous impact on ARI, the most common illnesses reported in medical exams in sub-Saharan Africa. Comparatively simple materials and design modifications to household stoves are now known not only to improve energy efficiency, but also to reduce particulate and greenhouse gas emissions (Bailis et al., 2005).

These benefits can be achieved at exceptionally low cost, just a few dollars per life saved, and have the added benefit of mitigating atmospheric carbon, at just a few dollars per ton of carbon (Ezzati and Kammen, 2002). By contrast, carbon today trades for roughly $30/ton on the London exchange, a price that reflects only the impact of greenhouse gases. By making the dissemination and use of improved cookstoves a component of a comprehensive Africa-assistance strategy, both local health and development needs and global environmental protection could be addressed with great economic efficiency.

The project in Kenya led to a number of unanticipated advances in “basic science.” The high pollution concentrations observed in rural African homes—as much as 100 times higher than those observed in the urban areas of many industrialized nations—provided a laboratory for examining the epidemiology of exposure-response in a pollution regime that had not been studied before (Ezzati and Kammen, 2001). These studies have greatly extended the cutting-edge epidemiological work being done largely in developed nations (Rich et al., 2005).

**Solar Electricity Markets in Developing Nations**

Household solar photovoltaics (PV) have emerged as the leading alternative to grid-based rural electrification in many developing countries. In Kenya, 30,000 PV systems are sold annually, making it a global leader, per capita, in sales of residential renewable energy systems (Figure 2). Advances in amorphous silicon (a-Si) PV technology, which led to the development of small, low-cost a-Si PV modules, played a critical role in the emergence and growth of the Kenyan solar market (Hankins, 2000; Jacobson, 2004).

A key aspect of these advances involved minimizing the initial light-induced Staebler-Wronski degradation of a-Si modules, a poorly understood materials issue with significant implications for low-cost solar cells. The power output of a-Si solar modules typically decreases by 15 to 40 percent during the first few months of exposure to solar radiation due to Staebler-Wronski degradation. Better quality brands have lower degradation levels (Staebler and Wronski, 1977; Su et al., 2002), and after the initial period of degradation, the power output stabilizes. Figure 3 shows degradation curves for two different brands of a-Si modules, showing that the initial power output of some brands drops significantly more than others. The rated power of most reputable brands of a-Si PV modules corresponds to the final, stabilized power output under standard test conditions of 1,000 W/m² and 25°C.

A second important design issue has been the development of cost-effective sealant materials and methods of preventing delamination. Water intrusion can lead to outright module failure, and the actual power output of modules with significant delamination is often reduced to less than 10 percent of the nameplate power rating. Figure 4 shows water-induced delamination in an a-Si module caused by low-quality seals. A number of a-Si manufacturers have developed highly effective sealing techniques, but a few brands continue to have water-intrusion problems.
These advances have been important for the PV industry as a whole, but have been especially significant for rural electrification with solar energy in developing countries. In contrast to laboratory and commercial rivalries over which company produces the most thermodynamically efficient solar cells, the firms that manufacture a-Si PV modules for markets in developing countries have focused on lower efficiency but significantly less expensive products (Green et al., 2005). The resulting 12 to 20W a-Si PV modules now available in Kenya and elsewhere cost 50 percent less than comparable crystalline silicon (c-Si) PV modules, and are, by far, the best-selling solar products in the region.

The dissemination of a-Si PV technology in Kenya has not, however, been without complications. In an extensive market survey (Figure 5), we found that, although most manufacturers produce high-quality products, one prominent brand performed well below its advertised levels. A previous study in 1999 showed a similar pattern, although for a different brand. Thus, the successful deployment of new technology requires market institutions that ensure quality and protect the public interest. The combination of technical studies of solar equipment performance and analyses of Kenyan market development, socio-cultural dynamics, and regulatory policy has led to progress toward eliminating low-performing products from the market, as well as insights into institutional aspects of renewable energy market development (Acker and Kammen, 1996; Duke et al., 2002; Jacobson, 2004; Kammen, 1995).

Making Sustainable Science the Norm

The first step in making sustainable science the norm is to demonstrate that, once funding and a research/action team have been assembled, these projects are no more difficult than traditional research projects. To be effective, however, projects must be neither exclusively in the academic or laboratory setting, nor entirely in the sphere of nonprofit organizations or local governments. To take maximum advantage of both the emerging science and the implementation capacity for sustainability, we must demonstrate support in each of the disciplines involved, both through actions and funding priorities.

Second, we must make sustainability science a basic precept of teaching in secondary schools, colleges, and postgraduate studies. Pre-college students have already demonstrated a tremendous aptitude for working in interdisciplinary areas. We must nurture and reward
this interest with courses in junior high schools, high schools, and colleges on energy, the environment, and the social drivers of resource degradation. In the United States, the Upward Bound Math-Science Program (DOEd, 2005) and Summer Science Program (2005) are models that could be adapted to the theme of sustainability science.

The launch of Sputnik in 1957 initiated an unprecedented mobilization of U.S. science and technology, a lesson in the power of a use-inspired drive to innovate. The Yale Environment Survey found overwhelming interest in energy and environmental sustainability (Yale University, 2005). Contrast that interest with the results of the 3rd International Mathematics and Science Study (TIMSS), in which American secondary school students ranked 19th out of 21 countries in both math and science (NRC, 1997). The TIMMS authors concluded that science and mathematics education in the United States lacked direction, vision, and motivation. Sustainability science could give science, mathematics, and engineering education renewed meaning and immediacy, with paradigm-changing possibilities in both developed and developing nations.

Third, we could establish sustainability awards—modeled after the Ashoka Innovators Awards (2005), the Ansari X Prize (X Prize Foundation, 2005) for the launch of a space vehicle, and the Ashden Awards (2005) for sustainable energy. These awards would bring together partners from developed and developing nations in academia, industry, civil society, and government and would encourage groups to take action on critical sustainability projects. Ideally, sustainability awards, jointly sponsored by private foundations and state or federal governments, would take advantage of the diversity of perspectives and skills that interdisciplinary, international teams would bring together.

Finally, we must address the principal weakness in the economies of many poor nations—a lack of capacity to compete in the global marketplace. Debt forgiveness for impoverished countries in Africa and elsewhere is laudable (Sachs, 2005), but it has already been criticized by African leaders who have noted that aid alone is not a panacea. Estimates of the percentage of overall economic growth from innovation in science and technology, virtually all in industrialized nations, are as high as 90 percent (Solow, 2000). Developing economies would be energized by dramatically increased investment in indigenous innovation. A natural way to do that would be to reward investments in science and technology capacity for sustainable development with additional debt relief or more favorable trade arrangements. This is a perfect time for the G8 to adopt this plan and assist all nations to invest in environmentally conscious innovation.
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References


It has been estimated that for every successful drug compound, 5,000 to 10,000 compounds must be introduced into the drug-discovery pipeline. On average, it takes $802 million and 10 to 15 years to develop a successful drug. Given this very low success rate and the incredibly high costs, drug companies must introduce as many drug candidates into their pipelines as possible.

Natural products have been important sources of drug leads; as much as 60 percent of successful drugs are of natural origin (Cragg et al., 1997), and some of the most potent natural products have been used as anticancer, antibacterial, and antifungal drugs. However, most natural products evolved for purposes other than the treatment of human disease. Thus, even though they can sometimes function as human therapeutics, their pharmacological properties may not be optimal. Furthermore, many are produced in miniscule amounts in their native hosts, thus making them expensive to harvest.

Organic chemistry methodologies are widely used to synthesize pharmaceuticals (of natural origin or not) and functionalize pharmaceutically relevant natural products. With appropriate protection and deprotection steps, chiral centers and functionalities can be introduced into molecules with precision. With the advent of combinatorial chemical synthesis, researchers have been able to construct entire families of molecules substituted at several positions with several different substituents, thus allowing drug companies to fill drug-discovery pipelines with variations of promising leads.
Despite the creation of complicated molecules made possible by advances in organic synthesis methodologies, the performance of these molecules is hardly comparable to the ease, specificity, and “green-ness” of enzymes. Indeed, many organic synthesis routes now incorporate one or more enzymes to perform transformations that are particularly difficult using non-enzymatic routes. Furthermore, enzymes are now being used for the in vitro, combinatorial functionalization of complex molecules. The next logical step in the synthesis of chemotherapeutics is the use of enzymes for combinatorial synthesis inside the cell, which would allow the production of drug candidates from inexpensive starting materials and avoid the need for purification of enzymes, which may be necessary for in vitro synthesis.

**Biological Engineering for the Synthesis of Drugs**

Rich, versatile biological systems are ideally suited to solving some of the world’s most significant challenges, such as converting cheap, renewable resources into energy-rich molecules; producing high-quality, inexpensive drugs to fight disease; detecting and destroying chemical or biological agents; and remediating polluted sites. Over the years, significant strides have been made in engineering microorganisms to produce ethanol, bulk chemicals, and valuable drugs from inexpensive starting materials; to detect and degrade nerve agents as well as less toxic organic pollutants; and to accumulate metals and reduce radionuclides.

However, meeting these biological engineering challenges requires long development times, largely because of a lack of useful tools that would enable engineers to easily and predictably reprogram existing systems, let alone build new enzymes, signal transduction pathways, genetic circuits, and, eventually, whole cells. The ready availability of these tools would drastically alter the biotechnology industry, leading to less expensive pharmaceuticals, renewable energy, and biological solutions to problems that do not currently offer sufficient monetary returns to justify the high cost of biological research.

Most of the biological engineering tools currently available to scientists and engineers have not changed significantly since genetic engineering began in the 1970s. Biologists still use natural, gene-expression control systems (promoters with cognate repressors/activators). The ability to place a single heterologous gene under the control of one of these native promoters and produce large quantities of a protein of interest is the basis for the modern biotechnology industry.

Although redesigned biological control systems have been generally effective for their intended purposes (controlling rather roughly the expression of a single gene or a few genes), not surprisingly they are often inadequate for more complicated engineering tasks (e.g., controlling very large, heterologous, metabolic pathways or signal transduction systems). In addition, these borrowed “biological parts” retain many of the features that were beneficial in their native forms but make them difficult to use for purposes other than the ones for which they evolved. Well characterized standard biological parts, and larger devices made from such parts, would make biological engineering more predictable and enable the construction and integration of larger systems than is currently possible.

In almost every other field of engineering, standards have been developed for building large integrated systems by assembling components from various manufacturers. However, biologists and engineers have not yet defined standards for the parts that might allow them to build larger biological devices. The design and construction of new devices (e.g., genetic-control systems) would benefit greatly from standards governing how various parts (e.g., regulatory proteins, promoters, ribosome binding sites) should interact and be assembled. Setting standards would also encourage manufacturing firms to develop parts.

Biological engineering has been held back because many of the most effective biological parts (promoters, genes, plasmids, etc.) have been patented and are available only to companies that can afford the royalty payments. This has not only increased the cost of drug development, but also hampered the development of new biological solutions to problems that may not have significant monetary payoffs (basically, anything other than drug development). Open-source biological parts, devices, and eventually whole cells would reduce the cost of engineering biological systems, make biological engineering more predictable, and encourage the development of novel biological solutions to some of
our most challenging problems. The development of open-source biological technology would improve awareness of, and minimize possible future biological risks, in the same way that open-source software tends to promote a constructive and responsive community of users and developers.

**Synthetic Biology**

Synthetic biology is the design and construction of new biological entities, such as enzymes, genetic circuits, and cells, or the redesign of existing biological systems. The goal of synthetic biology, which builds on advances in molecular, cellular, and systems biology, is to transform biology in the same way that synthesis transformed chemistry and integrated circuit design transformed computing. The element that distinguishes synthetic biology from traditional molecular and cellular biology is the focus on (1) the design and construction of core components (parts of enzymes, genetic circuits, metabolic pathways, etc.) that can be modeled, understood, and engineered to meet specific performance criteria, and (2) the assembly of these smaller parts and devices into larger integrated systems to solve specific problems. Just as engineers now design integrated circuits based on the known physical properties of materials and then fabricate functioning circuits and entire processors (with relatively high reliability), synthetic biologists will soon design and build engineered biological systems.

Unlike many other areas of engineering, however, biology is nonlinear and less predictable, and much less is known about parts and how they interact. Hence, the overwhelming physical details of natural biology (gene sequences, protein properties, biological systems) must be organized and recast via a set of design rules that hide information and manage complexity, thereby enabling the engineering of multicomponent integrated biological systems. Only when this is accomplished will designs of significant scale be possible.

Synthetic biology arose from four different intellectual premises. The first is the scientific idea that a practical test of understanding is the ability to reconstitute a functional system from its basic parts. Using synthetic biology, scientists are testing models of how biology works by building systems based on models and measuring differences between expectations and observations. Second, some consider biology an extension of chemistry, and thus synthetic biology can be considered an extension of synthetic chemistry. Attempts to manipulate living systems at the molecular level will likely lead to a better understanding, and new types, of biological components and systems. Third, natural living systems evolved to ensure their continued existence; they are not optimized for human understanding and intention. By thoughtfully redesigning natural living systems, it is possible simultaneously to test our current understanding and potentially implement engineered systems that are easier to interact with and study. Fourth, biology can be used as a technology, and biotechnology, broadly redefined, includes the engineering of integrated biological systems for the purposes of processing information, producing energy, manufacturing chemicals, and fabricating materials.

Although the emergence of the discipline of synthetic biology was motivated by these agendas, progress has only been practical since the recent advent of two foundational technologies, DNA sequencing, which has increased our understanding of the components and organization of natural biological systems, and synthesis, which has enabled us to begin to test the designs of (1) new, synthetic biological parts (Allert et al., 2004; Basu et al., 2004; Becskei and Serrano, 2000; Cane et al., 2002; Datsenko and Wanner, 2000; De Luca and Laflamme, 2001; Dwyer and Hellinga, 2004; Gardner and Collins, 2000; Gardner et al., 2000; Geerlings et al., 2001; Gerasimenko et al., 2002; Godfrin-Estevenon et al., 2002; Guet et al., 2002; Kobayashi et al., 2004; McDaniel et al., 1997) and (2) new biological systems (Bignell and Thomas, 2001; Blake and Isaacs, 2004; Hughes and Shanks, 2002; Iijima et al., 2004; Imler et al., 2000; Judd et al., 2000; Kumar et al., 2004; Le Borgne et al., 2001; Martin et al., 2001, 2002, 2003; Okamoto et al., 2004).

Each of these examples demonstrates the incredible potential of synthetic biology, as well as the foundational scientific and engineering challenges that must be met for the engineering of biology to become routine.

**References**


Control over agent-based systems can be achieved via modeling tools.

Agent-Based Modeling as a Decision-Making Tool

Zoltán Toroczkai and Stephen Eubank

Researchers have made considerable advances in the quantitative characterization, understanding, and control of nonliving systems. We are rather familiar with physical and chemical systems, ranging from elementary particles, atoms, and molecules to proteins, polymers, fluids, and solids. These systems have interacting particles and well defined physical interactions, and their properties can be described by the known laws of physics and chemistry. Most important, given the same initial conditions, their behavior is reproducible (at least statistically).

However, other types of ubiquitous systems are all around us, namely systems that involve living entities (i.e., agents) about which we have hardly any quantitative understanding, either on an individual or collective level. In this paper, we refer to collectives of living entities as “agent-based systems” or “agent systems” to distinguish them from classical particle systems of inanimate objects. Although intense efforts have been made to study these systems, no generally accepted unifying framework has been found. Nevertheless, understanding, and ultimately controlling the behavior of agent systems, which have applications from biology to the social and political sciences to economics, is extremely important. Ultimately, a quantitative control over agent-based systems can be achieved via modeling tools.
understanding can be a basis for designing agent systems, like robots or rovers that can perform tasks collectively that would be prohibitive for humans. Examples include deep-water rescue missions, minefield mapping, distributed sensor networks (for civil and military uses), and rovers for extraterrestrial exploration.

Even though there is no unifying understanding of agent systems, some control over their behavior can be achieved via agent-based modeling tools. The idea behind agent-based modeling is rather simple—build a computer model of the agent system under observation using a bottom-up approach by trying to mimic as much detail as possible. This can be rather expensive, however, because it requires (1) data collection, (2) model building, (3) exploitation of the model and the collection of statistics, and (4) validation, which normally means comparing the output of the model with additional observations of the real system.

The agent models described in this paper took about nine years to develop at Los Alamos National Laboratory. However, the framework for these models can be used to simulate many similar circumstances and to make predictions.

**Properties of Agent Systems**

Agent-based systems are hard to describe and understand within a unified approach because they differ from classical particle systems in at least two ways. First, an agent is a complex entity that cannot be represented by a simple function, such as a Hamiltonian function of a classical system (e.g., a spin system). Second, the interaction topology, namely the rules by which particles interact with each other, is generally represented by a complex, dynamic graph (network), unlike the regular lattices of crystalline solids or the continuous spaces of fluid dynamics. In many cases, the notion of “locality” itself is elusive in agent-based networks; in social networks, for example, the physical or spatial locality of agents may have little to do with social “distances” and interactions among them. To illustrate the complex structure of a “particle,” or agent, and its consequences we can use traffic, namely people (agents) driving on a highway, as an example. Keep in mind, however, that the statements in this description are generally applicable to other agent systems.

Agents have the following qualities:

- A set of variables, \( x \), describes the state of the agent (e.g., position on the road, speed, health of the driver, etc.). The corresponding state space is \( X \).
- A set of variables, \( z \), describes the perceived state of the environment, \( Z \), which includes other agents, if there are any (e.g., level of congestion, state/quality of the road, weather conditions, etc.).
- There is a set of allowable actions (output space), \( A \) (swerve, brake, accelerate, etc.).
- A set of strategies, which are functions, \( s: (Z \times X) \rightarrow A \), summon an action to a given circumstance, current state of the agent, and history up to time, \( t \). These are “ways of reasoning” for the agent. One might think of strategies as behavioral input space. For example, depending on age, background, and other factors, some drivers will brake and some will swerve to avoid an accident. Social studies and surveys can supply valuable statistical inputs, such as data showing that agents with \( n \) years of driving experience between ages \( a_1 \) and \( a_2 \) swerve \( f \) percent of the time and break \( g \) percent of the time.
- There is a set of utility variables, \( u \in U \) (e.g., time to destination, number of accidents, number of speeding tickets, etc.).
- A multivariate objective function, \( F: U \rightarrow R^m \), might include constraints (“rules”) (e.g., the agent has to stay on the road). The analogous version in physics is called action. The agent tries to optimize this objective function (e.g., by minimizing the time to destination, avoiding accidents, etc.).

The framework for developed models can be used to simulate other agent systems.

Unlike particles in classical systems, agents usually have memory, which they can use to change/evolve strategies, a process called learning. Another important aspect of agents is that they can reason and plan, which entail searching the choice tree and assigning weights and payoffs in light of what other agents might choose. In realistic situations that involve hundreds of agents (such as markets or traffic), long-term planning and reasoning are impossible because of the combinatorial explosion of possibilities and also because not all of the information is available to any single agent.
Therefore, agents try to identify and exploit patterns in the responses of the surrounding environment to past actions and use these patterns to discriminate among strategies, reinforcing some and diminishing others (reinforcement learning). This leads to bounded-rationality-like behavior and introduces de-correlations between strategies; for that reason, reinforcement learning actually makes statistical modeling plausible.

In the following sections, we briefly describe two large-scale agent-based models developed at Los Alamos National Laboratory, a traffic simulator (TRANSIMS) and an epidemics simulator (EPISIMS).

TRANSIMS

The transportation analysis and simulation system (TRANSIMS) is an agent-based model of traffic in a particular urban area (the first model was for Portland, Oregon). TRANSIMS conceptually decomposes the transportation planning task using three different timescales. A large time scale associated with land use and demographic distribution (Figure 1) was used to create activity categories for travelers (e.g., work, shopping, entertainment, school, etc.). Activity information typically consisted of (1) requests that travelers be at a certain location at a specified time and (2) information on travel modes available to the traveler. For the large timescale, a synthetic population was created and endowed with demographics matching the joint distributions in census data. Synthetic households were also created based on survey data from several thousand households that included observations of daily activity patterns for each individual in the household. These activity patterns were then associated with synthetic households with similar demographics. The locations of various activities were estimated, taking into account observed land-use patterns, travel times, and the dollar costs of transportation.

For the intermediate timescale (Figure 2), routes and trip chains were assigned to satisfy the activity requests. The estimated locations were fed into a routing algorithm to find minimum-cost paths through the transportation infrastructure consistent with constraints on mode choices (Barrett et al., 2001, 2002). For example, a constraint might be “walk to a transit stop, take transit to work using no more than two transfers and no more than one bus.”

Finally, a very short timescale (Figure 3) was used, associated with the actual execution of trip plans in the road network. This is done by a cellular automata simulation through a very detailed representation of the urban transportation network. The simulation, which resolved distances down to 7.5 meters and times down to 1 second, in effect resolved the traffic congestion caused by everyone trying to execute plans simultaneously by providing updated estimates of time-dependent travel times for each edge in the network, including the effects of congestion. These estimates were fed to a router and location estimation algorithms that produced new plans.

The feedback process continued iteratively until the system converged in a “quasi-steady state” in which no agent could find a better path in the context of every other agent’s decisions. The resulting traffic patterns compared well to observed traffic. Thus, the entire process estimated the demand on a transportation network using census data, land-usage data, and activity surveys.1

1 More information, including availability of the software, can be obtained from http://transims.tsasa.lanl.gov.
Another application of the TRANSIMS model is in the field of epidemiology. Diseases, such as colds, flu, smallpox, and SARS, are transmitted through the air between two agents. These agents must either spend a long enough time in proximity to each other or be in a building with a closed air-ventilation system to transmit the disease. Thus, we can assume that the majority of infections take place in locations, like offices, shopping malls, entertainment centers, and mass transit units (metros, trams, etc.).

By tracking the people in our TRANSIMS virtual city, we generated a bipartite contact network, or graph, formed by two types of nodes—people nodes and location nodes. If a person, \( p \), entered a location, \( l \), an edge was drawn between that person and the corresponding location node on the graph. The edge had an associated time stamp representing the union of distinct time intervals the person, \( p \), was at the location, \( l \), during the day. If two people nodes, \( p_1 \) and \( p_2 \), had an incident edge in the same location node, \( l \), the common intersection of the two time stamps told us the total time the two people spent in proximity to each other during the day, thus enabling us to determine the possibility of transmission of an airborne infection.

Using Portland as an example, there were about 1.6 million people nodes, 181,000 location nodes, and more than 6 million edges between them. This dynamic contact graph enabled us to simulate different disease-spread scenarios and test the sensitivities of epidemics to disease parameters, such as incubation period, person-to-person infection rates, influence of age structure, activity patterns, and so on. The epidemiological study tool thus generated, called EPISIMS, can be used as an aid to decision making and planning, for example, for an outbreak of smallpox.

Based on the Portland data, we arrived at the following findings for the spread of smallpox.\(^2\) First, a person who has been vaccinated can be removed from the contact graph, along with his or her incident links. Thus, an efficient vaccination strategy removes the smallest subset of nodes, so that the resulting graph has many small disconnected pieces, which eliminates the spread of disease throughout the population. Unfortunately, the smallpox vaccine is not entirely harmless. In some people, it causes a disease called vaccinia that is sometimes fatal. Therefore, to minimize the incidence of vaccinia, mass vaccination (proposed by Kaplan et al., 2002) must be a last resort.

After studying the projection of the bipartite graph onto people nodes, however, we found very high expansion properties, and the only way to avoid mass spread of the disease would be to vaccinate everyone who had 10 or more contacts during the day, which effectively meant mass vaccination. Ultimately, we found that vaccinating people who frequently took long-range trips across the city, corresponding to shortcuts in the network (Watts and Strogatz, 1998), made it possible for us to use a more localized graph with a larger diameter. In case of an outbreak, this would allow for a ring strategy for quarantining and further vaccinations to stop the spread of disease.

Finally, the crucial parameter in containing an epidemic is the delay in reaction time. If we assume that sensors can perform an online analysis of pathogens in the air, the question is where they should be placed to be most effective, that is, where they would capture the

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\(^2\) For more details on EPISIMS, see Eubank et al., 2004.
onset of the outbreak. Due to a particular so-called scale-free property (Albert and Barabási, 2002) of the locations projection of the bipartite network, one can pinpoint a small set of locations (the so-called dominating set, about 10 percent of all locations) that would cover about 90 percent of the population and would thus be optimal locations for detectors. The same locations could be used for distribution purposes (e.g., of prophylactics and supplies). Figure 4 shows the evolution of epidemics after a covert introduction in a particular location (at a university) when the disease is left to spread (left side) compared to using a targeted-contact tracing and quarantining strategy (right).

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**References**


Fuel cells, which convert chemical energy directly to electricity, are more efficient than current means of energy conversion. The question is where they might fit in the broad spectrum of energy choices. This paper briefly reviews and compares polymer-electrolyte fuels cells (PEFCs) and solid-oxide fuel cells (SOFCs) and then describes significant scientific challenges that must be overcome before these technologies can become commercially competitive.

Fuel cells are not a new idea. Sir William Grove first demonstrated the conversion of hydrogen to electricity using an acid-electrolyte fuel cell in 1839. However, turning this idea into a practical means of energy conversion has proved to be elusive. A major technical and cost barrier has been implementation of liquid electrolytes, the basis for most commercial fuel cells (e.g., alkaline fuel cells, molten-carbonate fuel cells). In contrast, the fuel cells of greatest commercial interest today are based on solid electrolytes, which have benefited from recent advances in materials and manufacturing.

For the purposes of discussion, we can divide solid-electrolyte fuel cells into two types: (1) PEFCs, often referred to as proton-exchange-membrane (or PEM) fuel cells; and (2) SOFCs. Figure 1 illustrates how these types of fuel cells function.

A common justification for fuel cells has been environmental protection—the idea that fuel cells produce only water as a combustion by-product and
thus are “zero emission” devices. However, it is difficult to make the case for fuel cells based on this argument alone. Although fuel cells themselves produce only water, the production of hydrogen from hydrocarbons, such as oil or coal, involves the production of carbon dioxide (CO$_2$) and requires the suppression of sulfur dioxide (SO$_2$). Thus fuel cells merely transfer the environmental problem elsewhere.

In addition, numerous technologies are already available that can eliminate SO$_2$ and nitrogen oxides (NO$_X$) from combustion. Widespread implementation of these technologies is simply a matter of cost and political will. Thus, one can easily imagine an energy economy based entirely on clean combustion of hydrogen or other multisource fuels that do not include fuel cells.

To understand the potential role of fuel cells, we must instead consider their primary advantage—efficiency. In this regard, fuel cells are an enabling (rather than a displacing) technology. They recover energy that is normally lost by the irreversible process of combustion. Thus, fuel cells offer a potential path toward overall reduction of fuel consumption that combustion simply cannot provide, even after many years of incremental improvements.

By reducing the overall amount of CO$_2$ produced per kilowatt (kW) of usable power, increased efficiency may, ultimately, have environmental benefits as well. In addition, the required retooling of the fuel infrastructure toward more generic, small-molecule fuels (e.g., H$_2$, CO, CH$_4$) might also lead to centralization of CO$_2$ production, which would facilitate carbon sequestration and reduce the vulnerability of particular energy sectors to fluctuations in the supply of particular fuel sources (e.g., the dependence of gasoline prices on the availability of oil from the Middle East).

### Comparisons between PEFCs and SOFCs

A primary factor influencing the trade-off between capital and efficiency in fuel cells is operating temperature. SOFC stacks, which operate at temperatures ranging from 550°C to 900°C, produce high-quality waste heat that can be captured for increased efficiency, combined heat and power, or reformation of hydrocarbons (HCs). SOFC stacks tend to operate adiabatically wherein excess air is used as the primary coolant, and thus heat can be recovered from the SOFC exhaust. This feature has made SOFCs very attractive for the production of stationary power, where efficiency is of high importance relative to capital cost, and operation on reformed HCs is an advantage. Allowable capital costs for stationary power ($400/kW) are about 10 times higher than for PEFCs in automotive applications (DOE, 2004b).

By using thin-film ceramics supported on low-cost metal alloys, SOFC developers have reduced material and manufacturing costs, lowered operating temperatures, and significantly mitigated cell-degradation problems. Figure 2 shows an example of a metal-supported cell based on a thin ceria electrolyte, capable of stable power densities of ~500 mW/cm$^2$ at 570°C (Brandon, 2005). Systems based on this type of cell are nearing efficiency and cost targets for use in homes (combined

![FIGURE 1](image-url) Two types of solid electrolyte fuel cells. **a.** In a PEFC, a proton-conducting polymer membrane is exposed on one side to fuel (hydrogen) and on the other to air. On the hydrogen side (anode), H$_2$ gas is oxidized, and the protons thus created migrate to the other side of the membrane (cathode), where O$_2$ gas in the air is reduced to water. Some portion of the reversible work of the net reaction is recovered as a voltage difference between cathode and anode, delivered to an external circuit by the flow of electrons. PEFCs typically operate at 80–100°C. **b.** In an SOFC, a ceramic oxygen ion conductor at elevated temperatures (500–1,000°C) serves as the electrolyte membrane. In this case, the fuel (which can be a mixture of H$_2$, CO, and/or hydrocarbons) is oxidized to H$_2$O and CO$_2$ at the anode, while O$_2$ is reduced to O$_2^-$ at the cathode. In both types of fuel cells, cells are normally assembled into multicell stacks to increase system voltage and provide a means of distributing gases (fuel and air) evenly.
heat and power) and auxiliary power units for trucks and aircraft.

In contrast, PEFCs have historically been designed to operate isothermally, at or below 80°C. Low operating temperatures have made them more suitable for small or mobile applications, for which capital cost requirements are much more stringent, pure hydrogen (H2) is assumed to be available, and the efficiencies of heat integration are less important. The most challenging market from a capital-cost perspective is motive power (cars), for which allowable capital costs are estimated to be on the order of $35/kW (Garman, 2003). PEFCs are also generally thought to match the size, weight, and start-up constraints for primary power in automobiles.

Substantial progress has been made in increasing the power density of PEFCs (>1 kW/kg) (Gasteiger et al., 2005), as well as reducing the amount of platinum (Pt) catalyst to a level that is reasonable to recycle (<15g/vehicle, three to four times the catalyst in a catalytic converter) (Cooper, 2004; Gasteiger et al., 2005). Based on these successes, several of the world’s biggest automakers, including General Motors, Ford, Daimler, and Honda (Figure 3), have built demonstration cars.

Despite these significant advances, solid-electrolyte fuel cells have not yet achieved widespread penetration into the energy market for many reasons. In particular, fuel cell systems are still too costly to be competitive with existing technology at current energy prices. Although this situation may change as fuel prices rise and capital costs come down with manufacturing improvements and economies of scale, fundamental technological barriers must also be overcome before cost reductions are likely. Many of these technological hurdles have been described in detail elsewhere (DOE, 2004a). The discussion below focuses on areas of fundamental research where breakthroughs might lead to significant technological advancements.

**Material Properties by Design**

Many of the materials used in SOFCs and PEFCs today are similar to the ones used 25 years ago. Examples
include the nickel (Ni)-cermet anode used in most SOFCs and the perfluorosulfonic acid (PFSA) membrane used as the electrolyte in most PEFCs (Dupont Nafion®). Despite numerous difficulties with these materials, they are still considered state of the art because their unique combination of properties is still unmatched. However, they also introduce fundamental problems (Figure 4). In SOFCs, Ni-cermet has very poor sulfur tolerance, especially below 800°C, which makes it unsuitable as a long-term SOFC anode (DOE, 2004a). PEFC developers have concluded, that to be successful in cars, the system must operate at 110~120°C, which introduces severe performance and degradation problems for PFSA (Gasteiger and Mathias, 2003). To date, a trial and error approach has been used to search for new materials. However, further advances are likely to require a directed design approach (Hickner et al., 2004) and/or combinatorial methods (Kilner et al., 2005).

Probing and Controlling Microstructure/Nanostructure

Despite the technological advances in SOFC and PEFC technology in the last ten years, our understanding and design capability are mostly at the macroscopic/empirical level. The microstructure of a PEFC electrode, for example, is still understood only in a very general sense; exactly how the catalyst, ionomer, and gas come together and affect performance is generally not well understood and thus not amenable to intelligent design. For example, one proposed strategy for improving the catalyst in PEFC cathodes is to concentrate Pt particles near the opening of the aqueous flow channel in the PFSA ionomer; at present they are distributed randomly throughout the electrode matrix. However, this type of nanostructural analysis, let alone control, is not possible today.

As shown in Figure 5, one possible technique on the horizon for SOFCs is focused-ion beam milling coupled with electron microscopy or other surface analytical techniques, which may make it possible to analyze and direct electrode microstructures in new ways (J. Wilson et al., 2005). Researchers have also recently demonstrated solution impregnation of materials into an electrolyte host matrix to obtain SOFC electrodes with improved hydrocarbon activity or O₂ reduction performance (Huang et al., 2005; McIntosh and Gorte, 2004).

Understanding Electrode Degradation and Other Degradation Processes

The vast majority of work in the last ten years has been focused on improving fuel cell performance. However, as the technology has now reached some performance targets, and as more cells and stacks have been tested for longer periods of time, long-term durability has risen to the top of the list of performance targets. For example, SOFC electrodes can be very sensitive to chromia (Cr) poisoning (Simner and Stevenson, 2004). Although electrode degradation has been positively linked to Cr contamination from metal interconnects, it is not clear why some electrode materials are more sensitive than others or why seemingly similar electrodes tested by different groups degrade at different rates. The answers to these questions require a much deeper mechanistic and scientific understanding of electrode processes than we currently possess.

Recent advances in microfabrication and diagnostics may significantly improve our ability to control and analyze electrode reactions (Adler, 2004; J.R. Wilson et al., in press). Recent work using nonlinear electrochemical impedance spectroscopy to resolve SOFC cathode reaction mechanisms may eventually improve our ability to diagnose how and why electrodes degrade and guide the selection of new materials and fabrications to mitigate degradation.

Outlook

Fuel cells continue to face major technological hurdles that may require many years of research and development before they can be overcome. In addition, fuel cells are not likely to be implemented in isolation. They must be part of a larger shift in fuel infrastructure.
and efficiency standards, which will require sustained political and economic pressure—and time. Finally, like any technology, economy of scale will require a natural maturation process over many years or decades (DeCicco, 2001).

Taken together, these hurdles suggest that the widespread adoption of fuel cell technology is not likely in the short term. Successful advancement of fuel cell technology will require a sustained, long-term commitment to fundamental research, commercial development, and incremental market entry.

References


Currently the world consumes an average of 13 terawatts (TW) of power. By the year 2050, as the population increases and the standard of living in developing countries improves, this amount is likely to increase to 30 TW. If this power is provided by burning fossil fuels, the concentration of carbon dioxide in the atmosphere will more than double, causing substantial global warming, along with many other undesirable consequences. Therefore, one of the most important challenges facing engineers is finding a way to provide the world with 30 TW of power without releasing carbon into the atmosphere. Although it is possible that this could be done by using carbon sequestration along with fossil fuels or by greatly expanding nuclear power plants, it is clearly desirable that we develop renewable sources of energy. The sun deposits 120,000 TW of radiation on the surface of the earth, so there is clearly enough power available if an efficient means of harvesting solar energy can be developed.

Only a very small fraction of power today is generated by solar cells, which convert solar energy into electricity, because they are too expensive (Lewis and Crabtree, 2005). More than 95 percent of the solar cells in use today are made of crystalline silicon (c-Si). The efficiency of the most common panels

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is approximately 10 percent, and the cost is $350/m². In other words, the cost of the panels is $3.50/W of electricity produced in peak sunlight. When you add in the cost of installation, panel support, wiring, and DC to AC converters, the price rises to approximately $6/W. Over the lifetime of a panel (approximately 30 years), the average cost of the electricity generated is $0.3/kW-hr. By comparison, in most parts of the United States, electricity costs about $0.06/kW-hr. Thus, it costs approximately five times as much for electricity from solar cells. If the cost of producing solar cells could be reduced by a factor of 10, solar energy would be not only environmentally favorable, but also economically favorable.

Although c-Si solar cells will naturally become cheaper as economies of scale are realized, dicing and polishing wafers will always be somewhat expensive. Thus, it is desirable that we find a cheaper way to make solar cells. The ideal method of manufacturing would be depositing patterned electrodes and semiconductors on rolls of plastic or metal in roll-to-roll coating machines, similar to those used to make photographic film or newspapers. Solar cells made this way would not only be cheaper, but could also be directly incorporated into roofing materials, thus reducing installation costs. Organic semiconductors that can be dissolved in common solvents and sprayed or printed onto substrates are very promising candidates for this application.

**Organic Semiconductors**

Because organic semiconductors have different bonding systems from conventional, inorganic semiconductors, they operate in a fundamentally different way. Conventional semiconductors are held together by strong covalent bonds that extend three-dimensionally, resulting in electronic bands that give rise to its semiconducting properties. Organic materials have similar intramolecular covalent bonds but are held together only by weak intermolecular van der Waals interactions. The electronic wave function is thus strongly localized to individual molecules, and the weak intermolecular interactions instigate a narrow electronic bandwidth formed in molecular solids.

**Bonding**

The semiconducting nature of organic semiconductors arises from the π electron bonds that exist when molecules are fully conjugated (i.e., have alternating single and double bonds). The weakly held π electrons are responsible for all interesting optical and electronic transitions in organic semiconductors. The π to π* transitions in organic semiconductors are typically in the range of 1.4–2.5 eV, which overlaps well with the solar spectrum and makes them very promising candidates as active light absorbers in solar cells. A few examples of organic semiconductors used in solar cells are shown in Figure 1.

**Excitons**

The main difference between organic semiconductors and inorganic semiconductors as photovoltaic materials is that optical excitations of organic semiconductors create bound electron-hole pairs (called excitons) that are not effectively split by the electric field (Gregg, 2003). To separate the bound electrons and holes, there must be a driving force to overcome the exciton-binding energy, typically 0.1–0.4 eV. Excitons in organic semiconductors that are not split eventually recombine either radiatively or

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**FIGURE 1** The chemical structures of four different organic semiconductors used in organic solar cells.
nonradiatively, thereby reducing the quantum efficiency of a solar cell.

In inorganic semiconductors the attraction between an electron-hole pair is less than the thermal energy kT. Therefore, no additional driving force is required to generate separated carriers. Research has shown that excitons in organic semiconductors can be efficiently split at a heterojunction of two materials with dissimilar electron affinities or ionization potentials.

**Bandwidth**

The narrow electronic bandwidth in organic semiconductors has a few consequences. First, the absorption-spectrum bandwidth is narrower than in conventional inorganic semiconductors. Consequently, a single organic material can be potentially photoactive only in a narrow optical-wavelength range of the solar spectrum (Figure 2). Although this is a disadvantage in terms of harvesting solar flux, multiple absorbers in stacks of solar cells connected in series can be engineered to expand the absorption range. Because the valence band and conduction band are concentrated in narrower energy regions, the absorption coefficient resulting from the excitation of electrons from the valence band to the conduction band is very strong, typically $>10^{-5}$ cm$^{-1}$ at peak absorption. This high absorption coefficient means that only a thin (100–200 nm) film is required to absorb most incident light, an attractive characteristic for solar cells because less material is required to make them.

Second, the charge carriers in organic semiconductors do not exhibit band-like transport as they do in inorganic semiconductors. Instead, they move around by a hopping mechanism between localized states. The charge-carrier mobilities in organic semiconductors are, therefore, inherently low, with typical values of $<10^{-2}$ cm$^2$/Vs. This low charge-carrier mobility puts a constraint on the thickness of organic materials that can be used in a solar cell because recombinative loss increases with increasing thickness. Fortunately, this drawback is offset because only a very thin layer of organic materials is necessary because organic semiconductors are highly absorptive. Organic solar cells may potentially perform better than conventional solar cells at higher temperature, because hopping is a thermally activated process. The performance of inorganic solar cells typically decreases as operating temperature increases.

A third key difference between organic and inorganic semiconductors is that organic materials do not have dangling bonds at surfaces. Therefore, organic-organic junctions or organic-metal junctions in organic solar cells (interface states) do not act as potential charge-carrier recombination sites.

**Production of Heterojunction Devices**

The simplest organic solar cells can be made by sandwiching thin films of organic semiconductors between two electrodes with different work functions. The work function is the amount of energy necessary to pull an electron from a material. When such a diode is made, electrons from the low-work-function metal flow to the high-work-function metal until the Fermi levels are equalized throughout the structure. This sets up a built-in electric field in the semiconductor. When the organic semiconductor absorbs light, electrons are created in the conduction band, and holes (positive-charge carriers) are created in the valence band. Thus, in principle, the built-in electric field can pull the photogenerated electrons to the low-work-function electrode and holes to the high-work-function electrode, thereby generating a current and voltage (Figure 3a). In practice, however, these cells have very low power-conversion efficiency ($< 0.1$ percent) because the electric field is not strong enough to separate the bound excitons (i.e., the excited-state species formed in organic semiconductors described above).

A significant improvement in the performance of organic solar cells was achieved by Tang (1986). His device consisted of a heterojunction between donor and acceptor semiconductors, resembling a p-n junction in...
conventional solar cells (Figure 3b). The benefit of this device derived from the use of two organic materials with offset electron affinities (lowest unoccupied molecular orbital, LUMO) or ionization potentials (highest occupied molecular orbital, HOMO). Excitons that diffuse to the interface undergo efficient charge transfer, as this offset in the energy levels provides a sufficient chemical potential energy to overcome the intrinsic exciton-binding energy. Upon charge transfer, the electrons are transported in the acceptor material and the holes in the donor material to their respective electrodes.

The efficiency of this type of planar heterojunction device is limited, however, by the exciton diffusion length, which is the distance over which excitons travel before undergoing recombination, approximately 5–10 nm in most organic semiconductors. Excitons formed at a location further than 5–10 nm from the heterojunction cannot be harvested. The active area of this type of solar cell is thus limited to a very thin region close to the interface, which is not enough to adsorb most of the solar radiation flux.

**Blend Cells**

In the mid 1990s, Yu and colleagues (1995) showed that excitons can be rapidly split by electron transfer before the electron and hole recombine if carbon-60 (C$_{60}$) derivatives are blended into the polymer (Figure 3c). Blend solar cells were made simply by blending the C$_{60}$ derivative, which acts as an electron acceptor, into the polymer at concentrations in the range of 18–80 wt. percent. At these concentrations, the polymer and the C$_{60}$ derivatives form a connected network to each electrode. The key to making efficient blend solar cells is to ensure that the two materials are intermixed very closely at a length scale less than the exciton diffusion length so that every exciton formed in the polymer can reach an interface with C$_{60}$ to undergo charge transfer.

At the same time, the film morphology has to enable charge-carrier transport in the two different phases to minimize recombination. The film morphology (i.e., phase separation between the two materials) and, ultimately, the efficiency of the device, are determined by the concentration of materials, film-casting solvent, annealing time, temperature, and other parameters. Solar cells made by this method have continuously improved to better than 2 percent power efficiency under solar AM 1.5 conditions over the last few years (Padinger et al., 2003; Shaheen et al., 2001), and recently, an efficiency of 5 percent was reported (Ma et al., 2005).
The work on polymer/C\textsubscript{60}-derivative blend cells has created a new paradigm in the field of organic-based solar cells, which is the notion of bulk heterojunction devices, wherein two semiconductors with offset energy levels are interpenetrated at a very small length scale to create a high interface area for achieving high-efficiency devices. Since then, similar bulk heterojunction devices using electron acceptors other than the C\textsubscript{60} derivative, such as CdSe nanorods (Huynh et al., 2002), a second semiconducting polymer (Granstrom et al., 1998), and titania nanocrystals (Arango et al., 1999), have been demonstrated, albeit with slightly lower efficiencies.

**Limits on Performance**

To understand the limits on the performance of bulk heterojunction devices and find ways to improve them, it is important to consider all of the processes that must occur inside the cells for electricity to be generated. These processes, shown in Figure 4a, are: (1) light absorption; (2) exciton transport to the interface; (3) forward electron transfer; and (4) charge transport. One must also consider undesirable recombination processes that can limit the performance of the cell, such as geminate recombination of electrons and holes in the polymer and back electron transfer from the electron acceptor to the polymer (Figure 4b).

**Light Absorption**

The necessity of absorbing most of the solar spectrum (process 1) creates two requirements. First, the band gap must be small enough to enable the polymer to absorb most of the light in the solar spectrum. Calculations to determine the band gap that optimizes the amount of light that can be absorbed and the voltage that can be generated show that the ideal band gap is approximately 1.5 eV, depending on the combination of semiconducting polymers and electron acceptors (Coakley and McGehee, 2004). Second, the film must be thick enough to absorb most of the light. For most organic semiconductors, this means that films must be 150–300 nm thick, depending on how much of the film consists of a nonabsorbing electron acceptor. The optimum film thickness will absorb much incident light without significant recombination losses.

**Exciton Transport**

Once an exciton is created in the polymer, it must diffuse or travel by resonance energy transfer (process 2) to the interface with the other semiconductor and be split by electron transfer before it recombines (process 5). Experiments have shown that an exciton can diffuse approximately 5–10 nm in most semiconducting polymers before recombination. Therefore, no regions in the polymer can be more than 5–10 nm from an interface. Templating or nanostructuring of the donor and acceptor phases to fabricate ordered bulk heterojunctions with controlled dimensions is an attractive approach to achieving full exciton harvesting (Figure 5) (Coakley and McGehee, 2003). Some small-molecule semiconductors have been shown to have larger exciton diffusion lengths (Peumans et al., 2003).

Research is under way to improve exciton transport in organic semiconductors, for example by using resonance energy transfer to funnel excitons directly to an absorber located at the charge-splitting interface or by incorporating phosphorescent semiconductors, which exhibit longer excited-state lifetimes (Liu et al., 2005; Shao and Yang, 2005).
The actual process of charge transfer (process 3) requires that the offset in LUMO levels of the donor and acceptor be sufficient to overcome the exciton-binding energy. However, this drop in energy must not be excessive, because the maximum voltage attainable from this type of bulk heterojunction solar cell is determined by the gap between the HOMO of the electron donor and the LUMO of the acceptor. The gap becomes smaller as the LUMO of electron acceptors is moved farther away from the LUMO of the polymer, which corresponds to a larger driving force for charge transfer.

As can be seen from processes 1, 2, and 3, the design of an efficient organic solar cell involves optimizing the various energy levels to achieve the optimum level of extracted current with respectable voltage, as the power supplied by a solar cell is the product of current and voltage. Fortunately, the wealth of chemical synthetic knowledge and the dependence of electronic properties of organic molecules on their molecular structures allow for flexible tuning of the band gap and energy levels of organic semiconductors by chemical synthesis. Significant research on band engineering of this type should yield very promising results in the near future.

Charge Transport

After forward electron transfer, the holes in the polymer and the electrons in the electron acceptor must reach the electrodes (process 4) before the electrons in the acceptor undergo back electron transfer to the polymer (process 6). Even in the best bulk heterojunction cells, this competition limits the efficiency of the cells.

The problem can usually be mitigated by making cells that are only 100-nm thick so that the carriers do not have to travel very far. Unfortunately, most of the light is not absorbed by films this thin. If the films are thick enough to absorb most of the light, then only a small fraction of the carriers escape the device. Many researchers are now trying to optimize the interface between the two semiconductors and improve charge transport in the films so that the charge can be extracted from 300-nm-thick films before recombination occurs.

Future Challenges

The outlook for organic solar cells is very bright. Efficiency greater than 5 percent has been achieved (Ma et al., 2005; Xue et al., 2004), and many are optimistic that 20 percent can be achieved by optimizing the processes described above. Once this goal is achieved, a primary research challenge will be making cells that are stable in sunlight and that can handle wide temperature swings. The survival of many organic pigments in car paints in sunlight and the production of organic light-emitting diodes with operational lifetimes greater than 50,000 hours are encouraging signs that the required stability can be achieved. The final challenge will be scaling up the process and manufacturing the cells at a cost of approximately $30/m². Shaheen and colleagues (2005) have described several approaches to making organic cells.

References


The BRIDGE

NAE News and Notes

NAE Newsmakers

Robert B. Fridley, Professor Emeritus and former department chair of Biological and Agricultural Engineering at University of California, Davis, received an Award of Distinction from the College of Agricultural and Environmental Sciences, University of California, Davis. The Award of Distinction is given to individuals whose contributions and achievements have enriched the image and reputation of the college and improved its public service capabilities. Dr. Fridley’s research, which was focused on the needs of agriculture, forestry, and aquaculture, led to the development of the tree harvester for mechanical harvesting of tree fruit. He is also the author of several books on the agricultural industry.

Edward D. Lazowska, Bill and Melinda Gates Chair in Computer Science and Engineering at the University of Washington, received the Computing Research Association 2005 Distinguished Service Award for outstanding service to the computing research community.

Tso-Ping Ma, Raymond John Wean Professor, Department of Electrical Engineering, Yale University, is the recipient of the 2005 IEEE Andrew S. Grove Award for his pioneering contributions to the development and understanding of CMOS gate dielectrics, the basis of silicon chips. The award is given in recognition of outstanding contributions to solid-state devices and technology.

George M. Whitesides, Woodford L. and Ann A. Flowers University Professor, Department of Chemistry and Chemical Biology, Harvard University, was awarded the Welch Foundation 2005 Welch Award in Chemistry. Dr. Whitesides received the award for his contributions in many areas of chemistry and his leadership in the scientific community.

2005 Annual Meeting

Stephen Intille, research scientist and technology director, House_n Consortium, Massachusetts Institute of Technology, delivered the Lillian M. Gilbreth Lecture.

On October 8, NAE members, foreign associates, and guests gathered in Washington, D.C., for the 2005 NAE Annual Meeting. An orientation session for new members on Saturday, October 8, was followed by the NAE Council dinner in the Great Hall of the National Academies Building in honor of the 74 new members and 10 new foreign associates.

NAE Chair Craig R. Barrett opened the public session on Sunday, October 9, with an appeal to new members to advocate for more research, better K-12 education, and a more innovation-friendly environment (p. 42). President Wm. A. Wulf then addressed the group and entreated support for improving the competitiveness and security of the United States in a globalized world (p. 44). The induction of the NAE Class of 2005 followed President Wulf’s address.

The program continued with the presentation of the 2005 Founders Award to C. Dan Mote Jr. and the Arthur M. Bueche Award to Leo Young. Dr. Mote, president of the University of Maryland and Glenn L. Martin Institute Professor of Engineering, was recognized “for the creation of a comprehensive body of work on the dynamics of moving flexible structures and for leadership in academia.” Dr. Young, director of research (retired) for the U.S. Department of Defense, received the Bueche Award for “sponsoring collaborative research programs among academic, industrial, and government engineers and scientists.”

Following short presentations by Drs. Mote (p. 48) and Young (p. 50),
Edward Coyle, a recipient of NAE 2005 Gordon Prize, spoke on behalf of the prizewinning program, the Engineering Projects in Community Service (EPICS) Program at Purdue University (p. 52). The Gordon Prize is awarded in recognition of new modalities and experiments in education that develop effective engineering leaders. The recipients in 2005 are Dr. Coyle, professor of electrical and computer engineering; Leah Jamieson, Ransburg Professor of Electrical and Computer Engineering, associate dean, and director, EPICS; and William C. Oakes, assistant professor of engineering and co-director of EPICS, all of Purdue University. They received their award at a ceremony in Washington, D.C., last February.

After a break, Dr. Stephen Intille presented the Lillian M. Gilbreth Lecture, which recognizes outstanding young engineers. Dr. Intille, research scientist and technology director of the Massachusetts Institute of Technology (MIT) Home of the Future Project, spoke on using ubiquitous computing technologies to encourage aging in place.

The final speaker was Bernard Amadei, professor of civil engineering at the University of Colorado, who spoke in his capacity as founder of Engineers Without Borders. The day ended with a reception for members and their guests.

At the Annual Business Session on Monday, October 10, members had an opportunity to discuss specific NAE activities and issues relevant to the engineering profession. The business session was followed by a symposium, “Adapting Engineering Education to the New Century,” moderated by G. Wayne Clough, president of Georgia Institute of Technology. Speakers included Charles M. Vest, President Emeritus of MIT; George Peterson, executive director of ABET Inc.; Theodore C. Kennedy, founder of BE&K Inc.; Jacquelyn F. Sullivan, codirector of the Integrated Teaching and Learning Laboratory at the University of Colorado; and Susan Ambrose, associate provost for education and director of the Eberly Center for Teaching Excellence at Carnegie Mellon University. In the afternoon, members and foreign associates participated in NAE section meetings at the Keck Center. The final event that evening was the annual reception and dinner dance, held at the Andrew W. Mellon Auditorium. Music was provided by the Radio King Orchestra.

The next annual meeting is scheduled for October 15–16, 2006.
Some of you may have heard about the DARPA grand challenge—autonomous, computing vehicles attempting to navigate a 130-mile course through the desert near Las Vegas. These specially equipped vehicles are totally computer driven, with no onboard human intervention. Last year, the Carnegie Mellon vehicle, which led the race, went a total of 7.5 miles but eventually ran off the road. No vehicles finished the course last year, but even 7.5 miles was a great accomplishment. This year, five vehicles finished the entire 130-mile course, which is quite an engineering achievement. It also shows the tremendous improvement and accomplishment in just one year.

I noted with interest that, coincident with the induction of the NAE class of 2005, the National Academies has released a new report (Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future) on competitive challenges the United States faces going forward. Although the report focuses on this country, I think it has equal application to just about every other established economy in the world today. The report talks about competition—economic competition—going forward. And if you translate that, very simply, economic progress and economic strength translate to standard of living, which is something we are all interested in. The report lists three general areas of significance for the strength of any country or any economy: (1) education, (2) the creation of ideas, and (3) an environment where educated people can take ideas and create new products, new services, and new businesses that drive economic growth and a better standard of living.

The report discusses in detail each of those areas and focuses on actions we must take for the United States to remain competitive. I will talk very briefly about some of those actions. I hope this will encourage new members of the Academy to join with existing members to make some of these things happen.

The first issue is education. In recent rankings of universities, the United States has 18 of the top 20 and 35 of the top 50 universities in the world in a semi-quantitative ranking system. The free competition of our university system continues to serve us well, even though there is increased competition from some prestigious foreign universities.

I urge you to support the recommendations in the report on K–12 education, which, I think, is first, second, and third on the list of priorities. The ability of any country to educate its young people, especially in math and science, is absolutely key to its success. All of us must raise our voices, collectively, to local officials, state officials, and national officials. I don’t see how our economy can continue to thrive with a 30-percent dropout rate and an inability to educate young people to be competent in math and science.

The second issue is the generation of ideas. Ideas are typically generated through research and development (R&D) efforts and expenditures. The good news is that the United States still has the premier basic research operation in the world—our research universities, which are funded primarily by the federal government, but also by local governments and private industry. But funding in physical sciences comes primarily from the National Science Foundation, and some from the U.S. Department of Energy. For about the last two decades, funding for basic research in the physical sciences in the United States has been flat in absolute dollars, roughly $5 billion spent in our major universities.
To put that into perspective, Intel Corporation alone spends $5.5 billion, not only on basic research, but on total research. And Intel is not alone. Companies like Microsoft and IBM spend equal amounts. The fact that one company can spend as much on R&D as the entire federal government of the United States is troubling. The new Academies report recommends a substantial increase in funding for basic research to keep our universities at the top. I encourage you all to support that recommendation.

Ironically, the United States spends roughly $25 billion a year on agricultural subsidies, five times the amount we spend on basic R&D in physical sciences. Is it better to fund the industries of the nineteenth century than the industries of the twenty-first century? If you talk to a congressman, ask him why we spend $25 billion to support traditional industries like agriculture at the expense of basic R&D.

The third area is creating and fostering an environment for innovation. A number of topics are included in this area, from patent systems to communication laws, rules, and regulations that have inhibited the proliferation of broadband conductivity in the United States. The United States now ranks about 15th per capita in terms of broadband penetration. If you assume that the Internet is the vehicle for information access, communication, and decision-making going forward, then you realize we are at a disadvantage. It is unfortunate that every small business, every home, and every large business in the United States is not yet connected with broadband capability. I encourage you to support the recommendations in the report related to increasing our broadband capability.

I want to leave you with this thought: The Irish poet, William Butler Yeats, talked about education in a simple, yet profound, way. He said education is not like filling a pail but like lighting a fire. The challenge for our society is to light that fire in every young child in the United States and give every child an opportunity to grow to his or her full potential.

As an engineer, I’ve never before quoted two poets in the same speech, but this poem is appropriate here. The poet is Will Allen Dromgoole. Actually, Will was a she—a Tennessean who lived in the late 1800s and was writing poetry about the time the National Academies was created. The title of the poem, appropriate for the National Academy of Engineering, is “The Bridge Builder.”

An old man, going a lone highway,  
Came, at the evening, cold and gray,  
To a chasm, vast, and deep, and wide,  
Through which was flowing a sullen tide.

The old man crossed in the twilight dim;  
The sullen stream had no fears for him;  
But he turned, when safe on the other side,  
And built a bridge to span the tide.

“Old man,” said a fellow pilgrim, near,  
“You are wasting strength with building here;  
Your journey will end with the ending day;  
You never again must pass this way;  
You have crossed the chasm, deep and wide.  
Why build you a bridge at the eventide?”

The builder lifted his old gray head:  
“Good friend, in the path I have come,” he said,  
“There followeth after me today,  
A youth, whose feet must pass this way.  
This chasm, that has been naught to me,  
To that fair-haired youth may a pitfall be.  
He, too, must cross in the twilight dim;  
Good friend, I am building the bridge for him.”

I think our task at the National Academies is to follow the advice in that poem, to build a bridge for the next generation.
These remarks were delivered on October 9, 2005, at the NAE Annual Meeting.

It is an immense honor to welcome once again our new members and foreign associates. The knowledge and experience you bring to the academy enables us to continue to play a unique role in service to our democracy. The academy is renewed and enriched by each new class. I also want to acknowledge the families and friends of the new members, whose support has been essential to every inductee.

My topic this year is what I believe the nation must do to prosper in the 21st century. By any objective measure, the United States is in great shape! We are the only superpower, our economy is the largest in the world and growing nicely, both unemployment and inflation are low, and we are dominant in most areas of science, technology, and high-tech industry.

Engineers have been responsible for much of that dominance and the resulting prosperity. There is no better way to convey the impact of engineers on our quality of life than by reading a list of the 20 greatest engineering achievements of the twentieth century. You can find the full list in A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives. But consider this.

In 1900, almost no home had electricity; very few people had automobiles, and there were just a few tens of miles of paved road in the entire country; the first airplane had not been flown; the average life expectancy was 46 (it’s now 77, and 20 of the additional 31 years are attributable to clean water and sanitation); almost no one had a telephone; there was no refrigeration, radio, TV, or antibiotics; and, of course, there were no computers, Internet, or satellites. In 1900, 50 percent of the U.S. population lived on farms, and it took that many to feed the other 50 percent. Today, 2 percent live on farms and feed not only the other 98 percent, but also a good number of folks overseas. And the list goes on . . .

The phenomenal transformation of our quality of life has been fueled by innovations created by engineers, and the pace of innovation, if anything, is accelerating. Many of us have believed that the United States has been a particularly fertile place for innovation. Our great research universities have created streams of new knowledge and provided educated engineers to exploit that knowledge. We have had a ready supply of capital, and our culture encourages risk taking.

The Flat, Global Playing Field

The world is not static, however, and recent books and reports have begun to raise warning flags that the status quo in the United States will not suffice for us to continue to prosper. I expect you have either read or heard about Tom Friedman’s book, The World Is Flat: A Brief History of the Twenty-first Century (Farrar, Straus and Giroux, 2005). Friedman’s premise is that the (economic) playing field has become more level—flatter in his parlance—and off-shoring, outsourcing, and Lou Dobbs’ “Exporting of America” are all manifestations of this. Flattening, Friedman argues, has happened because it is now technologically possible to locate call centers in the Philippines, coordinate the complex supply chains and work flows that enable manufacturing in China, and perform “back office” work in India, including having Indian radiologists read x-rays and CAT scans taken in U.S. hospitals.

Friedman is not the first one to say these things, nor is his analysis impeccable. But he has captured the attention of the country. He lists ten “flatteners” that have led to the leveling of the economic playing field—nine of which are technologies we (engineers) created. Engineers made possible, and now real, what many believe is a serious problem for the United States—competition on a rough-and-tumble, flat playing field.

Friedman argues that, despite the dangers, the trend toward a flat world is a good thing, both economically and geopolitically. Lower costs benefit consumers and shareholders in developed and developing countries alike, and a rising middle class in India and China will become consumers of their own products, and ours. That same rising middle class has a growing stake
in frictionless international commerce—and hence in stability, peace, and the rule of law. But, he says, there will be problems during the transition, and whether global flatness will be good for any particular country will depend on whether that country is prepared to compete on the new global playing field.

A few lines at the very end of Chapter 6 inspired me to choose this topic. “But have we [the United States] really been investing in our future and preparing our children the way we need to for the race ahead? . . . The answer is no.” When I combine those lines with the fact that engineers are the ones who created the enablers of a flat world, I can’t help but think that we have a responsibility to prepare the United States to play on a flat field.

NAE recently released Engineering Research and America’s Future, a study chaired by Jim Duderstadt, former president of the University of Michigan. The report documents the decline of (1) federal support for research in the physical sciences and engineering; (2) the number of U.S. students in physical sciences and engineering (the United States actually produces only 7 percent of new engineers in the world); (3) the U.S. share of papers and patents; and (4) the U.S. capacity for innovation.

Another report, Rising Above the Gathering Storm, issued by the National Research Council on October 12, also documents how the global innovation environment is changing. Chaired by NAE member Norm Augustine, the report was produced by a committee of CEOs, university presidents, and Nobel laureates. Backed by copious data, the report provides a reasoned discussion of why the strategies by which the United States achieved its current leadership position are no longer sufficient—and perhaps not even appropriate—in a globalized world.

Most Americans instinctively know that the way to prosper is to innovate. But innovation means change, and change can be difficult, especially when you are on top. As Charles Darwin said, “It is not the strongest of the species that survives, nor the most intelligent, but rather the one most adaptable to change.”

Clayton Christenson, the author of The Innovator’s Dilemma (Collins, 2003), noted that the best run companies are often the most resistant to new, “disruptive” technologies. It is no accident that only one of the 100 largest U.S. firms in 1900 was still on the list in 2000. Ironically, the most dangerous place to be seems to be at the top—for both companies and countries. It is hard for the leaders to change because what they have been doing is what got them to the top and because a large vocal cadre believes that deviating from the current course will lead to disaster. Therefore, the tendency is to circle the wagons—to protect the current advantage!

A recent experience will illustrate this kind of thinking. A few weeks ago, I testified before the House Subcommittee of the Judiciary Committee responsible for immigration. The subject was foreign-born students, especially in the physical sciences and engineering. Here are a few undisputed facts: between 1980 and 2000, the percentage of Ph.D. scientists and engineers employed in the United States who were born abroad increased from 24 percent to 37 percent; the percentage of foreign-born Ph.D. engineering students today is close to 60 percent; one-fourth of the engineering faculty at U.S. universities was born abroad; and from 1990 to 2004, more than one-third of Nobel Prizes in the United States were awarded to foreign-born scientists. To me those facts suggest that we have been skimming the best and brightest from around the world and that much of our prosperity is the result of our access to that incredible talent pool.

At a congressional hearing, only the congressmen get to ask questions, of course, so I don’t know their opinions. But reading between the lines, it seemed to me that many of the subcommittee members had a different take on these facts—namely that every foreign student is a potential spy trying to steal our technology and that the United States would be better off if there were no foreign students at American universities. One congressman said explicitly that if there were no foreign students, there would be room for all of the U.S. students who want to be scientists and engineers but can’t get into college.

I was stunned. Like the corporate types who cling to the notion that they are doing the right thing, these representatives obviously believe that the United States is the sole possessor of leading technology and the sole source of talent that can produce the next important ideas. So, let’s circle the wagons and make visas to study in the United States even harder to get!

What would have happened if that had been the prevailing attitude in the past? Fifty years ago many of our scientific leaders came from Europe—Einstein, Fermi, and Teller (without whom we might not have been the first to build the atomic bomb), von Braun (without whom we might not have ascendant in rockets and space), and von Neumann (without whom we might not be
Collectively encourages, or discourage, innovation. A few of the components of this environment are a vibrant research base; an educated workforce; a culture that permits, even encourages, risk-taking; a social climate that attracts the best and brightest from anywhere in the world to practice engineering; “patient capital” available to the entrepreneur; tax laws that reward investment; appropriate protections for intellectual property; and laws and regulations that protect the public while encouraging experimentation. We must do better in every one of these areas.

**Priority Areas for Improvement**

First, the erosion of our physical sciences and engineering research base and the increasing focus on short-term results will lead to a long-term decline in the quality of U.S. research capability. It takes 15 years for ideas to make their way from research laboratories to products, so the consequences of this neglect will not be apparent for a long time. When they do become apparent, even assuming we can muster the political will to reverse the decline, it will take a long time to undo the damage. Alas, it is clear that physical sciences and engineering research is not a current public priority, and hence not a priority of our government. Only the federal government can reverse this decline—by increasing funding for university research and providing incentives for industry-funded research.

Second, we must ensure the high quality of the workforce. This is our problem, and we, the engineering community, have the ability to fix it! A little money would probably help, but even without money, we can change a great deal. I have been calling for reform in engineering education since I became NAE president, and I think we have moved the ball down the field a ways. But not nearly far enough. We will not be able to compete with Chinese and Indian engineers on price, so we must make sure our engineers are worth five times as much. We can only do that by reforming engineering education.

Third, we must provide a nurturing social climate for U.S.-born students to pursue careers in physical sciences and engineering. The proportion of U.S. undergraduate students studying engineering is the lowest in the developed world—4 to 5 percent, as opposed to 12 to 13 percent in most European countries and more than 40 percent in China. The U.S. currently produces only 7 percent of new engineers in the world each year. Although engineering has historically been considered a pathway to upward economic mobility and, for decades, classes were overwhelmingly populated with immigrants and their offspring, minorities are largely absent from our engineering classes today.

Clearly, young people do not consider engineering an inviting, interesting, and rewarding occupation. That is partly perception and partly reality. Yes, K–12 teachers, counselors, and many parents are not well informed about engineering as a career and do not urge their charges to consider engineering as a career. And yes, there is an incorrect stereotype of engineers as geeks and nerds. And yes again, we have been incorrectly blamed for causing some environmental problems. But, we have also contributed to the uninviting image with our boot-camp style of curriculum and our nineteenth-century pedagogy!

Strategies for the Future

There is a widespread consensus that innovation is critical to our future prosperity. In my view, there is no simple formula for innovation. A multicomponent “environment” leaders in computing and information technology). Today, Europeans aren’t the only ones contributing to our prosperity and our security—think of Praveen Chaudhary (now director of Brookhaven National Laboratory); C.N. Yang (Nobel laureate physicist, from the Institute for Advanced Study in Princeton); and Elias Zerhouni (who was born in Algeria and is now the director of the National Institutes of Health). There are also an enormous number of journeyman scientists and engineers whose individual contributions will never be as celebrated, but without whom the United States would be neither as prosperous nor as secure as it is today.

Some of you saw my article in the fall issue of The Bridge in which I characterized the issue of visas for foreign students as just one tile in a mosaic that depicts short-term thinking, attempts to preserve the status quo, and a lack of long-term investment—in short, exactly the kind of thinking that Christensen argues dooms industry-leading, good companies that fail to adopt disruptive technologies.

I don’t have time to discuss all of the tiles in this mosaic, but I’ll just mention a few: proposed new policies for handling “deemed exports”; the creation of an undefined class of sensitive, but unclassified, information; and continuing reductions in federal support for research in physical sciences and engineering in favor of support for more short-term research.
Fourth, we must provide a welcoming social climate for international students and scholars. As most of you know, after 9/11, the United States imposed stringent requirements on students—even senior scholars—for getting visas to enter the United States. Thanks to the efforts of the National Academies and others, the average time for processing a student visa is now less than two weeks. However, that is not the whole story.

Even though the average time is less than two weeks, there is a long tail on the distribution—and many visas still take a year. Moreover, the process, both at the embassy and at the border, can be demeaning. International press reports tend to focus not on the average time to process a visa request, but rather on the extreme cases. More worrisome than the visa situation itself is that, in just a few years, the image of the United States abroad has changed from an inviting “land of opportunity” to a hostile, xenophobic country. The best and brightest have other options—and they are taking them!

The U.S. government must change this. Fortunately, it will cost nothing, but we have to make the case.

Finally, I alluded earlier to a multi-component environment that supports innovation. Some aspects of this environment were created in the context of technologies of the past, and today they are being strained to the breaking point to cope with emerging technologies. Here are some examples. First, the double-blind clinical trial, considered the gold standard of the FDA approval process, is not well suited to ensuring the efficacy and safety of emerging “designer drugs,” that is, drugs created to treat a specific disease in a specific patient. Second, the intellectual property system, which was designed for macroscopic, physical machines, is being strained, to say the least, when applied to sequences of microscopic DNA. Third, antitrust laws that were designed to break up railroad and steel monopolies are being applied to software companies.

In my remaining two years as NAE president, I hope to find a way for the National Academies to review all aspects of the environment that will support innovation with a view to suggesting reforms and renewals in light of current technology.

**Conclusion**

My message today can be summed up simply. The United States is enormously prosperous, in no small measure because of the innovative contributions of engineers. In the process of developing the very technologies that have made us prosperous, however, we have also enabled others to compete with us on a more level playing field. This is generally a good thing, because a rising tide lifts all ships, and a more prosperous world will surely be a safer world. But the strategies that helped us get to the top are not the ones that will lead us to greater security, prosperity, and health in the future. As difficult and uncomfortable as it is, we must change—and we must do it before it is too late. Some of what needs to be done is under our control or can be influenced by us. Therefore, it’s time we got started. Like NOW!
The 2005 National Academy of Engineering Founders Award was presented to C. Dan Mote Jr., president of the University of Maryland and Glenn L. Martin Institute Professor of Engineering. Dr. Mote was honored “for the creation of a comprehensive body of work on the dynamics of moving flexible structures and for leadership in academia.” These remarks were delivered on October 9, 2005, at the Annual Meeting of the National Academy of Engineering.

On the day of my induction into the Academy, I sat out in the auditorium, inspired by the entire Academy enterprise, especially by its members, its responsibilities, its opportunities, and indeed its mandate to leadership in the most advanced technological society in history. I haven’t gotten over all that yet. And over the years since, the Academy has gotten stronger, more confident, and more active in fulfilling its responsibilities.

On my induction day, Gordon Moore received the Founders Award in recognition of his remarkable accomplishments. I recall thinking that it was indeed a fitting tribute to Moore, but that I would sooner be elected president of the United States than qualify for it myself. Actually, I feel the same way at this moment. This is a truly humbling experience.

As is customary, the Founders awardee offers some comments to the captive audience that has some obligation to listen, if the remarks are short enough. That, I can promise. This may be an opportunity to offer you a nontraditional thought. As my friends lament, I seem to have a few of them, but one in particular has gnawed at me for decades and this may be an opportunity to put it before you.

While in high school I drove a delivery truck for a fuel and ice company in my hometown. On my last day on the job, after dropping off a 50 pound sack of ice cubes at a local bar, I told the proprietress I was quitting my job and going to Berkeley to become an engineer. She responded, “Hey, that’s great. Those driv’n jobs pay real good.” At the time I thought she was a little out of touch. I was so young I didn’t get the underlying message.

Ever since then, I have been continually amazed by questions like “what do engineers do?” and “what is engineering?” In the 1970s, I ran the undergraduate mechanical engineering program at Berkeley and heard these questions all the time from anxious parents and bewildered students. I used to say, “Look at everything around you. If you didn’t dig it out of the ground or grow it, it’s engineering.” Now even growing it is probably engineering, too.

It is impossible to exaggerate the importance of engineering in our society. How could something so obvious, so omnipresent, and so increasingly critical to the future of the world, let alone to each of us individually, remain so obscure to so many smart people—even the majority of people? Compounding the confusion is that essentially every engineering professional society has been promoting the public understanding of engineering for decades. It is a plank in every professional society mission statement and an item on every annual agenda. These societies have put time and money into improving public understanding of engineering through books, photographs, TV programs, our own A Century of Innovation coffee-table book, and other truly marvelous stuff. We deserve an A+ for effort for sure.

But still, most of us agree, the patently obvious remains remarkably obscure. Highly educated people, and many on our university campuses
too, still ask, “What is engineering?” They simply don’t get it.

So we have to face the reality that so far the “public understanding of engineering” theme has not sold well. If we were a business selling that product, we would have gone bankrupt long ago. Still, we persist, possibly because it seems like the right thing to do, or possibly because nobody has a better idea, or possibly because we don’t really care.

My wife once went shopping with a friend who bought scarves for her daughters. When asked if her daughters wore scarves, her friend said no . . . but they should! Does that remind you of anything? Our public understanding theme seems to fit Einstein’s definition of insanity fairly well. He noted that, “Insanity is doing the same thing over and over again and expecting different results.”

So why hasn’t it worked? Why does the public still not get it? That might be a good place to start. I can only speculate, because this is obviously a difficult question. But I will tell you what I think.

I believe the phrase itself, “public understanding of engineering,” projects the problem. The statement characterizes a divide between engineering and the public that has to be bridged. Ironically, the statement is an engineering concept in itself (as is the Academy logo) that fosters the idea that “engineering” is represented by engineers on one side of the bridge and the “public” is represented by everybody else on the other side. It says that we engineers on this side need to teach them over on the other side about the values of engineering. “Public understanding of engineering” is framed as a “them and us” concept. Furthermore, it seems that both engineers and the public have accepted the “them and us” idea.

Our acceptance of it shows up in various ways, like engineering curricula at universities that favor technical/scientific topics and place less emphasis on humanistic and social sciences. It shows up in Dilbert cartoon characters, whose dress, wit, and cynicism signal them as engineers. It shows up in the “nerd characterization” that many engineers, and the public, use to describe the bright, eccentric, antisocial characters who can do things but are a little strange. We don’t mind it. Actually, we like it. An engineer as highly organized but lightly humanized is widely accepted. Just recently at a charity event in Washington, a CEO expressed surprise to me that an engineer could serve as a president of a public university. I mean, it’s so public, I heard! And that was not the first time, either.

Many of us lament that the engineering profession is not well represented in Congress. But we are more likely to fault Congress for this deficiency than to fault ourselves. Congress is more them than us. I don’t recall us ever deciding to get after this problem.

I have long suspected that this them and us positioning has kept the public distant from engineering. The society’s deepening technological base has excavated the divide rather than bridged it. If we engineers decided to be a part of the public, felt a part of the public, and were seen as part of the public, the task of improving the public understanding of engineering might be more successful. After all, in that case we would be them.

It seems that a necessary first step in solving this problem might be a mission plank titled “Engineering Understanding of the Public.” The better we understand the public, the more likely we will come up with an efficacious method of improving its understanding of all sorts of things . . . including engineering. Our understanding of the public would lead us to new problems and new values for engineering, possibly even new commitments for the Academy.

On Earth Day 1970, Pogo remarked, “We have met the enemy, and he is us.” I wonder if Pogo was an engineer. But alas, we are who we are, although we can also shape what we will become. It’s the latter thought that offers me hope.

Thank you for your patient attention and the truly esteemed honor conferred by the 2005 Founders Award.

The Founders Award was established in 1965 by the National Academy of Engineering to honor an outstanding NAE member or foreign associate who has upheld the ideals and principles of NAE through professional, educational, and personal achievement and accomplishment. For further information, contact the NAE Awards Office at (202) 334-1237.
2005 Bueche Award Acceptance Remarks: Some Issues Affecting Science and Technology Policy

Craig Barrett, Leo Young, Wm. A. Wulf, and Paul Peercy.

The 2005 Arthur M. Bueche Award was presented to Leo Young, director of research (retired), Office of the Secretary of Defense, U.S. Department of Defense, for “sponsoring collaborative research programs among academic, industrial, and government engineers and scientists.” These remarks were delivered on October 9, 2005, during the Annual Meeting of the National Academy of Engineering.

I want to express my sincere thanks to the Academy for honoring me with the Arthur M. Bueche Award for contributions to science and technology policy. I met Dr. Bueche more than 25 years ago when he gave a talk at an annual IEEE technology policy conference here in Washington. I had no inkling then that one day you would bestow on me an award in his name.

I could not have received this award without the help and cooperation of many dedicated co-workers and the opportunities provided by my employers. In the interests of full disclosure, the five employers with whom I have been associated in the last 52 years are Westinghouse Electric Corporation, Stanford Research Institute, the Naval Research Laboratory, the U.S. Department of Defense (DOD), and, since retirement from full-time employment, as consultant to Filtronic.

Thus, my career in research and development has spanned all three sectors—government, academia, and industry. Much of my work has been in basic research, where the government is usually the largest bill payer, academia is the major performer, and industry is the chief beneficiary. I would like to give you three examples of science and technology policy issues that I have encountered in my career in basic research.

1. People sometimes ask: “If industry is the chief beneficiary of basic research, why should the federal government pay most of the cost?” The answer lies in the nature of basic research—its outputs are knowledge and understanding that are retained mainly in the mind of the investigator, who is free to leave Company A, which might have paid for the work, and join Company B, which competes with Company A and never intended to support its competitor. Naturally, Company A prefers to let the government pay for its basic research. The federal government in turn is motivated to pursue its basic research goals wherever it can find the most competent scientists and engineers, regardless of affiliation.

2. My second example concerns secrecy versus openness in science and technology. This issue has been addressed at length by committees I have served on at both the National Academies and the American Association for the Advancement of Science. You have probably admired the childlike statue of Einstein in front of this Academy building; you may even have noticed the three quotations from Einstein’s writings that are inscribed on the stone wall behind the statue. One of them reads as follows: “The right to search for truth implies also a duty; one must not conceal any part of what one has recognized to be true.” This is in direct contrast to the Code of Ethics of the National Society of Professional Engineers, which states in part: “Engineers shall not reveal facts, data, or information without the prior consent of the client or employer . . . ”
Both statements make sense in context, so I don’t think there is a major problem in the broad outlines of policy. However, the devil is in the details. Industry has proprietary interests in competitive products or process developments. Similarly, academic scientists competing for publication priorities or Nobel prizes have been known to be even less forthcoming than engineers, in spite of Einstein’s admonition. For examples, just read what two Nobel laureates have written, biologist James Watson in his book, *The Double Helix: A Personal Account of the Discovery of the Structure of DNA* (Simon & Schuster, 1998) and physicist Charles Townes in his book, *How the Laser Happened: Adventures of a Scientist* (Oxford University Press, 2002).

3. Now let’s return to the issue of funding for basic research, which may escalate to a major policy issue buried in a relatively minor budget detail that can have unintended consequences. DOD budgeted $1.5 billion for basic research for fiscal 2005. However, for fiscal 2006, DOD submitted to Congress a budget request of just $1.3 billion for basic research, that’s $200 million less (13 percent less, not counting inflation). Since DOD concentrates much more heavily on engineering than other agencies that sponsor research in science and technology, cutting the DOD basic research program will disproportionately cut into university research in engineering, although that was surely not the intention of the budget cutters. This is a policy issue that concerns this Academy and that Congress needs to address.

A final word. Policy gurus and research directors must endeavor to see the science and technology picture as a whole, to look for unexpected or unintended consequences of policy changes, to ensure open communications in fundamental research, to promote multidisciplinary research, and to encourage contact and cooperation among government, academia, and industry, which often boils down to something as simple as showing respect for, and understanding of, another person’s point of view.

Thank you for your attention.

The NAE Council established the Arthur M. Bueche Award in 1983 to honor statesmanship in science and technology. Arthur M. Bueche was senior vice president for corporate technology at General Electric and a member of the NAE Council who spoke out for the advancement of technology.
On February 20, 2005, the National Academy of Engineering recognized the achievements of the Engineering Projects in Community Service (EPICS) Program with the Bernard M. Gordon Prize for Innovation in Engineering and Technology Education. The lecture was delivered by Edward Coyle on behalf of the EPICS team.

My colleagues, Leah Jamieson and Bill Oakes, are sitting with you in the audience . . . but are with me in spirit here on the stage. As founders and directors of the EPICS (Engineering Projects in Community Service) Program, it is a great pleasure for us to be here to present the Gordon Prize recipient lecture.

The three of us once again thank the National Academy of Engineering, Mr. and Mrs. Gordon, and the Gordon Foundation for choosing the EPICS Program for this honor. We also thank you for creating this superb prize, which fosters innovations in engineering education that are critical to preparing engineering students at Purdue and elsewhere for the challenges they will face in the coming decades. With our students in mind, we will present an overview of the EPICS Program, describe the needs it was designed to address and its success in meeting those needs, and identify the challenges facing EPICS and other innovative programs.

EPICS was created as a result of discussions about the state of undergraduate engineering education in the early 1990s. At the time, the engineering education community was drawing fire from industry and elsewhere for graduating students with strong technical backgrounds but few of the other skills they needed for successful careers. The consensus was that students needed professional skills, such as the ability to work in a team environment, communicate effectively, work with customers, and manage projects; awareness of the many issues that affect engineering projects, including ethical, legal, and environmental issues; and the ability to work with people from many different backgrounds and in many social settings.

The challenge to educators was that teaching these skills is notoriously difficult in a traditional engineering curriculum. Therefore, we needed a new curricular structure that would not only continue to provide technical depth, but would also provide experiences that would build these additional capabilities.

At about the same time, community service organizations were faced with having to take advantage of technology to improve, coordinate, account for, and deliver services to the people who depend on them. Their challenge was to find long-term, low-cost, customized technical assistance.

EPICS was created out of the realization that these mutual needs provided a unique opportunity for long-term partnerships between the university and the community. Ideally, these partnerships would provide two benefits: (1) academic credit for significant learning opportunities for engineering students via long-term, large-scale, real-world design projects that would benefit the community; and (2) access for community partners to the low-cost technical expertise they need to improve their capabilities to serve the community.

The combination of challenging engineering design projects and long-term service to the community has proven to be extremely successful. EPICS students are learning both the technical and professional skills they need . . . and the products they develop and deliver are being used every day by their partners in the community. Perhaps the most compelling measure of success has been the dissemination of the EPICS model. In just 10 years, 15 other universities have adopted it. In addition, many EPICS alumni have remained involved with the program.
Examples of EPICS Projects

EPICS projects fall into four broad categories: education and outreach, human services, access and abilities, and the environment. We have chosen three of the more than 200 projects around the world to profile. Taken together, these three projects illustrate the technical depth, multidisciplinary breadth, and community impact of EPICS and demonstrate how it has been adapted for different environments.

The Imagination Station Project at Purdue University

This education and outreach project is based at Purdue University. The community partner, the Imagination Station, is a science and space museum in Lafayette, Indiana, that provides hands-on science, space, and technology experiences to stimulate young minds. The museum offers a variety of interactive displays, many of which were developed by Purdue EPICS teams.

The projects developed with and delivered to Imagination Station cover a very wide range of disciplines, including electromagnetism, aerodynamics, and hydrology. For example, an interactive wind tunnel was designed and created by an EPICS team to provide elementary-school children with an opportunity to learn about aerodynamics. The wind tunnel has a removable test section with different interactive modules illustrating the principles of lift and drag.

Another project, called the Mag Racer, teaches children about electromagnetism. It consists of a magnetic car inside a tube-shaped track that runs through a series of electromagnets. The kids try different strategies for activating the electromagnets to figure out how to make the car race down the length of the track. With practice, they can make the car really zip down the track!

The OLJMG Joint Services Project at Bedford-North Lawrence High School

The second example is an access and abilities project in the EPICS program at Bedford-North Lawrence (BNL) High School in Bedford, Indiana. The community partner, OLJMG Joint Services, is a five-county agency that coordinates special education in the North Lawrence Community School System. This is the first EPICS program not associated with a university.

We are proud to say that this project was started by EPICS alums who had taken jobs near Bedford. Working with their employers, the Crane Division of the Naval Surface Warfare Center and Visteon, and with teachers at the local secondary school, they created the first high school EPICS program. The commitment of these alums to continued service to the community demonstrates the long-term impact of EPICS on the lives of our students.

In this project, high school students developed a system consisting of several devices to enable a fellow student with cerebral palsy to sense when she needs to swallow in order to avoid drooling. One device, which measures the time between swallows, is integrated into an inconspicuous necklace. If the time between swallows does become too long, another device worn on the wrist or the waist can either vibrate or make a noise to remind her to swallow. This is clearly an innovative device—the students found nothing else like it, despite diligent patent and product searches.

This brings us to a new aspect of the EPICS Program—the EPICS Entrepreneurship Initiative, which is intended to spread the benefits of EPICS products by commercializing the ones that address the most significant unmet needs. The potential of products is determined via an annual product-feasibility competition called the EPICS Idea-to-Product Competition.

The BNL EPICS team’s system won second place in the competition last April. They used the funds they won to file a provisional patent on their product. Not bad for kids still in high school! Imagine what they might do once they have engineering degrees!

The Waiheke Island Waste Resource Trust Project at the University of Auckland

The dissemination of the EPICS Program made a great leap forward with the addition this past year of our first international site at the University of Auckland in New Zealand. Our third example, an environmental project, is from this new site.

Two teams from the Auckland EPICS program are working with the Waiheke Island Resource Trust to improve the environment and economy of the island. One team is developing a portable glass-crushing plant to process waste glass collected on the island into clean sand for use in construction materials. This project is turning a waste product that would otherwise have to be shipped off the island into an economic resource. A second team is developing a pilot facility for processing waste cooking oils, primarily from restaurants on the island, into biodiesel. A potential pollutant is thus being turned into an alternative fuel for municipal vehicles.
The Curricular Structure of EPICS

The unique curricular structure of EPICS enables our teams to design and deliver many different products to their community partners. Some EPICS teams have been in operation for as long as 10 years and have delivered many projects to their partners.

The EPICS curriculum is implemented as a “track” of courses, and an EPICS team corresponds to a division or lab section of a course. Each team has 10 to 20 students and is vertically integrated—that is, composed of freshmen, sophomores, juniors, and seniors. A student may be a member for up to four years, registering for one or two credits each semester. When seniors graduate, returning students move up a year and new students are added to the team. Many teams have even developed training processes for new members. The large team size, vertical integration, and credit structure enable a team to continue with some returning students each semester and each year. In effect, each team functions as a small engineering design firm with the community partner as its customer. This enables our teams to tackle and complete projects of significant size, complexity, and impact in the community.

EPICS began in electrical and computer engineering, but good solutions to real problems almost always require contributions from other disciplines. Thus, EPICS spread rapidly to other areas of engineering—first mechanical engineering, then civil engineering, and so on. It also spread to disciplines outside of engineering—to computer science, sociology, and then to many other disciplines. EPICS teams advertise each semester for the students and disciplines they need for their projects.

From an educational point of view, the long-term continuity of EPICS teams enables students to experience the whole design cycle, from problem definition through support of fielded projects. The EPICS Entrepreneurship Initiative takes this cycle one step further by providing opportunities for our students to learn about and pursue the commercialization of the products they create.

The long-term continuity of projects also enables each student to play different roles on the team. As new members, they are trained in their team’s technologies and processes by returning members. As seniors, they are often leaders of subteams or the entire team.

A Brief History of the EPICS Program

EPICS was launched at Purdue in the fall of 1995 and now has 30 teams and a total enrollment of more than 300 students per year. More than 2,000 students have participated at Purdue, and in a typical semester more than 20 disciplines are represented. The teams have delivered more than 200 projects to the Lafayette, Indiana, community.

EPICS has been named an exemplary program by the National Science Foundation (NSF) Corporate and Foundation Alliance. Its dissemination has been supported by NSF, the Corporation for National and Community Service, and several corporate partners. With this support, EPICS programs have been created at 15 additional universities and one high school.

But this is just the beginning. We hope that the recognition brought to EPICS by the Gordon Prize will accelerate its dissemination. Toward this end, the three of us have donated our personal portions of the Gordon Prize to create an endowment for EPICS. We also continue to work with schools that want to start new programs, particularly through an annual conference at which representatives of current programs share their experiences. When we talk with other schools about EPICS, we emphasize major themes woven into a student’s EPICS experience. Two of the most important themes are context and time.

The Context Theme

Long-term community partnerships have created a context for compelling projects that can engage students and hold their interest and commitment over the course of several semesters and years. Because projects are defined by needs identified by the community, the students know that, if the project is done well, it will be put to use. This adds the very important dimensions of responsibility, accountability, and commitment, which help students mature as individuals, as engineers, and as citizens.

Students must also address key questions. Will an exhibit for a children’s museum be able to withstand the use and abuse of hundreds of children over a period of many months? Will an upgraded software interface enable social-service workers to work more efficiently or will it slow them down—or, even worse, annoy them? Will a system meant to detect and reward good posture in young children with cerebral palsy measurably improve their posture? These kinds of questions rarely arise—and certainly cannot be answered—in project-based courses that do not have real customers. Yet, only by answering
these questions do students learn if they are really making a difference in the world.

The Time Theme

Very few real-world projects fit neatly into 15-week semesters or 30-week academic years. One of the most innovative aspects of the EPICS curriculum is that it enables project teams to bridge these artificial boundaries. Our teams have time to deliver well designed, well-tested projects, to gather feedback and improve their designs, and to work with their community partners to identify new opportunities.

From the students’ perspective, extended participation on an EPICS team gives them time to learn both disciplinary depth and multidisciplinary breadth. It also gives them time to gain a sense of the role of engineering in society, develop self- and team-awareness, and master a wide range of professional skills. The long-term participation of advisors, as well as students, provides many opportunities for mentoring. One of the greatest rewards of advising an EPICS team is getting to know students well and watching them develop throughout their academic careers.

Thoughts for the Future of Engineering Education

Long-term, large-scale, community-based projects have been a very effective way of providing students with many of the educational experiences they need to prepare them for their careers. EPICS has thus successfully addressed many of the challenges for which it was designed.

Of course, as we all know, the world changes and the challenges facing engineers continue to evolve . . . and we must evolve with them. To keep up with these changes, we must identify new challenges for engineering education, determine how the EPICS Program can provide insights into those challenges, and be aware of what else lies ahead.

Integrating Diverse Skills into the Curriculum

As demands on engineering education increase, we must ask ourselves fundamental questions about how to design efficient, affordable curricula that will prepare our students for future careers. As more is expected of our graduates, we face what could be called a grand challenge for engineering education—how to integrate an increasing number of necessary skills—for example, analytical, problem-solving, design, and professional skills—into the curriculum. We believe that programs such as EPICS, which can integrate sometimes disparate components of the curriculum, can prepare students to meet these expectations.

We also believe that context and time will be key enablers of this integration for many reasons:

- It motivates learning of fundamentals via compelling applications.
- It provides a setting where students can bring both analysis and design to bear.
- It encourages students to learn on their own to meet the needs of their projects.
- It realizes efficiencies in the curriculum by continually building on past experience.
- It provides time that bridges semesters and years to weave connections between content knowledge and design skills.
- It takes advantage of compelling contexts to make students passionate about what they can achieve and, therefore, passionate about what they are learning.

Changing the Face of Engineering

A second challenge facing engineering is the question of who will become an engineer. We are hopeful that EPICS partnerships between engineering and the community will not only transform our students, but will also help transform the face of engineering.

Since the early 1990s, the United States, as a nation, has made almost no progress in diversifying engineering in some key dimensions. There are fewer first-year female engineering students today than there were in 1990 and significantly fewer female students in computer science. EPICS, however, is resonating with young women.

There is a growing awareness that, for women and for students from some underrepresented groups, a major factor in career choice has to do with making a difference. However, engineering has not traditionally been thought of as one of the “caring professions.” But this is an image we can build, both for our students and for the community as a whole, through the results of our students’ work.

Conclusion

A fitting way to conclude this overview is with an anonymous quote from an end-of-semester course evaluation by an EPICS student at Purdue: “No longer is engineering just a bunch of equations. Now I see it as a means to help mankind.”

As William Butler Yeats said: “Education is not the filling of a pail but the lighting of a fire.” EPICS is clearly one of the matches that can light this fire.
Tammy Bosler was awarded a Ph.D. in physics from the University of California-Irvine (UCI) in October 2004. Her research was focused on observational astrophysics in the context of stellar spectroscopy, stellar evolution, and galaxy formation. Dr. Bosler also earned an M.S. from UCI and a B.A. in physics from Temple University in Philadelphia.

Tammy has a great deal of experience as an educator. She was coordinator of an astronomy and astrophysics outreach program at UCI, for which she created basic astronomy curricula and demonstrations for students from 3rd grade through high school. The goal of the program was to help schools that had low scores on standardized tests in math and science develop educational resources for educators and to stimulate interest in math and science. Tammy also taught physics and astronomy classes at UCI and was awarded a departmental award for teaching. She taught a course on thermodynamics at the University of Regensburg, Germany, and recently developed a two-day astronomy workshop for the general public, which was first presented in July 2005 at The Crossings: A Progressive Learning Center, Meeting Place, and Wellness Spa in Austin, Texas.

At NAE, Tammy is working at the Center for the Advancement of Scholarship on Engineering Education (CASEE) to develop the “Guide to Proposing and Managing NSF Engineering Education Projects” to promote gender equity in engineering. Her long-term goal is to contribute to the establishment of sound national and international science policy.

Amit S. Mistry is currently pursuing a Ph.D. in bioengineering at Rice University, where he also earned a B.S. in chemical engineering. His dissertation will address the degradation and biocompatibility of a polymer/ceramic nanocomposite bioengineered for the treatment of severe bone injuries. Amit has also taught chemistry, physical science, and algebra to high school students in an underserved community in New Orleans as a participant in Teach for America. Currently, he is a volunteer with Engineers Without Borders, where he works with other students to design and implement engineering technologies to improve the quality of life in developing countries. Amit also volunteers with Asha for Education, an organization that supports education projects in India.

At the National Academies, Amid hopes to work on broadening the study of science. He plans to combine his scientific knowledge with his policy experience gained at the Academies to pursue a career in science policy.
Camelia Owens is an Exxon-Mobil Scholar-in-Residence at the National Academy of Engineering Center for the Advancement of Scholarship on Engineering Education (CASEE). She received her B.S. from the University of Maryland Baltimore County (UMBC) and her Ph.D. from the University of Delaware, both in chemical engineering. Camelia’s thesis was focused on the development of an automated insulin delivery device for the management of blood glucose levels in people with Type 1 diabetes mellitus. During the past year (2004–2005), she was a visiting assistant professor in the Department of Chemical and Bio-chemical Engineering at UMBC. Her long-term goal is to work at the interface of technology and society to promote public knowledge of health issues.

At CASEE, Camelia’s first priority is to explore existing K–12 engineering activities to identify common objectives, dissemination routes, and standards. She will then develop a systems model of engineering education that highlights the critical steps in the education of an engineer.

Christina Vogt, currently a CASEE Scholar-in-Residence, is working toward increasing the number of women in engineering education programs. Before relocating to the National Academies in Washington, D.C., Dr. Vogt taught courses in the Urban Education Program at the University of Southern California (USC), where she had extensive experience with Title I school teachers and learned the ins and outs of the challenges facing inner-city school systems.

Dr. Vogt was a senior technical manager and product manager at a subsidiary of Lockheed, where she ran an international technical group working on computer graphics systems. After leaving the computer industry, she taught in India, eastern Asia, and the Middle East. When she returned to the United States, she spent seven years at the USC Rossier School of Education, where she held a number of teaching and research positions.
U.S. Frontiers of Engineering Holds 2005 Meeting at GE Global Research Center

The eleventh annual U.S. FOE Symposium was held at GE Global Research Center in Niskayuna, New York, on September 22–24. NAE member William F. Banholzer, former vice president of GE Plastics, arranged for GE Global Research to house the meeting, which not only gave participants an opportunity to visit a corporate research facility, but also defrayed a substantial portion of the cost of the symposium.

The 103 engineers who attended the 2005 symposium heard talks on four topics: ID and verification technologies, engineering for developing communities, engineering complex systems, and energy resources for the future. Papers based on six of the presentations are published in this issue of The Bridge.

The papers in the session on ID and verification technologies were based on the premise that the proliferation of cheap and novel sensors, faster computers, and intelligent algorithms has made it much easier to monitor, identify, and track objects and people. Two talks focused on face recognition—first, an overview on the difficulties of ensuring reliable identification, and second, a talk on challenge problems and independent evaluations in automatic face recognition; a third talk addressed advances in RFID and activity recognition.

The engineering for developing communities session included presentations on challenges and opportunities for engineering to alleviate poverty and achieve sustainability. Talks focused on the challenges of implementing appropriate technologies, exemplified by the experience of the DISACARE wheelchair project in Zambia; the contributions of engineering to the safe water system program of the Centers for Disease Control and Prevention; sustainable development through green engineering; and the importance of making sustainability science a guiding scientific principle, as illustrated by the development of solar electricity markets in developing nations.

The third session was on engineering complex systems, from metabolic pathways and ecosystems to the Internet and the propagation of U.S. Frontiers of Engineering Holds 2005 Meeting at GE Global Research Center

Eduardo Misawa (NSF) and Silvia Ferrari (Duke University) discuss an issue during one of the U.S. FOE meeting breaks.

Daniel Kammen (University of California, Berkeley) responds to a question about his presentation in the U.S. FOE session on Engineering for Developing Communities. Speaker Julie Beth Zimmerman (University of Virginia and Environmental Protection Agency) is standing on the left.
of HIV infection. Overall, the presentations provided an overview of theoretical and experimental tools for meeting the challenges posed by complex systems in a systematic way. Talks covered network theory as a tool for describing, analyzing, and understanding complex systems; the engineering of biological systems; and agent-based modeling, which is being used to study diverse systems, from ant colonies to trading in financial systems, traffic patterns, and the spread of epidemics.

The session on energy resources for the future included a presentation on organic-based solar cells; an overview of research by the U.S. Department of Energy on hydrogen production and storage; and a talk on advances in fuel cells.

A new feature at the meeting this year was “get-acquainted sessions” on the first afternoon, which enabled attendees to get to know more about each other relatively early in the program. Each participant was asked to bring one slide that captured the essence of his or her research or technical work. After breaking into small groups, participants presented their slides and answered questions. On the second afternoon, participants were given tours of GE’s nanotechnology, energy, and biotechnology labs. This was followed by a wonderful dinner at the Saratoga Automobile Museum. One of the high points of the meeting was an inspiring talk on Thursday evening, “Engineering for a New World,” by Shirley Ann Jackson, president of Rensselaer Polytechnic Institute. She described the links between the critical energy issues facing the world and the importance of encouraging innovation in future engineers and scientists.

Pablo P. Debenedetti, Class of 1950 Professor, Department of Chemical Engineering, Princeton University, chaired the organizing committee and the symposium for the third (and final) year. NAE president Wm. A. Wulf expressed his appreciation for Dr. Debenedetti’s contribution to the FOE Program in his opening remarks. The 2006 organizing committee, chaired by Julia M. Phillips, director of the Physical, Chemical, and Nano Sciences Center at Sandia National Laboratories, is already planning for the next U.S. FOE meeting, which will be held September 21–23, 2006, at Ford Motor Company in Dearborn, Michigan.


NAE has hosted annual U.S. FOE symposia since 1995. FOE also has bilateral programs with Germany, Japan, and India. FOE meetings bring together outstanding young engineers from industry, academia, and government and provides them an opportunity to learn about cutting-edge developments, techniques, and approaches in many fields of engineering, which is becoming increasingly important as engineering becomes more interdisciplinary. The meeting also facilitates contacts and collaborations among the next generation of engineering leaders.

All of the presentations of the 2005 symposium (including the papers in this issue of The Bridge) will be published in the annual FOE volume, which will be available in February 2006. For more information about the symposium series or to nominate an outstanding engineer to participate in future meetings, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at jhunziker@nae.edu.
The Japan-America Frontiers of Engineering (JAFOE) Symposium was held at Hitachi Global Storage Technologies (HGST) in San Jose, California. NAE member Frederick (Rick) Dill, Distinguished Engineer at HGST, was instrumental in facilitating the hosting of this event. Approximately 60 engineers—30 from each country—attended, with additional representation from HGST and NAE’s partners in this program—the Japan Science and Technology Agency and the Engineering Academy of Japan.

The four sessions at the meeting were focused on humanoid robots, pure water technologies, research and development on semiconductors, and the detection and destruction of pathogens. Presentations—by two Japanese and two Americans on each topic—focused on advances in autonomous and interactive behaviors of humanoid robots, the removal of arsenic from drinking water, silicon quantum computers, and DNA-directed formation of nanoscale wires for use in a DNA identification system.

The Thursday evening dinner speech was given by Thomas Baer, consulting professor in applied physics at Stanford University and founder of Arcturus Bioscience Inc. In a talk titled “Engineering Entrepreneurs,” Dr. Baer described the process of starting and sustaining an entrepreneurial enterprise, particularly in terms of financing cycles and human resources. He noted that the unique environment of Silicon Valley, which is an “incubator” for new companies, alleviates some risk because of the proximity of potential employers if a venture fails. Other highlights included poster sessions on the first afternoon, when all participants had a chance to describe their technical work or research; presentations by HGST staff on their work; and a tour and dinner at the Computer History Museum in Mountain View.

James G. Fujimoto, professor, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, and Kazuhiro Sakurada, head, Nihon Schering Research Center, Nihon Schering K.K., co-chaired the organizing committee and the symposium. Dr. Fujimoto, who completed his third year as U.S. co-chair of JAFOE, will be succeeded by Glenn H. Fredrickson, professor of chemical engineering and materials and director of the Mitsubishi Chemical Center for Advanced Materials at the University of California, Santa Barbara. The 2006 JAFOE meeting will be held November 9–11, 2006, in Japan and will cover topics in systems biology, solid-state lighting and displays, cybersecurity, and biomechatronics.

Funding for the 2005 JAFOE meeting was provided by Hitachi Global Storage Technologies, National Science Foundation, Japan Science and Technology Agency, and the NAE Fund. For more information about the symposium series or to nominate an outstanding engineer to participate in a future JAFOE meeting, contact Janet Hunziker at the NAE Program Office at (202) 334-1571 or by e-mail at jhunziker@nae.edu.
Leading Philanthropists Inducted into Einstein Society

Dr. and Mrs. Leon Kirchmayer’s son and daughter receive an Einstein statuette on their parents’ behalf at the annual meeting. From left to right: Craig Barrett, Karen Demuth, Kenneth Kirchmayer, and Wm. A. Wulf.

From left to right: Sheila Widnall, Wm. A. Wulf, and Craig Barrett display the Einstein statuette bestowed upon members of the Einstein Society.

Three leading philanthropists to NAE and the National Academies, Harold K. Forsen, William W. Lang, and Olga Kirchmayer (in memory of her husband, Leon K. Kirchmayer), were recently inducted into the Einstein Society, which was created in 2004 to honor members, private donors, and others whose cumulative lifetime donations total $100,000 or more. Thirty of the 86 members of the Einstein Society are NAE members.

In appreciation of their exemplary commitment, NAE president Wm. A. Wulf presented Forsen, Lang, and Kirchmayer’s son and daughter (attending on her behalf) with replicas of the original maquette of the Einstein monument on the front lawn of the National Academies Building on Constitution Avenue in Washington, D.C. Each replica includes the signature of sculptor Robert Berks and is engraved with the donor’s name and the following quotation from Albert Einstein: “The right to search for truth also implies a duty: One must not conceal any part of what one has recognized to be true.”

During the presentation ceremony, Dr. Wulf told the honorees, “You should take great pride in knowing that your philanthropic contributions are making a significant difference in NAE’s service as adviser to our nation.”

Members of the Einstein Society are recognized at annual meetings and meetings of the Presidents’ Circle of the National Academies. They will also be recognized in the headquarters building in Washington, D.C., and in annual reports and donor-recognition issues of Academies publications. For information about becoming a member of the Einstein Society, please contact the Office of Development at (202) 334-2431.

**NAE Members of the Einstein Society**

**John A. Armstrong** for contributions to the endowment for the Young Engineers Program

**Holt Ashley** for contributions to NAE Independent Funds

**Norman R. Augustine** for contributions to the Senior Scholars Program

**William F. Ballhaus Sr.** for contributions to NAE Independent Funds

**Jordan J. Baruch** for contributions to NAE Independent Funds and Capital Preservation
Bell Family Foundation for contributions to NAE Independent Funds
George M.C. Fisher for contributions to NAE Independent Funds and Capital Preservation
William L. Friend for contributions to NAE Independent Funds
Grainger Foundation for contributions to the establishment of the Grainger Challenge Prize
Bernard M. Gordon for contributions to the establishment of the Bernard M. Gordon Prize for Innovation in Engineering and Technology Education and for NAE Independent Funds
Anita K. Jones for contributions to NAE Independent Funds
Thomas V. Jones for contributions to NAE Independent Funds, Capital Preservation, and Industry Scholars
Ruben F. Mettler for contributions to support media relations, Public Understanding of Engineering, and Phil Smith Fund
Dane A. Miller for contributions to the Center for the Advancement of Scholarship on Engineering Education and NAE Independent Funds
Richard M. Morrow for contributions to the Center for the Advancement of Scholarship on Engineering Education, NAE Independent Funds, and Capital Preservation
Kenneth H. Olsen for contributions to NAE Independent Funds
Doris Pankow (in memory of Charles J. Pankow), for contributions to Engineering Ethics, Capital Preservation, Public Understanding of Engineering, Frontiers of Engineering, and NAE Independent Funds
Jack S. Parker for contributions to the Presidents’ Circle Communication Initiative, How People Learn, and NAE Independent Funds
Robert A. Pritzker for contributions to the Bruce Alberts Fund for Science Education, NRC Presidents’ Fund, and NAE Independent Funds
Dolores H. Russ (in memory of Fritz J. Russ), for contributions to the establishment of the Russ Prize
Alan M. Voorhees for contributions to Urban Infrastructure for Sustainability in China and NAE Independent Funds
Wm. A. Wulf for contributions to NAE Independent Funds

Calendar of Meetings and Events

2006

January 17  NRC Executive Committee Meeting
February 6–7  NRC Governing Board Meeting
February 8–9  NAE Council Meeting
              Irvine, California
February 9  NAE National Meeting
            Irvine, California
February 15  NRC Executive Committee Meeting
February 21  NAE Awards Forum/Awards Dinner
March 2–4  Indo-U.S. Frontiers of Engineering Symposium
            Agra, India
March 14  NRC Executive Committee Meeting
April 6  NAE Regional Meeting
        University of Michigan
April 11  NRC Executive Committee Meeting

All meetings are held in the Academies Building, Washington, D.C., unless otherwise noted. For information about regional meetings, please contact Sonja Atkinson at satkinso@nae.edu or (202) 334-3677.
In Memoriam

SPENCER H. BUSH, 85, president, Review and Synthesis Associates, died on October 2, 2005. Dr. Bush was elected to NAE in 1970 for work on the physical and mechanical metallurgy of materials used in nuclear reactors.

MARVIN CHODOROW, 92, Professor of Applied Physics and Electrical Engineering, Emeritus, Edward L. Ginzton Laboratory, Stanford University, died on October 7, 2005. Dr. Chodorow was elected to NAE in 1967 for his outstanding work on microwave tubes.

LELAND C. CLARK JR., 86, vice president of research, Synthetic Blood International Inc., died on September 25, 2005. Dr. Clark was elected to NAE in 1995 for inventions and contributions to biosensors and artificial organs and blood and for medical applications of these devices worldwide.

W. KENNETH DAVIS, 87, retired vice president, Bechtel Corporation, former deputy secretary of energy, and consultant, died on July 29, 2005. Mr. Davis was elected to NAE in 1970 for his contributions to the development and industrial application of nuclear power technology.

FREDERICK J. ELLERT, 76, retired general manager, Systems Development and Engineering Department, General Electric Company, died on July 13, 2005. Dr. Ellert was elected to NAE in 1987 for his leadership in the development and application of high-voltage direct-current technology for large-scale electric utility power networks.

LEOPOLD B. FELSEN, 81, professor of aerospace and mechanical engineering and professor of electrical and computer engineering, Boston University, died on September 24, 2005. Dr. Felsen was elected to NAE in 1977 for his contributions to the theory and application of microwave propagation in complex media and for his leadership in engineering education.

DONALD R.F. HARLEMAN, 82, Ford Professor of Environmental Engineering, Emeritus, Ralph M. Parsons Laboratory for Water Resources and Environment Engineering, Massachusetts Institute of Technology, died on September 28, 2005. Dr. Harleman was elected to NAE in 1974 for his leadership in the development of theoretical and experimental techniques in the field of fluid mechanics.

ALAN S. MANNE, 80, Professor Emeritus of Operations Research, Stanford University, died on September 27, 2005. Dr. Manne was elected to NAE in 1990 for outstanding contributions to operations research methodology and applications for production scheduling, plant capacity decisions, and energy planning.

RONALD F. SCOTT, 76, Dotty and Dick Hayman Professor of Engineering, Emeritus, California Institute of Technology, died on August 16, 2005. Dr. Scott was elected to NAE in 1974 for contributions to the theory and application of soil mechanics.

CHEN-TO TAI, 88, Professor Emeritus, Department of Electrical Engineering and Computer Sciences, University of Michigan, died on July 30, 2004. Dr. Tai was elected to NAE in 1987 for basic contributions to the advancement of electromagnetic theory and applications to antenna design.

HARVEY A. WAGNER, 100, retired executive vice president, Detroit Edison Company, died on June 30, 2005. Mr. Wagner was elected to NAE in 1970 for leadership in the development of high-temperature conventionally fueled and nuclear power plants.
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, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at http://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.)

**Globalization of Materials R&D: Time for a National Strategy.** The global spread of materials science and engineering (MSE) R&D is accelerating. As a result, the U.S. position in a number of MSE subfields is in a state of flux. To analyze the implications of these trends for the U.S. economy and national security, the U.S. Department of Defense asked the National Research Council to assess the status and impacts of the global spread of MSE R&D. This report includes a discussion of the factors that influence U.S. companies’ decisions about where to locate MSE R&D facilities, impacts on the U.S. economy and national security, and recommendations for ensuring continued U.S. access to critical MSE R&D.

NAE member Peter R. Bridenbaugh, retired executive vice president, Automotive, Aluminum Company of America, chaired the study committee. Other NAE members on the committee were Uma Chowdry, vice president, Central Research and Development, DuPont Company Experimental Station, and Jennie S. Hwang, president, H-Technologies Group Inc., and chief executive officer, Asahi America Inc. Paper, $35.00.

**Review of the Research Program of the FreedomCAR and Fuel Partnership: First Report.** The FreedomCAR and Fuel Partnership is a collaborative effort by the U.S. Department of Energy (DOE), the U.S. Council for Automotive Research (USCAR), and five major energy companies to oversee research on a “clean and sustainable transportation energy future.” The goal of the project is to enable a transition first to more efficient internal combustion engines (ICEs), then to advanced ICE hybrid electric vehicles, and ultimately to a private-sector decision, by 2015, on the development of hydrogen-fueled vehicles. This report, which builds on an earlier NRC study, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, includes an evaluation of research on hydrogen-fueled transportation systems and findings and recommendations for technical directions, strategies, funding, and management.

NAE member Craig Marks, retired executive vice president, Technology and Productivity, AlliedSignal Inc., chaired the study committee. Other NAE members on the committee were Peter Beardmore, retired director, Chemical and Physical Sciences Laboratory, Ford Motor Company; John B. Heywood, Sun Jae Professor of Mechanical Engineering and director, Center for 21st Century Energy and Sloan Automotive Laboratory, Massachusetts Institute of Technology (MIT); John G. Kassakian, professor of electrical engineering and director, Laboratory for Electromagnetic and Electronic Systems, MIT; Christopher L. Magee, professor, Engineering Systems Division, MIT; Michael P. Ramage, retired executive vice president, Exxon Mobil Research and Engineering Company; Bernard I. Robertson, senior vice president, Engineering Technologies and Regulatory Affairs, and general manager, Truck Operations, DaimlerChrysler Corporation (retired); and Kathleen C. Taylor, retired director, Materials and Processes Laboratory, General Motors Corporation. Paper, $18.00.

**Earth Science and Applications from Space: Urgent Needs and Opportunities to Serve the Nation.** The Earth is a dynamic planet with changes and variations that affect communications, energy, health, food, housing, and transportation infrastructure. Understanding these changes requires a range of observations from a variety of land-, sea-, air-, and space-based platforms. To help the National Aeronautics and Space Administration, National Oceanic and Atmospheric Administration, and U.S. Geological Survey develop these tools, the National Research Council was asked to develop a
decadal strategy for surveying Earth from space. The study committee was asked (1) to identify key scientific questions to be answered by Earth and environmental observations from 2005 to 2015 and (2) to provide a prioritized list of space programs, missions, and supporting activities to address these questions. This interim report outlines the rationale for linking Earth observations to societal needs and a discussion of the most urgent near-term actions. A final report, due in late 2006, will recommend space missions, programs, and related activities.

NAE member Warren M. Washington, senior scientist and section head, Climate Change Research Section, Climate and Global Dynamics Division, National Center for Atmospheric Research, was a member of the study committee. Paper, $12.00.

Policy Implications of International Graduate Students and Postdoctoral Scholars in the United States. This report provides an in-depth discussion of the impact of foreign-born students and scholars on U.S. educational institutions and the U.S. economy. The United States has depended increasingly on human resources from abroad for its science and engineering workforce. However, competition for talent has been increasing as other countries expand their research infrastructures and provide more opportunities for workers educated in science and engineering. The report analyzes trends in international student enrollments and retention rates and the impact of visa policies.

NAE members on the study committee were William G. Agnew, retired director, Programs and Plans, General Motors Corporation; John A. Armstrong, retired vice president for science and technology, IBM Corporation; Alice P. Gast, vice president for research and associate provost, Massachusetts Institute of Technology; Joel Moses, Institute Professor, professor of computer science and engineering, and professor of engineering systems, Massachusetts Institute of Technology; and Elsa Reichmanis, director, Materials Research Department, Lucent Technologies. Paper $43.00.

Technology Pathways: Assessing the Integrated Plan for a Next Generation Air Transportation System. In 2003, Congress directed the secretary of transportation to establish the Next Generation Air Transportation System (NGATS) Joint Planning and Development Office (JDPO) to plan the development of an air transportation system capable of meeting potential air traffic demands for 2025. To break down interagency barriers and promote cooperation and collaboration, all federal agencies involved in aviation are participants in the JDPO. The National Research Council was asked to examine the first NGATS Integrated Plan prepared by JPDO and submitted to Congress in 2004. This assessment includes a review of the vision and goals, operational concepts, and R&D road map; an analysis of the JDPO integrated product teams created to plan the initiative; and an assessment of the implementation process.

NAE member David C. Wisler, manager, University Programs and Aero Technology Labs, GE Aircraft Engines, was a member of the study committee. Paper, $18.00.

Effects of Nuclear Earth-Penetrator and Other Weapons. Many nations use underground facilities to conceal and protect strategic military functions and weapons stockpiles. These strategic, hardened, deeply buried targets are often only reachable by conventional or nuclear earth-penetrating weapons (EPWs). Recently, an engineering feasibility study, the Robust Nuclear Earth Penetrator Program, was initiated by U.S. Department of Energy and U.S. Department of Defense to determine if a weapon based on the major components of existing nuclear weapons would be an effective EPW. The program has generated a great deal of controversy about the collateral damage such a weapon would cause. To clarify the issues, Congress (P.L. 107-314) directed the secretary of defense to request that the National Research Council conduct a study to assess the anticipated health and environmental effects of nuclear EPWs and other weapons and the comparative effectiveness of using conventional and nuclear weapons to destroy biological and chemical weapons storage facilities. The study committee undertook detailed numerical calculations to compare the effectiveness and expected collateral damage of nuclear EPWs and surface nuclear weapons under a variety of conditions.

NAE member John F. Ahearne, director, Ethics Program of the Sigma Xi Center, chaired the study committee. Other NAE members on the committee were Richard L. Garwin, Emeritus Fellow, IBM T.J. Watson Research Center, Eugene Sevin, independent consultant, Lyndhurst, Ohio, and Robert H. Wertheim, Rear Admiral, U.S. Navy (retired), and consultant, Science Applications International Corporation. Paper, $33.00.
Review of the GAPP Science and Implementation Plan. Water managers rely on predictions of seasonal, annual, and interannual changes in hydrologic cycles. Predictions of hydrologic cycles are based on local and remote influences, including land processes and ocean processes, such as the El Niño Southern Oscillation. A better understanding of land-surface processes can potentially improve climate predictions, but using this information to make water-management decisions is still risky because current models provide only limited information on seasonal and longer term changes. The Global Energy and Water Cycle Experiment (GEWEX) of the Americas Prediction Project (GAPP) was established in 2001 to improve predictions of changes in water resources on intraseasonal-to-interannual time scales for the continental United States. GAPP developed a Science and Implementation Plan, which describes strategies for improving predictions and decision support in the hydrologic sciences. This report by the National Research Council reviews the GAPP Science and Implementation Plan and suggests improvements for the plan and the GAPP overall program.

NAE member Soroosh Sorooshian, UCI Distinguished Professor and director, Center for Hydrometeorology and Remote Sensing, University of California, Irvine, was a member of the study committee. Paper, $31.75.

Monitoring at Chemical Agent Disposal Facilities. Under the direction of the U.S. Army’s Chemical Materials Agency (CMA), and as mandated by Congress, the nation is destroying its chemical weapons stockpile. This study was requested by the Army to advise CMA about the status of analytical instrumentation technology and systems suitable for monitoring airborne chemical warfare agents at chemical weapons disposal and storage facilities. The report includes an assessment of current monitoring systems used to detect airborne agents at CMA facilities and of the applicability and availability of innovative new technologies. The report also includes a discussion of how new regulatory requirements would affect CMA’s current agent monitoring procedures and whether new measurement technologies could be effectively incorporated into CMA’s overall chemical agent monitoring strategies.

NAE member Elisabeth M. Drake, retired associate director for new energy technology, Energy Laboratory, Massachusetts Institute of Technology, was a member of the study committee. Paper, $25.25.

Spinal Cord Injury: Progress, Promise, and Priorities. An estimated 11,000 spinal cord injuries occur each year in the United States, and more than 200,000 Americans suffer from maladies associated with spinal cord injuries. These include paralysis, bowel and bladder dysfunction, sexual dysfunction, respiratory impairment, temperature regulation problems, and chronic pain. In the last two decades, long-standing beliefs about the inability of the adult central nervous system to heal itself have been eroded by a flood of information based on research in the neurosciences and related fields. However, there are still no cures, and restoring function after spinal cord injuries remains extremely complex. This report by the Institute of Medicine recommends directions for future research that might accelerate the development of cures for spinal cord injuries. Although many of the recommendations are presented in the context of specific needs articulated by the New York Spinal Cord Injury Research Board, the panel of experts approached research priorities for the field in general. The panel also recommends ways to improve and coordinate the existing infrastructure. Funders at federal and state agencies, academic organizations, pharmaceutical and medical device companies, and nonprofit organizations will find this report essential reading.

NAE member P. Hunter Peckham, professor of biomedical engineering, Case Western Reserve University, was a member of the study committee. Hardback, $49.95.

Going to Extremes: Meeting the Emerging Demand for Durable Polymer Matrix Composites. Advanced polymer matrix composites (PMCs) have many advantages, such as light weight and high specific strength, that make them useful for many aerospace applications. Their use has been limited, however, by uncertainties about the long-term changes in properties of PMCs under extreme conditions. The U.S. Department of Defense requested a study focused on methodologies for predicting long-term performance. This report provides a review of the challenges to the use of PMCs in extreme environments, the current understanding of PMC properties and behavior, a discussion of the data necessary for the development of effective models, and recommendations for improving long-term predictive methodologies.
Tank Wastes Planned for On-Site Disposal at Three Department of Energy Sites: The Savannah River Site: Interim Report. In response to a request from Congress, the U.S. Department of Energy (DOE) asked the National Academies to evaluate its plans for managing radioactive wastes from spent nuclear fuel at sites in Idaho, South Carolina, and Washington. This interim report evaluates storage facilities at the Savannah River site in South Carolina, with a particular focus on plans to seal the tanks with grouting. The report finds that tanks do not necessarily have to be sealed as soon as the bulk of the waste has been removed. Postponing permanent closure allows time for the development and application of emerging technologies for removing and immobilizing residual waste, without increasing risks to the environment or delaying final closure of the “tank farms.” The report also recommends alternatives to address the lack of tank space at the site, as well as the need for focused research to reduce the amount and improve the immobilization of residual waste and to test the assumptions used in evaluations of long-term risks.

NAE member Kenneth L. Reifsneider, Pratt & Whitney Chair of Design and Reliability, University of Connecticut, was a member of the study committee. Paper, $18.00.

Public Water Supply Distribution Systems: Assessing and Reducing Risks. First Report. The Water Science and Technology Board of the National Research Council is studying water quality issues associated with public water supply distribution systems and their potential risks to consumers. The distribution system—a critical component of every drinking water utility—poses significant challenges from the operational and public health standpoints. This report was requested by the Environmental Protection Agency (EPA), which is considering revisions to the Total Coliform Rule and potential new requirements for ensuring the integrity of distribution systems. The report identifies trends relevant to the deterioration of drinking water quality in distribution systems and prioritizes the issues of greatest concern. The committee reviewed nine EPA white papers and concluded that cross connections and backflow, new or repaired water mains, and finished water storage facilities presented the highest potential health risks. In addition, the committee identified premise plumbing and operator training as high-priority issues. This report will be followed in about 18 months by a more comprehensive final report evaluating approaches to characterizing risk and identifying strategies for reducing risks.

NAE members on the study committee were David C. Larbalestier, David Grainger Professor and L.V. Shubnikov Professor of Materials Science Engineering, University Wisconsin-Madison, and John M. Rowell, Distinguished Visiting Professor, Arizona State University. Paper, $39.00.

Prospective Evaluation of Applied Energy Research and Development at DOE (Phase One): A First Look Forward. In 2001, the National Research Council (NRC) completed Energy Research at DOE: Was It Worth It?, a congressionally mandated assessment of the benefits and costs of DOE’s fossil energy and energy efficiency research and development (R&D) programs. Congress then directed DOE to request that the NRC develop a methodology for assessing prospective benefits. The first phase of the project to develop a methodology began in December 2003. Phase one focuses on (1) the adaptation of the retrospective methodology to a prospective context; (2) develops transparent methodology that does not require extensive resources for implementation and produces easily understood
results; and (3) describes a practical and consistent process for using it. In phase two, the methodology will be made more robust and related issues will be explored. In subsequent phases, the methodology will be used to review the prospective benefits of DOE fossil energy and energy efficiency R&D programs.

NAE members on the study committee were Wesley L. Harris, department head and Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology, and Maxine L. Savitz, retired general manager, Technology/Partnerships, Honeywell Inc. Paper, $38.00.