Winter 2003

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The BRIDGE

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The
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Volume 33, Number 4 • Winter 2003

Editorial

Features

NAE News and Notes

(continued on next page)

Testimony before Congress

The National Academies Update

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Advisers to the Nation on Science, Engineering, and Medicine

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Editorial

George Bugliarello is chancellor of Polytechnic University in Brooklyn, New York, and foreign secretary of NAE.

The Ongoing Expansion of Frontiers of Engineering

In Samuel Johnson's 1755 *Dictionary of the English Language*, "frontier" is defined as "the marches [the utmost border bounding the jurisdiction of the King's Steward]; the limit; the utmost verge of any territory; the border: properly that which . . . terminates not at sea, but fronts another territory." Webster's less exuberant dictionary concurs and extends the concept, by analogy, beyond geography to the frontiers of knowledge. Since Vannevar Bush's famous report, *Science: The Endless Frontier*, the word frontier has been widely used as a metaphor for the cutting edge of science and technology.

Frontiers constantly front the unknown, which is to be explored, made knowable, and possibly conquered. Like the proverbial drop of oil on water, the frontiers of engineering continue to expand, and the farther they advance, the greater the territory to be explored and the greater the challenges and opportunities for our society. Ten years ago we thought of microelectronics and the most advanced piloted planes as frontiers. Today we think of nanoelectronics, UAVs, and microplanes. Once we thought of hybrid, energy-saving vehicles as being on the frontier. Today we think of hydrogen-fueled vehicles.

From materials to energy to information systems, frontiers in every domain of engineering impact our biology, our society, and our environment and have the potential of revolutionizing them. Consider one small example, designer materials built atom by atom that can lead to new information devices of great capacity and logical power, direct connections between our brains and information machines, ubiquitous information networks, machines with an element of consciousness, and the construction and operation of extremely complex systems.

The societal implications of engineering frontiers are not always recognized. History is replete with examples of great advances in engineering that either were not implemented or were implemented after long delays for lack of understanding and support—Napoleon's indifference to the potential of the steamship, the British Admiralty's reluctance to change from paddle wheels to screw propulsion, the Italian post office's lack of interest in Marconi's wireless device, and the decision not to develop Goddard's rockets.

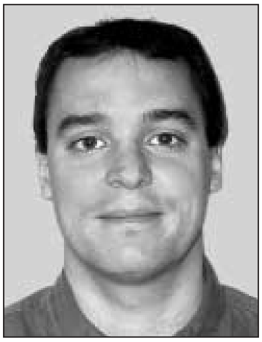
The annual NAE Frontiers of Engineering symposia endeavor to initiate a dialogue among some of the brightest young engineers working in frontier areas where the ferment and excitement of discovery are palpable. Their work may lead to unimagined advances. Seven papers from the 2003 symposium are gathered in this issue of *The Bridge*. Most of them describe technologies that could barely have been imagined just a few years ago, such as DNA computing by self-assembly (the subject of the paper by Eric Winfree) and the programming of living cells (the paper by Ron Weiss). Dianne Newman discusses microbial mineral respiration, which is still not fully understood but is nevertheless being put to work in many fields. James Heath introduces the tantalizing subject of molecular electronics, which has advanced to the point that industry is taking up the research. Bill Cheswick tackles the problems of Internet security, and Alan Russell, Joel Kaar, and Jason Berberich turn our attention to the use of biotechnology to detect and counteract chemical weapons. The paper by Greg Characklis describes a multidimensional frontier—water-resources engineering—where economics, public policy, and engineering come together to optimize water use, an increasingly scarce resource all over the world.

Only the future will tell if these frontiers will be conquered and how they will change engineering and our world.

George Bugliarello

Interdisciplinary analyses are being used to assess the consequences of water-policy choices.

Water-Resource Engineering, Economics, and Public Policy



Gregory W. Characklis is assistant professor in the Department of Environmental Sciences and Engineering at the University of North Carolina at Chapel Hill.

Gregory W. Characklis

Water-resource engineering is a branch of environmental engineering that involves the analysis and manipulation of hydrologic systems, particularly in areas related to water quality and water availability (e.g., water supply and flooding). Since the mid-1970s, concerns about improving water quality and meeting future demands have multiplied in scope and magnitude, prompting significant changes in public policy at the federal, state, and local levels (Cech, 2003). The strong influence of public policy on the research agenda in water-resource engineering (and most other environmental fields) differentiates it from other engineering disciplines in some important respects.

In non-environmental disciplines, the primary motivation for developing a solution (e.g., a product or process) is economic—doing something "faster, better, cheaper." The solution is then implemented by consumers and organizations based on their determination of how well the new product or process fits their needs. By contrast, the motivation for developing solutions to water-resource challenges is often related to meeting regulatory objectives (e.g., public health or environmental quality) that cannot be easily quantified in economic terms. Although attempts are made to estimate costs and benefits when evaluating and setting regulatory policy, implementation of a policy is generally dictated by centrally controlled directives that often entail high compliance costs.

A number of factors can justify this command-and-control approach, but the growing number of environmental regulations, and their increasingly restrictive nature, have stimulated a growing interest in supplementing the traditional approach with market principles. The development of market-based schemes for regulating water resources can be greatly facilitated by interdisciplinary evaluations that integrate analytical tools from engineering and economics. An interdisciplinary analysis can not only help in the identification of potential methods of regulatory implementation, but can also improve assessments of the consequences of policy choices.

Water-Resource Policy

Regulations of water-resource systems usually involve limits on access and generally come in two forms. The first, restrictions on the physical removal of water from a system, is based on concerns about causing adverse environmental impacts. The second involves limiting access to a hydrologic system's capacity to assimilate waste by restricting the kind and amount of waste that may be released into it (e.g., wastewater effluent standards). In both cases, limits are generally based on some form of scientific analysis. Once a target range for limiting access has been defined, engineering analyses are performed to generate information on the effectiveness and cost of available technical solutions. These might involve the development of new water sources or the installation of a new technology that reduces emissions. The cost associated with each alternative is then calculated, and policy alternatives based on these technical solutions are assembled.

Although this approach does provide useful results, it often leaves out important considerations. Water-resource policy making generally involves a combination of moral, technical, and economic factors, and fully informed decisions require that these disparate kinds of information be integrated. The moral aspects are usually judged by elected officials (or their surrogates at the regulatory level) on the basis of personal values or political motivations. Technical and economic information, however, can be more difficult to evaluate and generally requires some level of synthesis before it can be readily "digested" by policy makers. Furthermore, even though the technical and economic implications of water-resource policy decisions are often inextricably linked, they are frequently analyzed independently, using tools specific to each discipline.

Translating technical and economic factors into a common context involves more than just estimating the costs and benefits of a potential regulatory scheme (although these are important). It also entails an analysis of trade-offs and an exploration of alternative means of implementation (NRC, 1996). Interdisciplinary analyses can integrate engineering and economic considerations into terms that policy makers can more readily incorporate into their decision-making process.

The following case study involves a region in which restrictions were placed on aquifer access in response to environmental concerns about declining aquifer levels. In this case, studies have been done to characterize the environmental impact of current pumping rates, with study results used as the basis for setting limits on withdrawals that are designed to mitigate adverse effects. Policy decisions must now be made on the method of implementing and managing these regulatory limits.

Interdisciplinary analyses include trade-offs and means of implementation.

Case Study: Edwards Aquifer

The Edwards Aquifer is a porous, fractured-limestone aquifer in south-central Texas that has been the sole source of water for most of the region's agricultural, municipal (e.g., San Antonio), and industrial users. Regional population growth and economic development have increased pumping rates to the point that the water height in the aquifer frequently drops to levels that substantially reduce the flow of water to several natural springs. These springs provide habitat for several endangered species, and a federal court has ruled that allowing spring flow to drop below specified levels constitutes a "taking" under the Endangered Species Act (Votteler, 1998). As a result, the state of Texas has been instructed to take whatever actions are necessary to ensure that acceptable flow rates are maintained.

This ruling led to a number of biological and hydrological studies to determine the effects of various pumping rates on the aquifer level and water flow in the springs. Based on the results of these studies, the amount of water allowed to be pumped from the aquifer has been limited to 450,000 acre-feet per year, a level that will be insufficient for any party to continue using water at the present rate. In addition to the annual limits, more severe temporary restrictions will be imposed when aquifer levels fall below specified levels. In response to these limits on aquifer access, regional municipalities are considering the development of new water supplies, but the few alternative sources available in this semi-arid region would be very expensive to exploit (SCTRWPG, 2000). Economic analyses of agricultural water use suggest that the value of water in irrigation is quite low relative to the cost of accessing new sources (Keplinger and McCarl, 2000), making transfers of water from agriculture to municipal and industrial users an economically attractive solution (Figure 1).

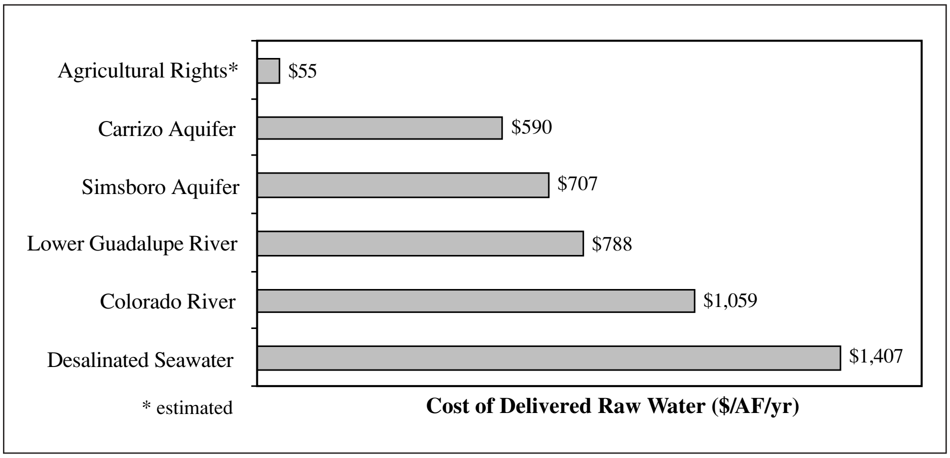


FIGURE 1 Cost of alternative water supplies in the Edwards Aquifer region. Source: SCTRWPG, 2000.

Consequently, a property-rights system has been put in place to allocate the reduced pumping capacity of the Edwards Aquifer among regional consumers, and institutions have been established to facilitate the trading of these rights. Because of concerns about the impact of this regulatory framework on the rural economy, authorities were generous in their initial allocation of rights to irrigators, but left municipal users with a deficit of approximately 43,000 acre-feet per year relative to their current average use (and a considerably larger deficit during dry years). Municipalities also bear the burden of "emergency" measures, which call for urban users to reduce monthly pumping by 5 percent, 10 percent, or 15 percent during months in which the aquifer level drops below 650 feet (above mean sea level), 640 feet, or 630 feet, respectively.

To augment their supplies, municipalities have resorted to purchasing agricultural water rights, the most inexpensive and immediately available source of water. Although a general policy of market-based trading has been used to allocate the newly scarce pumping capacity, critical issues are still unresolved. Policy makers would like to find a solution that minimizes the amount of water transferred out of agriculture. But if municipalities cannot achieve their supply-reliability goals under the proposed framework, then the market-based solution becomes much less valuable (McCarl et al., 1999).

An analysis that incorporates both hydrologic modeling and market simulation was undertaken to evaluate approaches that would maximize the average volume of water available to agriculture and still meet municipal objectives related to supply reliability (high) and cost (low). Although water transfers from agricultural to urban use are inevitable, if the only transfer mechanism available is a permanent sale, municipalities will be forced to buy rights and maintain a volume well in excess of average usage to ensure supply reliability during periodic droughts. These purchased rights are unlikely to be transferred back to agriculture once they are acquired. Thus, in many normal and wet years a significant fraction of the aquifer's total capacity may not be used. If more flexible types of transfer were available, such as transfers that would allow water to be acquired on an "as needed" basis, the capacity maintained by municipalities could be reduced and the average volume of water available to agriculture increased (Characklis et al., 1999).

Purchase decisions regarding these more flexible transfer instruments could be greatly facilitated by improved information about future supplies. In the case of the Edwards Aquifer, future shortfalls will be largely the result of the temporary pumping restrictions imposed when aquifer levels drop below specified levels, conditions that can be accurately predicted through hydrologic modeling (Durbin, 2002).

Flexible transfers allow for more responsive purchase decisions, particularly when supply conditions are known in advance. Annual leases provide for the temporary transfer of pumping rights over a one-year period (beginning January 1), and probabilistic information on future aquifer levels at the time of purchase could be used to estimate the volume necessary to meet supply-reliability goals. Another potential transfer instrument is the option, a transaction in which the buyer pays a small fee at the beginning of the year for the right to purchase water, or exercise the option, at a later date (June 1) at a prearranged price. The accuracy of predictions of aquifer level would have a significant bearing on decisions to purchase and exercise options. Finally, spot-market leases would provide ultimate flexibility, allowing municipalities to acquire water at any time, but also subjecting them to price volatility (i.e., dry weather = high prices).

An assessment of the benefits of including all or some of these transaction types could indicate whether the costs of developing the marketing and monitoring framework necessary to regulate these more complex transactions is justified. Because the Edwards Aquifer market is still in its infancy, little information is available on market behavior. As a result, a market simulation was developed to evaluate monthly supply and demand throughout a given year. The information was then used to calculate spot-market prices as a basis for calculating the prices of the other transaction types.

The monthly pumping restrictions imposed as a result of declining aquifer levels can considerably disrupt municipal water supplies, so the ability to assess the likelihood of restrictions can be valuable when formulating planning strategies. Therefore, a hydrologic model was developed to predict the aquifer level in the "J-17" well (the regulatory reference point) as a function of the previous month's well level, aquifer inflows, agricultural pumping, and municipal pumping. A comparison of model results with empirical data measured over a 25-year period suggests that the model provides a very good estimate of the aquifer level (Figure 2); therefore, the model was embedded in the market simulation.

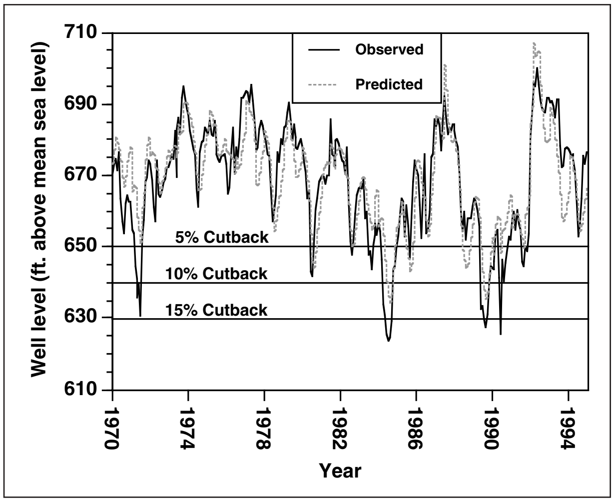


FIGURE 2 Predicted vs. observed aquifer level in the J-17 reference well. Source: Durbin, 2002.

Market simulations are run many times for a range of initial aquifer levels, with input obtained via Monte Carlo sampling from a joint, multivariate distribution created from inflow and withdrawal data. Simulated supply and demand conditions are translated into market prices for each transfer type, and the expected cost and reliability of various combinations, or "portfolios," of transfer types can be computed. The transfer types are specified for each scenario, and a sequential search method is then used to identify minimum cost portfolios that meet designated supply-reliability constraints (Figure 3). Differences in the cost of the

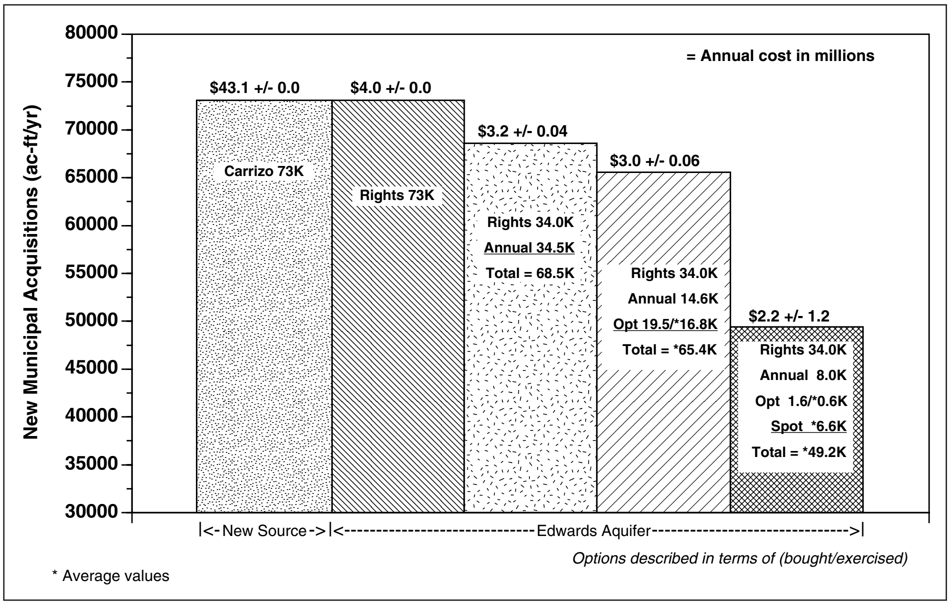


FIGURE 3 Comparison of approaches to meeting municipal demand with at least 99 percent monthly reliability.

respective portfolios indicate the value of including each transaction type in the market, as well as how the cost of market-based approaches compares with the development of the least expensive new water source (Carrizo Aquifer).

Although the model shows that spot-market leasing would have considerable economic advantages, because of the risk averse nature of municipal utilities, a strategy that involves exposure to spot-market price volatility, even if the expected costs are lower, is not likely to appeal to municipal decision makers. They may, however, feel comfortable entering into annual leasing and option contracts, which provide much greater certainty about water availability and cost. The advantages of using these two instruments include savings of close to $1 million dollars per year relative to the cost of depending on permanent transfers alone. More flexible transfers would also increase the average amount of water available to agriculture by 5,000 to 25,000 acre-feet per year, a feature that is important to policy makers. Consequently, the dual objectives of maintaining municipal supply reliability and reducing the economic impacts on agriculture would appear to be furthered by the introduction of more flexible market instruments. Thus, an excellent argument can be made to justify an investment in institutions to monitor and regulate these types of transfers.

Conclusions

Integrating technical and economic analytical techniques provides a means of identifying and evaluating a range of solutions to water-resource challenges. The example above describes the application of these methods to the development of strategies for managing regulatory limits on resource acquisition; similar approaches could be used for regulating emissions. As demands continue to increase for both water resources and the assimilative capacity these resources provide, the need for creative, interdisciplinary solutions will also increase.

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The effects of human activities on the environment pale by comparison with the effects of unicellular microorganisms.

Microbial Mineral Respiration

Dianne K. Newman

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Contributions from anthropogenic sources generally dominate the discussion on global change. And yet, although human activities have unquestionably left their mark on the environment, when averaged over geologic time, their importance pales in comparison with changes that have been effected by the activities of unicellular microorganisms (e.g., Bacteria, Archaea, and single-celled Eucarya). Not only does the number of microorganisms on Earth significantly exceed the number of humans (Whitman et al., 1998), microorganisms, unlike humans, are also found everywhere, are remarkably efficient at catalyzing a wide range of chemical reactions through their metabolisms, and have been around for billions of years (Figure 1).

Microbial metabolisms have brought about many changes in the Earth's environment. Microorganisms have altered the chemistry of the atmosphere via oxygenic photosynthesis, nitrogen fixation, and carbon sequestration. They have modified the composition of oceans, rivers, and pore fluids by controling mineral weathering rates or by inducing mineral precipitation. They have changed the speciation of metals and metalloids in water, soils, and sediments by releasing complexing agents and/or by enzymatically catalyzing redox reactions. And they have shaped the physical world by binding sediments, precipitating ore deposits, and weathering rocks (Newman and Banfield, 2002).

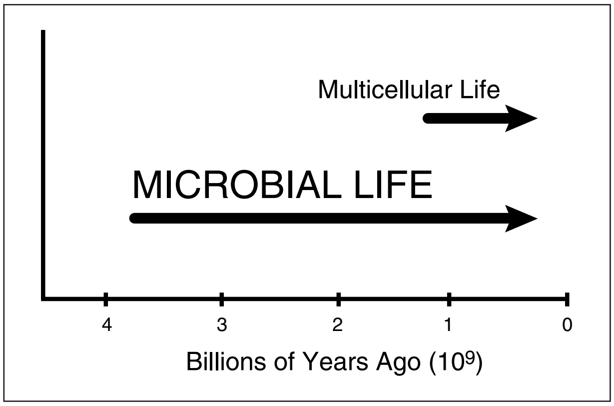

FIGURE 1 Microorganisms have dominated the history of life on Earth and have been major agents of global change. Although we will never know the exact date when microbial life first developed, a variety of geochemical and geobiological indicators suggest that this happened several billion years ago.

Mineral Respiration

Respiratory metabolisms have impacted mineral formation and/or dissolution. The thought of respiring a mineral may seem suffocating, but bacteria have been doing it for billions of years (Figure 2). Respiration is fundamentally the process of making energy available by transferring electrons from an electron donor to an electron acceptor. Typically, the transfer occurs down a respiratory chain embedded in the cell membrane; specific molecules hand off electrons from one end to the other. In the process, they generate a potential across the membrane that can be harnessed to do work (i.e., to store chemical energy in the form of ATP) (Mitchell, 1961). For respiration to succeed, a terminal electron acceptor, such as oxygen, must be available to receive the electrons. Before the evolution of oxygen in the atmosphere, microorganisms had to respire with alternative electron acceptors.

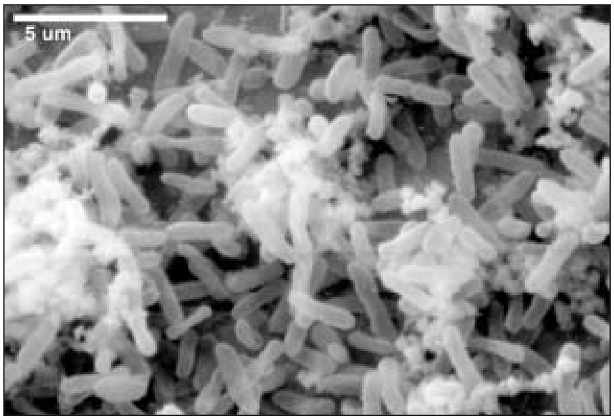

FIGURE 2 A scanning electron micrograph of the metal-reducing bacterium, *Shewanella oneidensis* strain MR-1, attached to a steel surface. As steel corrodes, ferric iron oxides are produced. MR-1 can reduce these minerals during respiration.

Most of the terminal electron acceptors used by bacteria for respiration, such as oxygen, nitrate, and sulfate, are soluble. This means they can make their way to the cell to receive electrons from the membrane-bound molecules of the respiratory chain. The real question is how bacteria transfer electrons to solids like hematite (α-Fe_2O_3) and goethite (α-FeOOH) (Figure 3). Because these minerals are effectively insoluble under environmentally relevant conditions, simple dissolution and diffusion of ferric iron to the cell cannot be the answer (ferric iron is the constituent of the mineral that receives electrons). Therefore, bacteria must have other strategies for transferring electrons to minerals during respiration. The question is, what are they?

Several mechanisms have been proposed (Figure 4). Some have suggested that bacteria solubilize the minerals by producing chelators. Although the addition of synthetic chelators has been shown to stimulate microbial electron transfer to iron minerals, no evidence has been found that bacteria use this mechanism in respiration. Another suggestion is that they may use soluble shuttles, such as organic compounds with quinone moieties, to transfer electrons from the cell to the mineral. These shuttles may be exogenous substances, or they may be substances produced by the organisms themselves (Lovley et al, 1998; Newman and Kolter, 2000).

Another mechanism, possibly the dominant one, is that bacteria transfer electrons directly from the cell surface to the mineral after a regulated search and attachment process. A variety of biomolecules (including cytochromes, quinones, and dehydrogenases) have been identified as part of this electron-transfer pathway (Schröder et al., 2003). Several of these biomolecules are located on the outer membrane of the cell and presumably make contact with the mineral directly (Lower et al., 2001). Given that the initial rate and long-term extent of electron transfer is correlated with their surface area and the concentration of reactive sites, this seems like a reasonable explanation (Zachara et al., 1998). Yet the nature of the electron-transfer event remains obscure and is a subject of active research.

Putting Mineral Respiration to Work

Despite uncertainties about the molecular mechanisms of mineral respiration, environmental microbiologists and engineers have been putting it to work for more than two decades. The best example is

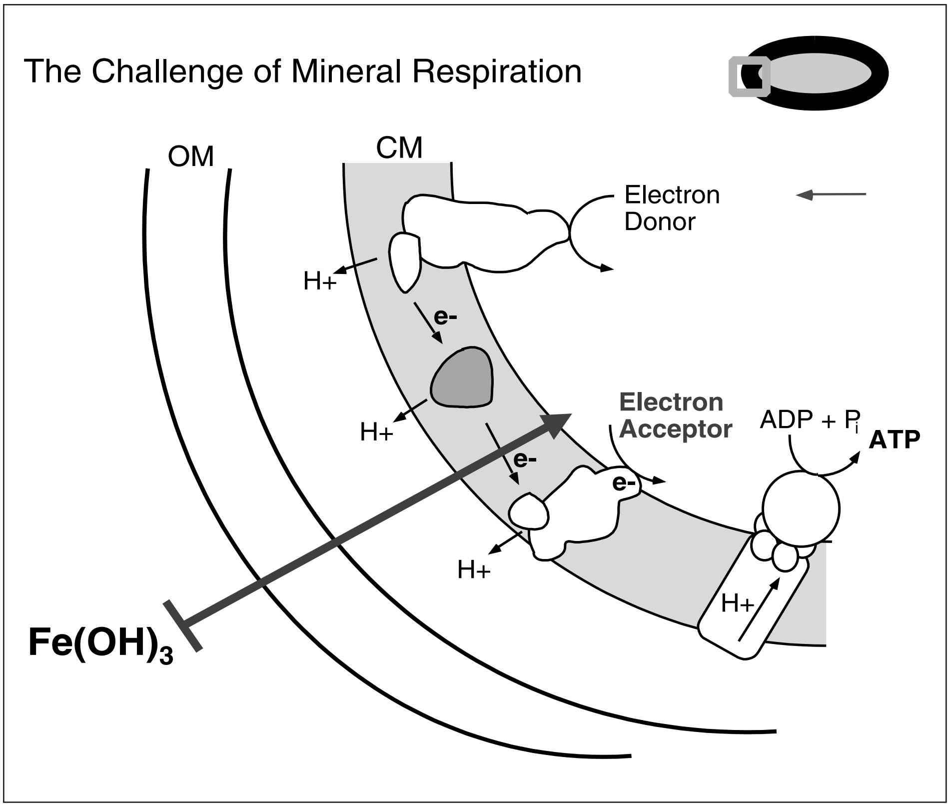

FIGURE 3 A schematic drawing illustrating the process of mineral respiration.

bioremediation; microbial metabolisms based on mineral respiration have been used to clean up organic and/or inorganic contaminants in groundwater (Figure 5).

In the late 1980s, researchers at the U.S. Geological Survey observed that the oxidation of aromatic hydrocarbons (e.g., benzene, xylenes, and toluene) in contaminated shallow aquifers was associated with the depletion of Fe(III) oxides from contaminated sediments and the accumulation of dissolved Fe(II) over time (Lovley et al., 1989). Hypothesizing that Fe(III)-respiring microorganisms may have been responsible for this phenomenon, Derek Lovley and his coworkers showed that the oxidation of added toluene to CO_2 was dependent on active microbial metabolism. They went on to demonstrate that *Geobacter metallireducens* strain GS-15, an Fe(III)-respiring bacterium, could oxidize a variety of aromatic compounds. Two decades later, members of the *Geobacteraceae* family have been observed to account for a significant portion of the microbial population in contaminated sediments (Snoeyenbos-West et al., 2000), and the U.S. Department of Energy (DOE) is actively investing in research to get a better understanding of and to stimulate Fe(III) respiration for bioremediation (DOE, 2003a).

In addition to coupling the oxidation of organic contaminants to the reduction of Fe(III), microbial activity can be of value for the bioremediation of inorganic contaminants, uranium (U) and technetium (Tc), for example, two abundant radioactive metals that contaminate the subsurface environments at some DOE sites. Fe(III)-respiring bacteria have been shown to enzymatically reduce highly soluble U(VI) carbonate complexes and $Tc(VII)O_4^-$ to the insoluble tetravalent phases, UO_2 and TcO_2 (Lloyd, 2003). The theory is that if organisms with this capacity are stimulated *in situ*, toxic inorganic compounds may be precipitated from groundwater and immobilized in the subsurface (Barkay and Schaefer, 2001).

Although the long-term efficacy of this approach is still a subject of debate, encouraging preliminary field

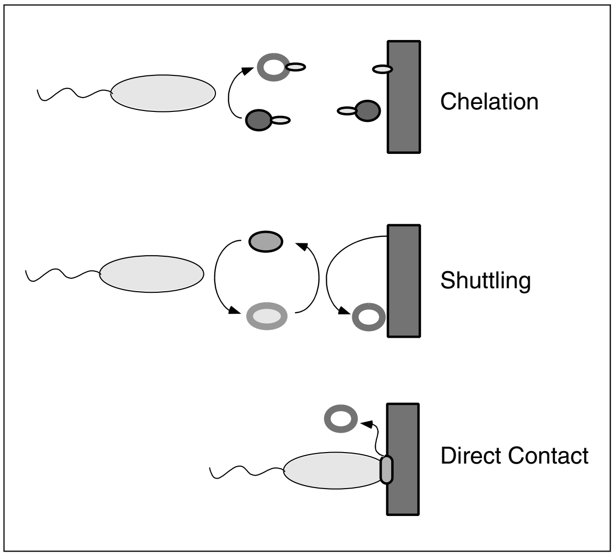

FIGURE 4 Three models that explain how bacteria respire minerals.

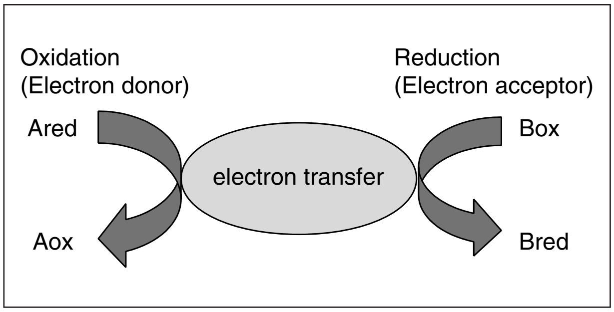

FIGURE 5 Catabolic electron-transfer metabolisms (e.g., fermentation, respiration, and photosynthesis) generate energy. Microorganisms are extraordinarily versatile and can use a variety of compounds as electron donors or electron acceptors in these reactions. For example, Ared can be toxic organic compounds, such as benzene and toluene. Microbes can oxidize these to CO_2 under both aerobic and anaerobic conditions; in anaerobic groundwater systems, Fe(III) is the primary oxidant (i.e., electron acceptor). In addition to Fe(III), bacteria can use other metal(loids) as electron acceptors. These include As(V), Cr(VI), U(IV), Tc(VII), Se(V), and graphite electrodes. When these inorganic compounds are used as electron acceptors, their reduction may lead to their mobilization or precipitation, depending on the metal(loid). Such reactions may be important for the bioremediation of contaminated sites and/or the generation of electricity from marine sediments. Note: In a chemical reaction, Ared + Box = Aox + Bred. Ared = the electron donor for the reaction. Box = the electron acceptor for the reaction. Aox = the oxidized product of the reaction. Bred = the reduced product of the reaction.

studies show that a significant percentage of soluble U can be removed rapidly from groundwater by stimulating the indigenous microbial population (Finneran et al., 2002). Similarly, hexavalent chrominum [Cr(VI)] is a strong, highly mobile carcinogen that forms an insoluble Cr(III) precipitate when reduced. Efforts are currently under way at the Hanford DOE site to determine whether stimulation of the indigenous microbial population with lactate (a carbon source) can enhance Cr immobilization (DOE, 2003b).

Besides removing toxic inorganic compounds from groundwater, microbial respiratory metabolisms also have the potential to generate electricity. In a recently reported example, members of the family *Geobacteraceae* were shown to grow by oxidizing organics with a graphite electrode as the sole electron acceptor (Bond et al., 2002). When fuel cells consisting of anodes embedded in the sediment connected to cathodes positioned in the overlying seawater were deployed in two coastal marine environments (a salt marsh near Tuckerton, New Jersey, and the Yaquina Bay Estuary near Newport, Oregon), oxidation of both organic and inorganic electron donors in the sediment supported power generation (Tender et al., 2002). Although much work remains to be done before we can understand how microbial communities catalyze electron-transfer reactions to the anode, this process has the potential to sustain long-term power generation from marine sediments.

Lest microbial respiratory metabolisms be considered uniformly beneficial, it is important to point out that mineral respiration does not always improve water quality. A tragic example of this can be seen today in Bangladesh, where thousands of people are dying from drinking arsenic-contaminated well water. It is now widely believed that microbial respiratory activities are contributing to this problem by mobilizing arsenic in the groundwater (Harvey et al., 2002). Although the details have not yet been determined, evidence points to the reductive dissolution of iron arsenate minerals as a likely mechanism (Oremland and Stolz, 2003).

Conclusions

Microbial respiratory metabolisms based on minerals are fascinating from a purely scientific standpoint because of what they can teach us about electron-transfer reactions. They are also of great interest to environmental engineers seeking novel ways to remediate contaminated environments and/or to generate electricity. How organisms evolved the capacity to transfer electrons to mineral surfaces is not well understood but merits further investigation. It is possible that horizontal gene transfer has accelerated the distribution of this capability in both time and space; if so, this mechanism could be exploited in the future to deliver useful genetic material to targeted microbial populations.

Acknowledgments

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Spectacular science is coming out of research on molecular electronics.

Molecular Electronics

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In molecular-electronics research, molecules are used to yield the active and passive components (switches, sensors, diodes, resistors, LEDs, etc.) of electronic circuits or integrated circuits. For certain applications, such as molecular-based memory or logic circuitry, the devices are simply molecular-based analogues of devices with more conventional silicon-based circuitry. In those cases, molecular-electronics components may have the advantages of less manufacturing complexity, lower power consumption, and easier scaling. The field of molecular electronics is evolving rapidly, and even though there are no commercial applications as yet, the science coming out of this research is spectacular.

Consider the circuits of nanowires shown in the electron micrograph in Figure 1 (Melosh et al., 2003). The smallest (100-element) crossbar in this image is patterned at a density approaching 10^{12}/cm^2, and the wire diameter is approximately 8 nm. With species like boron or arsenic, at a doping level of 10^{18}/cm^3, a similar 8-nm diameter micrometer-long segment of silicon wires would have 20 to 30 dopant atoms; a junction of two crossed wires would contain approximately 0.1 to 0.2 dopant atoms. Thus, conventional field-effect transistors fabricated at these wiring densities might exhibit nonstatistical, and perhaps unpredictable behavior. In fact, the patterning method (called superlattice nanowire pattern transfer [SNAP]) that produced the generation of patterns shown in Figure 1 can be used to prepare

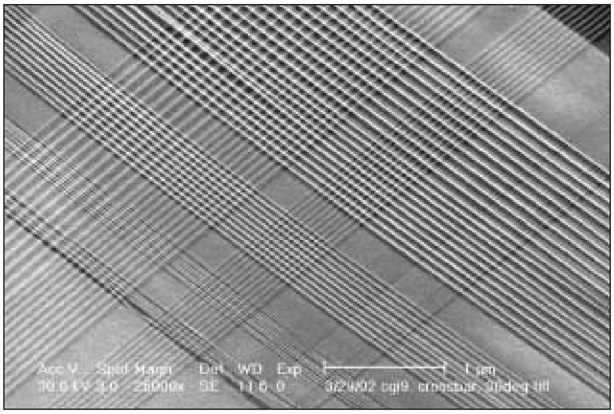

FIGURE 1 A series of 100-element crossbar circuits, the prominent circuits of molecular electronics. The molecule of interest is typically sandwiched between the intersection of two crossed wires. This very simple circuit can be used even in the presence of manufacturing defects and can be fabricated at dimensions that far exceed the best lithographic methods. The device densities in these circuits approach $10^{12}/\text{cm}^2$ for the smallest crossbars.

ultradense arrays of silicon nanowires. Thus, for the first time, researchers can interrogate the statistics of doping and other materials-type fluctuations that are expected to become important at the nanoscale.

Doping fluctuations, however, are relatively trivial compared to other problems encountered by engineers trying to scale conventional, silicon-based integrated circuits to significantly higher densities than are produced now. Power consumption (just from leakage currents through the gate oxide) is perhaps the most serious issue, but the lack of patterning techniques and high fabrication costs are also important.

In fact, no one is seriously contemplating scaling standard electronics device concepts to molecular dimensions (Packan, 1999); alternative strategies are being pursued, although they are all in early stages. These alternatives include molecular electronics, spintronics, quantum computing, and neural networks, all of which have so-called “killer applications.” For quantum computing, it is the reduced scaling of various classes of NP-hard problems. For spintronics, it is a memory density that scales exponentially with numbers of coupled spin transistors. For molecular electronics, it is vastly improved energy efficiency per bit operation, as well as continued device scaling to true molecular dimensions. For true neural networks, it is greatly increased connectivity and, therefore, a greatly increased rate of information flow through a circuit.

Because molecular electronics borrows most heavily from current technologies, in the past few years it has advanced to the point that many major semiconductor-manufacturing companies, including IBM, Hewlett-Packard, and LG (Korea), are launching their own research programs in molecular electronics.

At device areas of a few tens of square nanometers, molecules have a certain fundamental attractiveness because of their size, because they represent the ultimate in terms of atomic control over physical properties, and because of the diverse properties (e.g., switching, dynamic organization, and recognition) that can be achieved through such control.

In the crossed-wire circuit shown in Figure 1 (called a crossbar circuit), the molecular component is typically sandwiched between the intersection of two crossing wires. Molecular-electronics circuits based on crossbar architectures can be used for logic, sensing, signal routing, and memory applications (Luo et al., 2002). To realize such applications, many things must be considered simultaneously: the design of the molecule; the molecule/electrode interface; electronically configurable and defect-tolerant circuit architectures; methods of bridging the nanometer-scale densities to the submicrometer densities achievable with lithography; and others (Heath and Ratner, 2003). Using a systems approach in which all of these issues are dealt with consistently and simultaneously, we have been able to fabricate and demonstrate simple molecular-electronics-based logic, memory, and sensing circuitry.

The active device elements in these circuits are molecular-mechanical complexes (Figure 2) organized at each junction within the crossbar, as shown in Figure 3 (Heath and Ratner, 2003; Luo et al., 2002). The molecular structure in Figure 2 (left) is a [2]catenane that consists of two mechanically interlocked rings. One ring is a tetracationic cyclophane (TCP^{4+}); the other is a crown-ether-type ring with two chemical recognition sites, a dioxynapthyl (DN) group and a tetrathiafulvalene group (TTF). The structure on the right side of Figure 2 is a [2]rotaxane that consists of similar chemical motifs. Here the TCP^{4+} ring encircles a dumbbell-shaped structure that has both DN and TTF recognition groups. The molecules are switched via a one- or two-electron process that results in a molecular-mechanical transformation (and a significant change in the electronic structure) of the molecule. This type of molecular actuation, which can be rationally optimized through molecular design and synthesis, provides the basis for information storage or for defining the “open” and “closed” states of a switch.

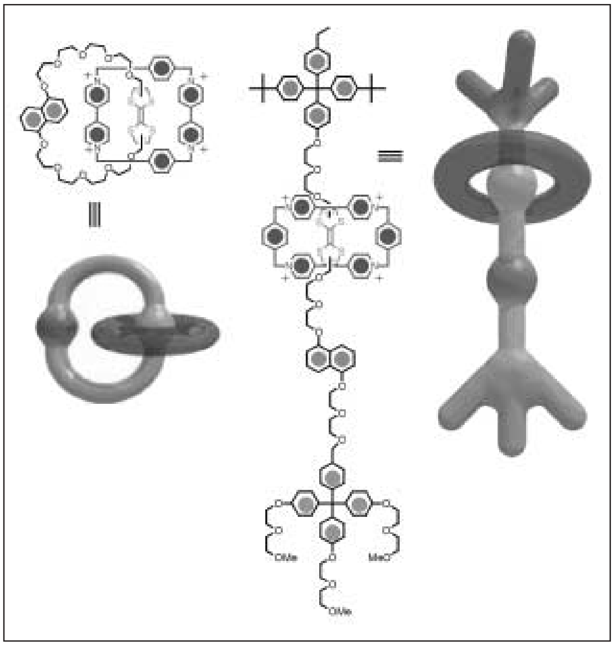

FIGURE 2 Two types of molecular mechanical complexes that have been demonstrated to work as molecular electronic switches. At left is a [2]catenane complex, and at right is a [2]rotaxane complex. For both structures, the tetracationic cyclophane (TCP^{4+}) ring encircles the tetrathiafulvalene (TTF) recognition unit. The lowest energy-oxidation state of either complex corresponds to removal of an electron from the TTF group. This leads to a coulombic repulsion of the TCP^{4+} ring so that it encircles the dioxynapthyl group. Molecular switches based on this concept have been demonstrated to work in solution, in solid polymer matrices, immobilized on solid surfaces, and sandwiched between two electrodes. Source: Collier et al., 2002.

Typical data from one of our molecular switches is shown in Figure 4 (we have incorporated additional data from various control molecules in this figure). For the structures shown in Figure 2, the controls include [2]catenanes with identical recognition sites (i.e., two DN groups), the dumbbell component of the [2]rotaxane structure, the TCP^{4+} ring, and others. One always does control experiments, of course, but controls are critical here, because these devices are difficult to characterize fully, and one of the few experimental variables is molecular structure. Perhaps the most fundamental challenge facing scientists constructing solid-state molecular-electronic devices and circuits is developing an intuition for guiding the design of the molecular components.

Charge transport through molecules has been known and studied for a long time, but it has traditionally been a solution-phase science (Joachim et al., 2000; Kwok and Ellenbogen, 2002; Mujica and Ratner, 2002; Nitzan, 2001; Ratner, 2002). For example, a critical component of electron-transfer theory in molecules is the solvent-reorganization coordinate. Molecular synthesis is also a solution-phase endeavor, and all of the analytical techniques (e.g., mass spectrometry, NMR, optical spectroscopy) are primarily designed to investigate the structure and dynamics of molecules in solution. When molecules are sandwiched between two electrodes, none of these theories and analytical techniques is of any use, and new concepts must be developed.

This situation is exacerbated because certain critical aspects of basic solid-state-device physics cannot be translated directly into the world of molecular electronics. For example, consider the following two fundamental tenets of solid-state materials. First, when two different materials are brought together, their Fermi levels align with each other. Second, if a conducting wire of length *L* has a measured resistance of *R*, then a wire of the same material and diameter, but with a length *2L*, will exhibit a resistance of *2R*. This is called ohmic conductance. Neither of these rules holds true for molecules. This is because molecular orbitals are spatially localized, whereas in solids the atomic orbitals form extended energy bands. When a molecule is adsorbed or otherwise attached to the surface of a solid, there is no straightforward way to think about the position of the molecular orbitals with respect to the Fermi level of the solid. Furthermore, if a molecule of length *L* yields a resistance value of *R*, then a similarly structured, but longer molecule could actually be a better

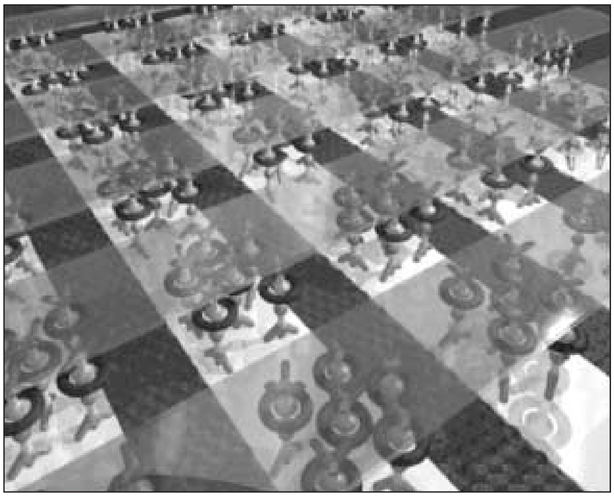

FIGURE 3 A computer graphic showing the molecular components in a crossbar circuit. The [2]rotaxanes molecules shown here are bistable molecular-mechanical compounds. The switching mechanism involves the translation of the ring between two binding sites along the backbone of the molecule. Molecular-electronic circuits have been demonstrated to work as both random-access memory circuits and simple logic circuits.

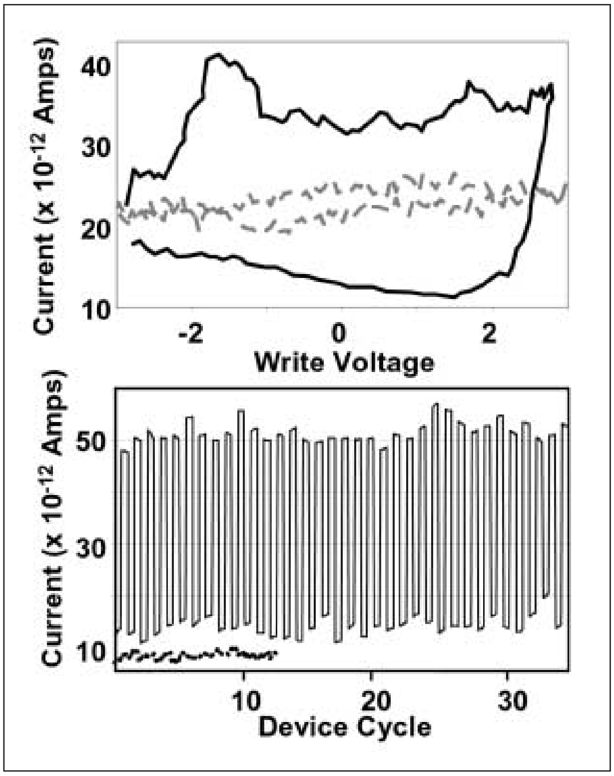

FIGURE 4 The hysteretic response (top) and switch cycling (bottom) of a molecular-electronic switch consisting of a bistable [2]rotaxane sandwiched between a polysilicon bottom electrode and a Ti/Al top electrode. The device dimensions are approximately 50 x 50 nm. Control data from the dumbbell component (the [2]rotaxane without the TCP^{4+} ring) are included.

conductor or, perhaps, a far worse conductor. There is no real ohmic conductance in molecules.

Thus, the fundamental challenge is to develop an intuition of how molecules behave in solid-state settings and to use that intuition as feedback to molecular synthesis. In fact, we need a method of characterizing molecular-electronic devices that yields the type of rich information generated by modern NMR spectroscopic methods. Perhaps the most promising approach is single-molecule, three-terminal devices in which a single molecule bridges a very narrow gap (called a break junction) between a source and a drain electrode. A third electrode (called the gate) provides an electric field for tuning the molecular-electronic energy levels into and out of resonance with the Fermi energies of the source and drain electrodes. These devices were originally developed by Park and McEuen and were then further explored by their two groups separately (Liang et al., 2002; Park et al., 2002). Figure 5 shows data from a single-molecule device containing the dumbbell component of the [2]rotaxane molecule shown in Figure 2 (Yu et al., 2003). These data show clearly that these types of device measurements represent a very high information-content analytical method. In an analogy to optical methods, the energy levels resolved in such a device span a very broad range of the spectrum, from ultraviolet to far infrared. This means that molecular orbital energies, and even low-frequency molecular vibrations, might be observable. How molecular orbitals align with the Fermi levels of electrodes, the coupling of molecular vibrations with charge transport through the molecule, and the nature of the molecule/electrode interface states are questions being addressed in various laboratories around the world.

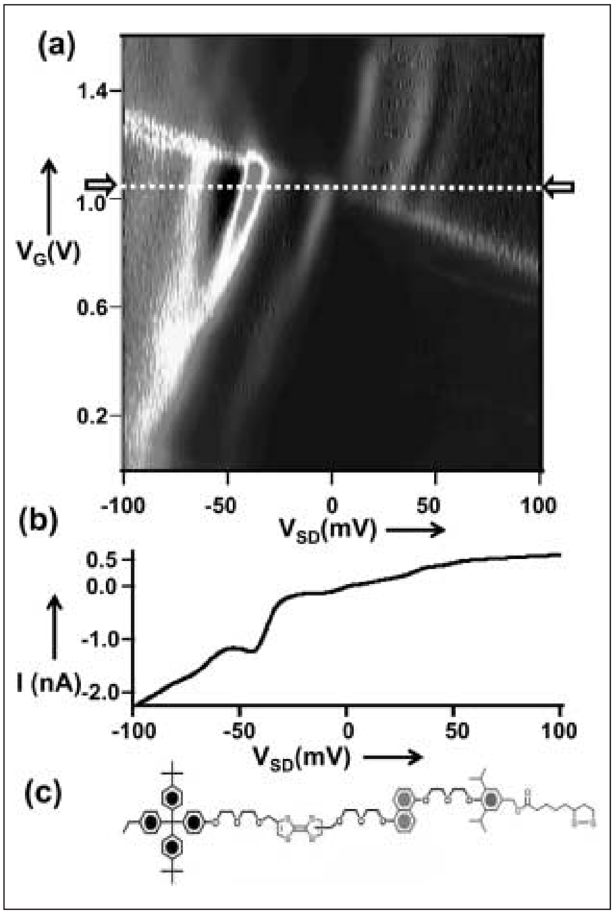

FIGURE 5 Data from a single-molecule, three-terminal device in which the dumbbell component of a [2]rotaxane molecular switch bridges a 4-nm gap separating a source and drain electrode. Voltage on a gate electrode is used to tune the molecular-energy levels into resonance with the electrode-energy levels. 5a. The conductance (dI/dV) of the molecular junction is plotted as a function of source-drain voltage (x-axis) and gate voltage (y-axis). Light colors indicate high conductance values. 5b. The current-voltage trace, drawn through the point indicated by the arrows and the dashed white line on the conductance plot. 5c. The structure of the molecule being measured in this junction. All measurements are carried out at 2 Kelvin.

Some of the critical length scales of circuits that can now be fabricated, such as the diameter of the wires and the interwire separation distance (or pitch), are more commonly associated with biological macromolecules, such as proteins, mRNA oligonucleotides, and so on, than with electronics circuitry. In fact, one unique application of nanoscale molecule-electronics circuitry, and perhaps the application that sets this field apart from traditional electronics, is the potential construction of an electrical interface to a single biological cell (Cui et al., 2001). One of our ongoing projects is constructing such an interface designed to measure, simultaneously and in real time, thousands of molecular signatures of gene and protein expression (Heath et al., 2003; Zandonella, 2003). This type of circuitry may eventually provide a direct connection between the worlds of molecular biology and medicine and the worlds of electrical engineering and integrated circuitry.

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Biocatalytic methods of detection and decontamination offer several advantages over existing methods.

Using Biotechnology to Detect and Counteract Chemical Weapons

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The tragedy of September 11, 2001, and the ensuing anthrax attacks heightened public and governmental awareness of the need for reliable, cost-efficient, and deployable diagnostic and treatment systems for chemical weapons. Many of the present methods require cumbersome equipment and complex analytical techniques. In addition, many decontamination solutions are toxic, corrosive, and flammable, and therefore not appropriate for use over large areas or with personnel. Biocatalytic methods of detection and decontamination/demilitarization offer several advantages over existing methods.

Enzymes are environmentally benign, highly efficient biological catalysts on appropriate reactants, with hydrolysis rate enhancements exceeding a million fold over the uncatalyzed reactions. They may also be used in conjunction with other processes to limit the environmental impact of existing systems. Perhaps the most attractive feature of enzymes is that they can function effectively under ambient conditions, thus decreasing energy costs and increasing safety (especially when agents are stored in proximity to explosives). To date, enzymes are the most effective known catalysts for

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degrading nerve agents (organophosphates [OP] are the class of compounds commonly referred to as nerve agents). Enzyme concentrations in the micromolar range are sufficient to degrade nerve agents on contact, and just 10 milligrams of enzyme can degrade as much nerve agent as 1 kilogram of concentrated bleach (a conventional method of degrading nerve agent).

> *Enzyme concentrations in the micromolar range are sufficient to degrade nerve agents on contact.*

The study of OP biocatalysis dates back to the mid-1940s, when Abraham Mazur found that mammalian tissue hydrolyzed OP esters (Mazur, 1946). Douglas Munnecke (1977) used cellular extract from a mixed bacterial culture as a catalyst to detoxify organophosphorous pesticide. The rate of enzymatic hydrolysis of parathion, an OP ester commonly used in pesticides, was found to be nearly 2,500 times the rate of hydrolysis in 0.1 *Normal* sodium hydroxide. Munnecke (1979) later attempted to immobilize the extract on porous glass and porous silica beads. It was reported that 2 to 5 percent of activity present in a cellular extract could be retained by the beads, and 50 percent of the immobilized activity could be maintained for a full day under ambient conditions.

The enzyme organophosphorus hydrolase (OPH) was later isolated and shown to be an effective catalyst for the degradation of a range of OP esters. Frank Raushel and colleagues have studied extensively the activity and stability of OPH from *Pseudomonas diminuta* (Dumas et al., 1989). At Texas A&M University, James Wild's laboratory has even produced the enzyme in corn (personal communication). Squid diisopropylfluorophosphotase (DFPase), an enzyme capable of degrading nerve agents, such as soman, is now in commercial production. In expanding the library of such enzymes, Joseph DeFrank and colleagues from the U.S. Army have discovered and analyzed another nerve agent-degrading enzyme, organophosphorus acid anhydrolase (OPAA) (DeFrank and Cheng, 1991).

Many species produce enzymes that efficiently degrade nerve agents, although the natural function of these enzymes remains unknown. The class of OP compounds has only been exposed to nature for a few decades, certainly not long enough for natural systems to have evolved enzymes to degrade them. Thus, the ability of enzymes to degrade these compounds is still an unexplained quirk of fate. The only nerve agent-degrading enzyme with a known natural function is OPAA, which is a peptidase enzyme (an enzyme that catalyzes the hydrolysis of peptides into amino acids). Interestingly, this enzyme is far less active with its natural substrate than with soman.

Cells must constantly control their environments and, therefore, must be in a position to rapidly manipulate the concentrations of biocatalysts. Thus, many proteins, such as enzymes, last for only minutes or hours under ambient conditions, and enzymes have generally evolved to be unstable molecules. A number of research groups around the world have been working for many years to stabilize enzymes for numerous applications, including catalysts for the decontamination of nerve agents. These mostly military researchers are also part of a NATO project group (PG31) working to formulate "green" enzyme-based decontamination systems.

Because the preparation and purification of enzymes can be costly, enzymes must be immobilized to increase their reusability and stability. Effective immobilization requires that the enzyme-containing material be prepared so that the enzyme maintains most of its native activity, maintains a high operational stability in its working environment, and maintains a high storage stability. In conventional immobilization methods, either covalent or ionic interactions link the protein to a support material. Enzymes have been immobilized on a wide variety of support materials, including alumina pellets, trityl agarose, and glass/silica beads. Polymers also make excellent enzyme-support materials because of their structural flexibility and solvent resiliency. Numerous polymers, including nylons, acrylates, and several copolymer blends, have been used as effective supports.

Combining the power of biology with the sophistication of polymers presents considerable opportunities. Synthesis of enzyme-containing polymers involves the covalent immobilization of the enzyme directly into the polymer network via reactive functionalities on the enzyme surface, thus ensuring retention of the enzyme in the polymeric material. Bioplastics prepared in this way exhibit remarkable stability under normally deactivating conditions and, thus, are ideal for the development of the next generation of responsive, smart biomaterials. One of the most pressing needs at the beginning of the twenty-first century is for active, smart materials for chemical defense.

The threat of chemical weapons is now ubiquitous, and these poor man's nuclear weapons can kill on contact. Existing chemical defense polymers are designed to provide an impenetrable barrier between us and our environment. By contrast, layered materials use polymers to bind toxic chemical agents irreversibly to the material. Degrading toxic chemicals requires catalysts that can be incorporated into the polymer in a stable and active form.

In protective clothing, a layer of polyurethane, foam-entrapped, activated charcoal is embedded between several layers of polyester fabric. Polyurethanes are effective substrates for OP adsorption, and reports have documented that polyurethane foam particles can be used as adsorbent materials for pesticide vapors in farming fields. If proteins could be incorporated into polyurethanes, some interesting materials might emerge.

Enzyme-containing polyurethane materials are ideal matrices because of their ease of preparation, the large range of polymer properties that can be prepared, and multipoint, covalent attachment of the enzyme to the polymer. Bioplastics are prepared by reacting a polyurethane prepolymer that contains multiple isocyanate functionalities with an aqueous solution containing the enzyme. The solubility of enzymes in this aqueous phase can be significant, enabling loadings up to 15 percent. Foams, gels, and coatings can be prepared depending on the reactivity of the isocyanate. Any enzyme that is present in the aqueous solution can participate in the polymer synthesis, effectively creating an enzyme-containing-polymer network with multipoint attachment.

The key question is how well such biopolyurethanes function. The answers are striking. Enzymes can be stabilized from days to years, and the enzymes in no way alter the physical properties of the polyurethane. The derived materials are so active that just 1 kilogram of enzyme immobilized in a multipoint covalent fashion is enough to degrade up to 30,000 tons of chemical agent in one year.

Detoxifying a chemical agent is only part of the technology we will need to combat the real and present danger posed by these materials. Once a toxic agent binds to a surface, it must be degraded and identified. Indeed, every time a chemical or biological sensor gives a false-positive result, tens of thousands of dollars are invested in responses that are not needed. In the Middle East and Africa, false positives could lead to war; and spurious, sensor-triggering events could change the course and nature of a war.

Chemical sensors in particular are generally unreliable, and engineering solutions to the problem will require overcoming some formidable technical challenges. We must first understand how chemical weapons work and use that knowledge to design biologically based sensing devices. The common feature of biosensors to date has been a lack of stability. An effective chemical-weapon sensor must not only be able to operate under ambient conditions, but must also be able to operate in extreme desert and arctic conditions.

A material that is inherently catalytic and can therefore be used to monitor continuously and detoxify detected molecules in real time represents the "holy grail" of this emerging discipline. Indeed, a surface that can both self-decontaminate and sense the progress of decontamination would represent a quantum improvement in protection for war fighters. The rapid detection of chemical agents is critical to inspections performed under the Chemical Weapons Convention, because inspectors are rarely able to control the environment at the inspection site. It is therefore essential that analytical tools vary in sensitivity, specificity, and simplicity.

Chemical weapons are the poor man's nuclear weapons.

The selectivity of enzymes that are active on, or inhibited by, chemical agents of interest, makes them attractive components for biosensor technology. Nerve agents exert their biological effect by inhibiting the hydrolytic enzyme, acetylcholinesterase. Thus, the inhibition of this enzyme makes it ideal for use in nerve agent-sensing systems. The most common kit available today for agent detection, the M256A1, uses enzymes and colored substrates to detect nerve agents. Unfortunately, current continuous enzyme-based sensing is limited by the instability of most enzymes and their sensitivity to changes in the environment. The M256A1 functions by reacting phenylacetate with eel acetylcholinesterase to produce a colored material. If an agent or other inhibitor is present, the color does not appear. The test takes 15 minutes to perform and is subject to interference from a number of sources (Table 1). Another drawback is the inability of the M256A1 to distinguish between different nerve agents. All of these techniques rely on the absence of a reaction to signal the presence of an agent. These sensors would be much more informative if they provided positive responses (e.g., undergoing a color change when the surface is either clean or contaminated). Nevertheless, enzyme-inhibition assays are commonly used to detect nerve agents.

TABLE 1 Sensitivity of Nerve-Agent Sensors to Various Kinds of Interference

	Sensor				
Interference	**M8**	**M9**	**M256**	**M272**	**CAM**
High temperature	Yes	Yes	Yes	Yes	No
Cleaning solvents	Yes	Yes	No	No	No
Petroleum products	Yes	Yes	Yes	Yes	Yes
Antifreeze	No	Yes	No	No	No
Insect repellant	Yes	Yes	Yes	No	Yes
Dilute bleach	Yes	Yes	Yes	Yes	No
Water	No	Yes	No	No	No

Source: Longworth et al., 1999.

Note: "Yes" indicates the sensor is sensitive to the interference. "No" indicates the sensor is not sensitive to the interference.

In 2001, an enzyme-based sensor was developed and fielded that combines all of the desirable features and is resistant to almost all types of interference. The sensor is based on coupling the hydrolytic activity of acetylcholinesterase (an acid-producing reaction) with the biocatalytic hydrolysis of urea (a base-producing reaction). In an unbuffered solution containing substrate, the formation of acid by acetylcholinesterase-catalyzed hydrolysis would lead to a rapid drop in pH. Because changes in pH affect the ionization state of amino-acid residues in a protein's structure, every enzyme has an optimal pH at which its catalytic activity is greatest (Figure 1). As the pH deviates from the optimal level, enzyme activity decreases. Therefore, the pH of the unbuffered solution ultimately reaches a point at which acetylcholinesterase is completely inactivated.

Now consider the idealized situation in which the unbuffered solution containing the acid-producing enzyme is supplemented with a second enzyme that catalyzes the formation of base (Figure 1). In this system, the base-producing enzyme (light line) has a pH optimum significantly lower than that of the acid-producing enzyme (dark line). Thus, the formation of base will counteract the production of acid, thereby maintaining pH by creating a dynamic pH equilibrium between the competing enzyme reactions (pH 7.5 in Figure 1). Because the generation of base is biocatalytic, base is produced only in response to a decrease in pH. If the catalytic activity of one of the enzymes is altered via inhibition, the dynamic equilibrium of the system is destroyed; the subsequent shift in pH caused by the inactivation of the dynamic equilibrium can then be used to induce a signal indicating the presence of a target enzyme inhibitor.

This is the basis for biocatalytic, dynamic-reaction equilibrium sensing. The advantages over traditional enzyme sensors include: rapid signal development; strong and intuitive responses; and high resistance to interference by temperature. An interferant-resistant nerve-agent sensor manufactured by Agentase, LLC, couples acetylcholine, acetylcholinesterase, urea, and urease in a polymer with a pH-sensitive dye.

In the rare event a weapon of mass destruction is used, such as another release of sarin in the Tokyo subway, no effective, environmentally benign decontamination systems are available. Even though enzymes provide an efficient, safe, and environmentally benign method of decontaminating nerve agents, several major hurdles still hinder their use. To decontaminate significant quantities of nerve agent, the system will require a good buffering system to handle the large amounts of acid produced from the enzyme-catalyzed hydrolysis. This problem is amplified in low-water environments, where the localized concentration of agent can easily reach 0.3 molar.

Currently, the preferred buffer for enzymatic decontamination systems under development by the U.S. Army is ammonium carbonate. The addition of solid ammonium carbonate to water results in a pH of 8.5 to 9.0 with no adjustment needed, and the ammonium ions are known to stimulate the activity of OPAA (Cheng and Calomiris, 1996). Ammonium carbonate, however, does not have a high buffering capacity, thus making it impractical for use in large-scale decontamination.

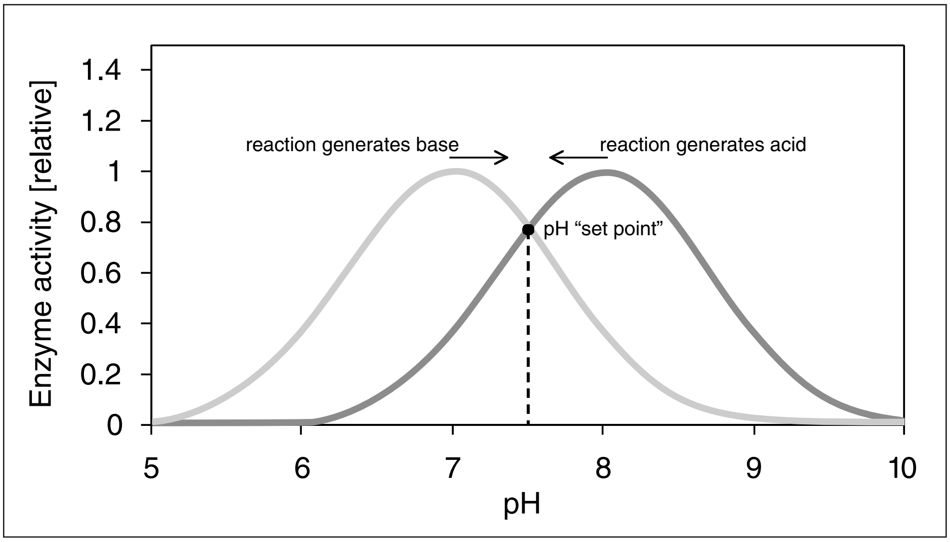

FIGURE 1 The pH dependence curves of two enzyme-catalyzed reactions. The base-producing enzyme (light line) has a lower optimal pH than the acid-producing enzyme (dark line). When both enzymes are present, the pH instantaneously stabilizes at the intersection point, which we call the pH "set point."

Recent studies at Porton Down, U.K., demonstrated that in detergent and microemulsion systems containing 50 *millimolar (mM)* ammonium carbonate buffer, enzymatic degradation of high concentrations of soman (1.3 to 1.5 percent) resulted in a drop in pH from 9 to 6 in less than five minutes, at which point the enzyme was inactive. Complete decontamination of the agent was not achieved. Increasing the concentration of buffer two-fold decreased the rate of drop in pH; the pH fell to 6 in less than eight minutes. However, complete decontamination was still not achieved. The use of conventional biological buffers at concentrations sufficient to maintain pH in an optimum range for enzyme activity introduces additional obstacles, including potential enzyme inhibition and chelation of essential metals in the enzyme structure.

The biocatalytic, dynamic-reaction equilibrium approach previously described can overcome such obstacles in the large-scale decontamination of nerve agents. Base can be generated on demand in response to the decrease in pH resulting from agent degradation. Consider an unbuffered aqueous system that includes a nerve agent-degrading enzyme, urea, and urease. In the presence of a nerve agent, biocatalytic hydrolysis would cause a rapid decrease in pH. In a method analogous to biocatalytic, dynamic-reaction, equilibrium sensing, this decrease activates urease, which generates base via the conversion of urea. Our laboratory has successfully demonstrated using biocatalytic, dynamic-reaction, equilibrium sensing for the complete decontamination of paraoxon by OPH, using urease-catalyzed urea as a buffering agent (Russell et al., 2002). Such defense systems present a significant advancement in chemical weapons defense, giving military personnel and emergency response teams the ability to achieve complete decontamination using minimal amounts of buffering material.

In summary, chemical weapons exert their terrifying effects on human physiology by interrupting biological processes. The chemicals bind tightly to enzymes, but they can also be degraded by enzymes through fortuitous side reactions. The inhibition and activity of these enzymes can be part of our defensive arsenal. Thus, biotechnology is both the target and a potential weapon in the war on terrorism.

Acknowledgements

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Attacks on the Internet can be expensive and inconvenient, but they are not generally dangerous.

Internet Security

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William R. Cheswick

One of the design principles of the Internet was to push the network intelligence to the "edges," to the computers that use the network rather than the network itself (Saltzer et al., 1984). Any given edge computer could send packets to any other edge host, leaving the details of packet delivery to the routers in the center of the network. This principle greatly simplified the design of the routers, which simply had to hot-potato packets toward the appropriate edge host as efficiently as possible. Routers could drop packets if there was congestion, leaving the edge hosts to provide reliable data delivery. Under this scheme, routers could relay packets with few complications, and they could be implemented in state-of-the-art hardware. Routers at the core of the Internet have benefited from Moore's Law and operated at its limits since the late 1970s.

This approach is in direct contrast to the standard telephone system, in which the intelligence resides in centrally controlled phone switches, and the edges have dumb terminals (i.e., standard telephones). In the phone system, the phone company invents and implements the technology. In the decentralized Internet approach, edge computers can install arbitrary new protocols and capabilities not envisioned by the designers of the Internet; the World Wide Web is the most obvious example.

As a result of this design, most current newspaper articles covering the Internet refer to things that happen at the edges. Viruses infect PC clients, worms attack network servers, and the Internet dutifully delivers denial-of-service attack packets to the edges. (For the security concerns of edge hosts, see Wagner, in press.)

Most Internet edge hosts play the role of "clients" or "servers," despite the popular use of the term "peer-to-peer" networking. A client requests a connection, and a server provides the service. Servers usually take all comers and must be accessible to a large number of hosts, most of which are clients and are privately owned. Hosts must connect to servers but aren't necessarily servers, which makes them harder to attack.

A large majority of edge computers on the Internet are probably susceptible to attack and subversion at any given time. Because it is not economically feasible to harden all of these hosts, they are isolated from the rest of the Internet and many potential attacks by breaking the end-to-end model. It is impossible to mount a direct attack on a computer that cannot be reached. The trade-off between security and functionality does decrease the envisioned power and functionality of the Internet somewhat. Often, there is no satisfactory trade-off: the choice is between an unsafe service and no service at all.

> *There may be no satisfactory trade-off. The choice may be between an unsafe service and no service at all.*

Enclaves of edge computers are isolated topologically, through firewalls, routing tricks, and cryptography. At the same time, trusted communities of hosts, called intranets, allow businesses to operate with a reduced probability of successful attacks. This approach tends to create an organization with a hard outside and a soft, chewy center. Insider attacks can (and do) occur fairly often, and perimeter defenses often, even usually, contain holes.

Firewalls

Although network services can (and should) be hardened when necessary, the easiest defense is to get out of the game—to turn off the service or render it unreachable by attacking hosts. This can done by completely disconnecting the network from the Internet (as some high-security government networks have done) or by connecting it through a device that blocks or filters incoming traffic, called a firewall. Complete disconnection offers the best security, but it is very unpopular with most users, who may then seek to use *sub rosa* connections.

Nearly all corporate networks, and portions of many university networks (which have traditionally been open and unfiltered), use firewalls of varying strictness to cleanse incoming packet flows. Most consumers also have firewalls in their cable modems, DSL routers, wireless base stations, or client computers.

Firewalls provide a central site for enforcing security policies. Many companies provide a few firewalls as gateways between the corporate intranet and the Internet, equipped with the rules and filters to enforce the company's security policies. The Internet security expertise, which is scarce and expensive, is situated at a few centralized choke points. This lowers the costs of configuring perhaps hundreds of thousands of corporate hosts to resist software attacks from random strangers and malicious software ("malware").

Firewalls, a form of the classic perimeter defense, are supposed to offer the only connections between an intranet and the Internet, but long perimeter defenses can be difficult to monitor. A firewall may amount to circling the state of Wyoming, but modern corporate intranets can span the world. Therefore, it can be easy to add an unauthorized connection that breaches the perimeter without the knowledge of the centralized authority. Company business units and rogue employees may believe they have a compelling need—often a business need—to access the Internet in a way not permitted by corporate policy. For example, it may take time to get approvals for new services, and the new services may require filters that take time to install or may simply be impractical—overconstrained by a poorly designed protocol that doesn't admit to easy filtering. An employee who decides it is better to apologize later than to get permission now might make his or her own connection.

Unauthorized connections that pierce the corporate perimeter may come from business partners, misconfigured gateways, or newly acquired companies. Even if unauthorized connections have been installed for good business reasons, the reason, and the person who understood the reason, may be long gone by the time a problem is identified. A new network administrator may have to choose between (1) closing down a suspect Internet connection and risking a vital business service and (2) leaving the connection up and allowing invaders into the company.

Rogue connections are often mistakes. It is easy to misconfigure virtual private networks (VPNs), Internet tunnels linking disconnected islands of trust (e.g., linking remote office networks or home computers with headquarters). Company employees often connect to a corporate network using encryption to conceal their data, thus creating a VPN that can interconnect home and office. An employee can also create a hole in the corporate perimeter. (My company's principal business is to find these holes.)

If you are in charge of such a network, how can you deal with these problems? The most effective network administrators aggressively manage their networks. They control new and existing connections carefully. They use mapping tools to detect new routes and connections. They are equipped with, and use, aggressive management controls—violators of policy can be and are fired and even prosecuted.

Perimeter defenses like firewalls can be effective, and there are periodic pop-quizzes from the Internet itself that prove this. For example, if a widespread worm does not appear on an intranet, you may be reasonably sure that the perimeter does not have overt holes. Firewalls have limitations, of course. Attacks can come from inside an intranet, and many attacks or weakness are caused by stupidity rather than malice. (One government network administrator said he had more problems with morons than with moles.) An intranet must be hardened from internal attacks, which brings us back to host-based security.

Routing Limitations

You cannot directly attack a host you cannot reach. Besides firewalls, which can block access to a community of hosts, the community can also use network addresses that are not known to the Internet. If the Internet routers don't know how to reach a particular network, an Internet edge host probably cannot send packets to that network. A community with an official set of private addresses that are guaranteed never to be announced on the Internet can use these addresses to communicate locally, but the addresses are not reachable from the Internet. The community can still be attacked through intermediate hosts that have access to both private and public address spaces, and many viruses and worms spread this way.

Some attacks on the Internet come from host communities that are only announced on the Internet intermittently. The networks connect, the attacks occur, and then the networks disconnect before a pursuit can be mounted. To give a community using private address space access to the Internet, one uses network address translation.

> *By one account, a class B network (about 65,000 IP addresses) has a street value of $1 million.*

Network Address Translation

The Internet has grown, with very few tweaks, by more than nine orders of magnitude—a testament to its designers. But we are running uncomfortably close to one design limit of IP version 4, the technical description of the Internet and intranets, and their basic protocols. We have only about three billion network addresses to assign to edge hosts, and about half of them are currently accessible on the Internet, and more have been assigned. Thus, address space has gotten tight; by one common account, a class B network (roughly 65,000 IP addresses) has a street value of $1 million.

A solution that emerged from this shortage was a crude hack called "network address translation" (NAT). Many hosts hide on a private network, using any network address space they wish. To communicate with the real Internet, they forward their packets through a device that runs NAT, which translates the packet and sends it to the Internet using its own address as the return address. Returning packets are translated to the internal address space and forwarded to the internal host. A home network full of game-playing children probably looks like one busy host from the Internet.

Instead of the end-to-end model, in this model many hosts route their packets through a single host, sharing that host's network address. Only one, or one small set of network addresses is used, conserving official Internet address space.

This model has had a useful implication for security. Hosts on the home network cannot be easily scanned and exploited from the outside. Indeed, it takes some work to detect NAT at all (Bellovin, 2002). Internal hosts enjoy considerable protection in this arrangement, and it is likely that some form of NAT will be used often, even when (if?) IP version 6 (a new protocol description with support for a much larger address space) is deployed. A special configuration is required on the NAT device to provide services to the Internet. The default configuration generally offers no services for this community of hosts, and safe defaults are a good design.

Emerging Threats to the Internet

Although one can connect safely to the Internet without a topological defense, like skinny dipping, this involves an element of danger. Host security has to be robust, and the exposed machines have to be monitored carefully. This is exactly the situation faced by web servers. A server like *www.budweiser.com* must have end-to-end connectivity so customers can reach it. Often commercial web services have to connect to sensitive corporate networks (think of FedEx and its shipping database or a server for online banking.) These web sites must be engineered with great care to balance connectivity and security.

Like skinny dipping, connecting to the Internet without a topological defense involves an element of danger.

The Internet is a collaboration of thousands of Internet service providers (ISPs) using the TCP/IP protocols. There is somewhat of a hierarchy to the interconnections; major backbone providers interconnect at important network access points and feed smaller, more local ISPs.

The graphical and dynamic properties of the Internet are popular research topics. Some recent studies have suggested that the Internet is a scale-free network, which would have important implications for sensitivity to partitioning. But this conclusion overlooks two issues. First, the raw mapping data used to build graphical descriptions are necessarily limited. Internet mapping is not perfect, although it is getting better (Spring et al., 2002). Second, the most critical interconnections were not formed by random processes or by accident, as perhaps are other "six degrees of separation" networks. Internet interconnections, especially backbone connections, have been carefully engineered by their owners over the years and have had to respond to attacks and a variety of misadventures, occasionally backhoes. These experiences have helped harden critical points in the network. (Network administrators do not like wake-up calls at 3 a.m., and unreliability is a bad component of a business model.)

But there are weaknesses, or at least obvious points of attack, in the core of the Internet. These include routing announcements, the domain name system (DNS), denial-of-service (DOS) attacks, and host weaknesses in the routers themselves.

Routing Announcements

A typical Internet packet goes through an average of 17 routers; the longest paths have more than 30 hops. A router's job is to direct an incoming packet toward the next hop on its way to its destination. For a router near an edge, this is simple—all packets are directed on a default path to the Internet. But routers on the Internet need a table of all possible Internet destinations and the path to forward packets for each one.

A routing table is built from information exchanged among Internet routers using the border gateway protocol (BGP). When a network connects or disconnects from the Internet, an announcement is sent toward the core routers; dozens of these routing announcements are generated every minute. If a core router accepts an announcement without checking it, it can propagate trouble into the Internet. For example, a router in Georgia once announced a path to MIT's networks through a local dial-up user. As a result, many parts of the Internet could not reach MIT until the announcement was rescinded. Such problems often occur on a smaller scale, and most ISPs have learned to filter routing announcements. Only MIT should be able to announce MIT's network announcements.

One can easily imagine an intentional attempt to divert or disrupt the flow of Internet traffic with false announcements or by interfering with BGP in some way. Because ISPs frequently have to deal with inadvertent routing problems, they ought to have the tools and experience to deal with malicious routing attacks, although it may take them a while, perhaps days, to recover.

The Domain Name System

Although the domain name system (DNS) is technically not part of the TCP/IP protocol, it is nearly essential for Internet operation. For example, one could connect to *http://207.171.181.16/*, but nearly all Internet users prefer *http://www.amazon.com*. DNS translates from name to number using a database distributed throughout the Internet. The translation starts at the root DNS servers, which know where to find *.go*, *.eddo*, *.czar*, etc. Servers' databases contain long lists of subdomains—there are tens of millions in the *.com* database—that point to the name servers for individual domains. For example, DNS tells us that one of the servers that knows about the hosts in *amazon.com* is at IP address *207.171.167.7*.

DNS can be and has been attacked. Attackers can try to inject false responses to DNS queries (imagine your online banking session going to the wrong computer). Official databases can be changed with phony requests, which often are not checked very carefully. Some domains are designed to catch typographical errors, like *www.amazon.com*.

In October 2002, the root name servers came under massive denial-of-service (DOS) attacks (see below). Nine of the 13 servers went out of service—the more paranoid and robust servers kept working because they had additional redundancy (a server can be implemented on multiple hosts in multiple locations, which can make it very hard to take down). Because vital root DNS information is cached for a period of time, it takes a long attack before people notice problems.

Denial-of-Service Attacks

Any public service can be abused by the public. These days, attackers can marshal thousands of hacked computers, creating "botnets" or "zombienets." They can subvert large collections of weak edge hosts and run their own software on these machines. In this way, they can create a large community of machines to direct packets at a target, thus flooding target computers, or even their network pipes, to degrade normal traffic and make it useless. These packets can have "spoofed" return addresses that conceal their origins, making trace-back more difficult. DOS attacks occur quite often, frequently to politically unpopular targets; Amazon, Microsoft, and the White House are also popular targets. Some PC viruses spread and then launch DOS attacks.

The Internet infrastructure does not provide a means for trace-back or suppression of DOS attacks, although several techniques have been proposed. Targeted hosts can step out of the way of attacks by changing their network addresses. Added host and network capacity at the target is the ultimate protection.

Routers as Edge Hosts

Security problems for routers are similar to those for hosts at the edge of the network. Although routers' operating systems tend to be less well known and not as well understood as those of edge hosts, they have similar weaknesses. Cisco Systems produces most of the Internet routers, and common failures in their software can subject those routers to attack. (Of course, other brands also have weaknesses, but there are fewer of these routers.)

Attacks on routers are known, and underground groups have offered lists of hacked routers for sale. The holes in routers are harder to exploit, but we will probably see more problems with hacked routers.

Attackers can marshal thousands of hacked computers, creating "botnets" or "zombienets."

Botnets

Attackers are looking for ways to amplify their packets. The Smurf attacks in early 1998 were the first well known attacks that used packet amplification (CERT® Coordination Center, 1998). The attackers located communities of edge computers that would all respond to a single "directed-broadcast" packet. These "tickling" packets had spoofed return addresses of the intended target. When community members all responded to the same tickling packet, the target was flooded with hundreds or even thousands of packets.

Most amplification networks now block directed-broadcast packets. At this writing, *netscan.org* has a list of some 10,000 broken networks with an average amplification of three, barely enough for a meaningful attack. So the hacking community began collecting long lists of compromised hosts and installed slave software on each one. These collections have many names—botnets and zombienets, for example. A single anonymous host can instruct these collections to attack a particular site. Even though the target knows the location of these bot hosts (unless they send packets with spoofed return addresses), there are too many to shut down.

Worse, the master can download new software to the bots. They can "sniff" local networks, spread viruses or junk e-mail, or create havoc in other ways. The master may use public key encryption and address spoofing to retain control over the botnet software and hide the source of the master.

The latest development is the use of botnets to hide the identity of web servers. One can put up an illegal web server, and traffic to the server can be laundered through random corrupted hosts on the Internet, making the actual location of the server quite difficult to find.

Conclusion

Most hypothesized Internet security problems on the Internet have eventually appeared in practice. A recent one, as of this writing, was a virus that patches security problems as its only intended action—in other words, a "good" virus. (Of course, it had bugs, as most viruses do.) I first heard proposals for this approach some 15 years ago. Although well intentioned, it is a bad idea.

The good news is that nearly all Internet attacks, real or envisioned, involve flawed software. Individual flaws can be repaired fairly quickly, and it is probably not possible to take the Internet down for more than a week or so through software attacks. Attacks can be expensive and inconvenient, but they are not generally dangerous. In fact, the threats of cyberterrorism devalue the meaning of "terror."

There's more good news. The Internet continues to be a research project, and many experts continue to work on it. When a dangerous, new, and interesting problem comes along, many experts drop what they are doing and attempt to fix it. This happened with the Morris worm in 1988 and the SYN packet DOS attacks in 1996, for which there was no known remediation at the time. Major attacks like the Melissa virus were quelled within a week.

The success of the Internet has fostered huge economic growth. Businesses have learned to control the risks and make successful business models, even in the face of unreliable software and network connections. Insurance companies are beginning to write hacking insurance, although they are still pondering the possible impact of a widespread, Hurricane Andrew-like Internet failure. I think we have the tools and the experience to keep the Internet safe enough to get our work done, most of the time.

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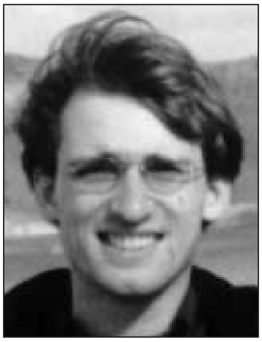
The engineering and programming of biochemical circuits, in vivo *and* in vitro, *could transform industries that use chemical and nanostructured materials.*

DNA Computing by Self-Assembly



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Erik Winfree

Information and algorithms appear to be central to biological organization and processes, from the storage and reproduction of genetic information to the control of developmental processes to the sophisticated computations performed by the nervous system. Much as human technology uses electronic microprocessors to control electromechanical devices, biological organisms use biochemical circuits to control molecular and chemical events. The engineering and programming of biochemical circuits, *in vivo* and *in vitro*, would transform industries that use chemical and nanostructured materials. Although the construction of biochemical circuits has been explored theoretically since the birth of molecular biology, our practical experience with the capabilities and possible programming of biochemical algorithms is still very young.

In this paper, I will review a simple form of biochemical algorithm based on the molecular self-assembly of heterogeneous crystals that illustrates some aspects of programming *in vitro* biochemical systems and their potential applications. There are two complementary perspectives on molecular computation: (1) using the astounding parallelism of chemistry to solve mathematical problems, such as combinatorial search problems; and (2) using biochemical algorithms to direct and control molecular processes, such as complex fabrication tasks. The latter currently appears to be the more promising of the two.

Some major theoretical issues are common to both approaches—how algorithms can be encoded efficiently in molecules with programmable binding interactions and how these algorithms can be shown to be robust to asynchronous and unreliable molecular processes. Proof-of-principle has been experimentally demonstrated using synthetic DNA molecules; how well these techniques scale remains to be seen.

Algorithmic Self-Assembly as Generalized Crystal Growth

The idea of algorithmic self-assembly arose from the combination of DNA computing (Adleman, 1994), the theory of tilings (Grunbaum and Sheppard, 1986), and DNA nanotechnology (Seeman, 2003). Conceptually, algorithmic self-assembly naturally spans the range between maximal simplicity (crystals) and arbitrarily complex information processing. Furthermore, it is amenable to experimental investigation, so we can rigorously probe our understanding of the physical phenomena involved. This understanding may eventually result in new nanostructured materials and devices.

DNA Computing

Leonard Adleman's original paper on DNA computing contained the seed of the idea we'll pursue here—that the programmability of DNA hybridization reactions can be used to direct self-assembly according to simple rules. In the first combinatorial-generation step of Adleman's procedure, DNA molecules representing all possible paths through the target graph were assembled by DNA hybridization in a single step. The basic idea (Figure 1) is for a set of molecules with unique sequences to represent the vertices and edges of the graph, thus governing which vertices can follow which other vertices. Each possible sequence of hybridization reactions, occurring spontaneously in any order, produces a double-stranded DNA molecule whose sequence encodes a valid path through the graph. By thus generalizing one-dimensional polymerization to include programmable binding, Adleman coaxed the DNA to generate patterns that follow certain mathematical rules. This is an elegant idea—and it works! The problem is that only simple computations can be performed with linear self-assembly. Paths through graphs correspond to regular languages, which have the complexity of finite-state machines—thus more sophisticated aspects of computation cannot be reached by this technique.

Tiling Theory

A tiling is an arrangement of a few basic shapes (called tiles) that fit together perfectly in the infinite plane. For each tiling, the set of shapes must be finite; for example, the tile set could consist of an octagon and a square, both with unit-length sides. One motivation for studying tiling is that the tiles correspond to the periodic arrangement of atoms in crystals. A remarkable result is that all possible periodic arrangements can be classified according to their fundamental symmetries; in three dimensions there are 230 symmetries, and in two dimensions there are 17 symmetries. This suggests that, given a finite set of polygonal tiles, one should be able to determine whether they can be arranged according

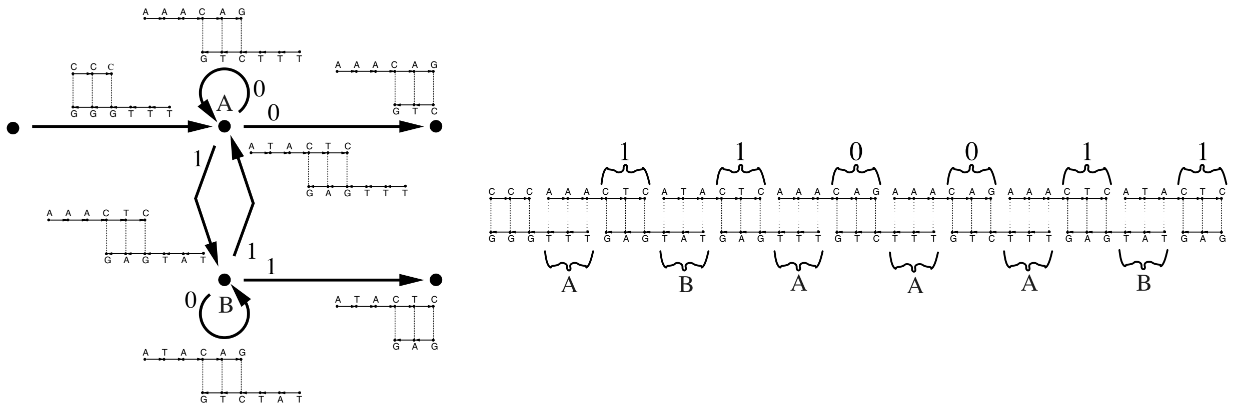

FIGURE 1 Linear self-assembly of DNA can be directed to follow valid paths through a graph. Sequences used in practice would have 15–30 nucleotides for each domain, rather than 3 nucleotides as shown here.

to one of the known symmetries, or whether there is no way to arrange them on the plane.

This is what Hao Wang thought in the 1960s, but when he looked into the question, known as the tiling problem, he discovered that it is provably unsolvable (Wang, 1963)! That is to say, aperiodic tilings are also possible. In addition, it can be incredibly difficult to determine whether a given set of tiles can tile the plane aperiodically or whether every attempt will ultimately fail. To prove this result, Wang developed a way to create a set of tiles that fit together uniquely to reproduce the space-time history of any chosen Turing[1] machine, in such a way that, if the Turing machine halts (with an output), then the attempted tiling has to get stuck; if the Turing machine continues computing forever, then a consistent global tiling is possible.

Thus, the tiling problem reduces to the halting problem, the first problem proved to be formally undecidable. This result shows that tiling is theoretically as powerful as general-purpose computers. In fact, the tiles Wang used were all essentially square, distinguished only by labels on their sides that had to match up when the tiles were juxtaposed. Thus, the complexity arises from the logical constraints in how the tiles fit together, rather than from the tiles themselves.

Given the intimate relation between crystals and tiling theory, it is natural to ask if crystal growth has the potential to compute as powerfully. To answer this question, we need two things: (1) the ability to design molecular Wang tiles; and (2) precise rules for crystal growth that can be implemented reliably.

DNA Nanotechnology

We now turn to DNA nanotechnology, the brainchild of Nadrian Seeman's vision of using DNA as an architectural element. Like RNA, DNA can make structures other than the usual double helix. These other structures include hairpins and three- and four-way branch points, which are important for biological function. Seeman, however, pictured these structures as hinges and joints, bolts and braces that could be programmed to fold and bind to each other by careful design of the DNA base sequence. Seeman and his students constructed a wide variety of amazing nanostructures: a wire-frame cube and truncated octahedron; single-stranded DNA and RNA knots, including the trefoil, the figure-eight, and Borromean rings; and rigid building-block structures, such as triangles and four-armed "bricks" known as double-crossover (DX) molecules; and more (Seeman, 2003).

The idea, then, is to use these "bricks" as molecular Wang tiles (Winfree et al., 1998a). The four arms of the DX molecules can be given sequences corresponding to the labels on the four sides of the Wang tiles. Thus, any chosen Wang tile can be implemented as a DNA molecule. Appropriate design of the molecule will encourage assembly into two-dimensional sheets.

In the 1960s, Hao Wang discovered that the tiling problem is provably unsolvable.

The problem, then, is to ensure that the growth process results in tile arrangements in which all tiles match with their neighbors. It is easy, however, to envision ways of putting the tiles together so that the tiles match at each step but soon create a configuration for which there is no way to proceed without creating a mismatch or having to remove offending tiles. This situation is analogous to the distinction between uncontrolled precipitation, which occurs rapidly when there is a strong thermodynamic advantage to aggregation, and quality crystal growth, which occurs slowly when there is a slight thermodynamic advantage for molecules that bind in the preferred orientation, but other possible ways to bind are disadvantageous.

A formalization of this notion for Wang tiles, the Tile Assembly Model, supposes that each label on a Wang tile binds with a certain strength (typically, 0, 1, or 2) and that tiles will only stick to a growing assembly if they bind (possibly via multiple bonds) with a total strength greater than some threshold τ (typically 1 or 2); tiles that bind with a weaker strength immediately fall off (Winfree, 1998). Under these rules, growth from a "seed tile" can result in a unique, well defined pattern. Because Turing machines and cellular automata can be simulated by this process, the Turing-universality of tiling is retained.

As an example, consider the seven tiles shown in Figure 2 assembling at $\tau = 2$. These tiles perform a simple computation—they count in binary. Starting with the seed tile, labeled S, the tiles with strength-2 bonds polymerize to form a V-shaped boundary for the computation. There is a unique tile that can fit into the nook of the V; because it makes *two* strength-1 bonds, it can in fact be added. Two new nooks are created, and again a unique tile can be added in each location. The assembly thus grows forever, counting and counting with unabated madness.

Tiles can be added in any order, but the resulting pattern is the same. The same basic self-assembly mechanisms used here are sufficient to perform more sophisticated computations. No new ideas or mechanisms are necessary to obtain fully programmable Turing-universal behavior.

Experimental Advances

The first demonstration of these ideas—two-dimensional, periodic arrays of DNA tiles—could hardly be called "algorithmic," but it did show that the sequences given to the tiles' sticky ends could be used to program different periodic arrangements of tiles (Winfree et al., 1998a). The encoding of tiles as DNA DX molecules is illustrated in Figure 3; Figure 4 shows small crystals of DX molecules adsorbed on mica, as they appear in the atomic force microscope. Subsequent studies have shown that DNA tiles can be made from a variety of different molecular structures. Thus, the principle that the arrangement of two-dimensional tiles can be directed by programmable, sticky-end interactions appears to be quite robust.

The goal of creating three-dimensional, periodic arrays of DNA tiles, originally formulated by Seeman more than 20 years ago, remains an open problem in the field. Once solved, it will allow for more sophisticated information-processing techniques in algorithmic self-assembly, roughly analogous to the increase in power from one-dimensional to two-dimensional cellular automata or Turing machines.

For the time being, experimental demonstration of algorithmic self-assembly has been confined to one- and two-dimensional assemblies. The first use of one-dimensional algorithmic self-assembly appeared as the first step in Adleman's original DNA-based computing demonstration; this process formally corresponds to the generation of languages by finite-state machines. Furthermore, using one-dimensional, tile-based assembly, it is possible to read an input string (encoded as a one-dimensional tile assembly) and generate an output string consisting of the cumulative[2] exclusive-OR (XOR) of the input string (Mao et al., 2000); this formally corresponds to a finite-state transducer.

The first two-dimensional, algorithmic self-assembly process to be experimentally demonstrated with DNA is a generalization of the one-dimensional XOR example (Rothemund and Winfree, in preparation). Beginning with an input row consisting of a single 1 in a sea of 0's, the next layer grows by placing a 0 where both neighbors in the layer below are the same and a 1 where they are different. This process, an example of a one-dimensional cellular automaton, generates a fractal pattern known as the Sierpinski gasket.

In addition to the DNA required to construct the input, only four DNA tiles are required (in principle) to grow arbitrarily large Sierpinski triangles. Experimentally, error-free Sierpinski

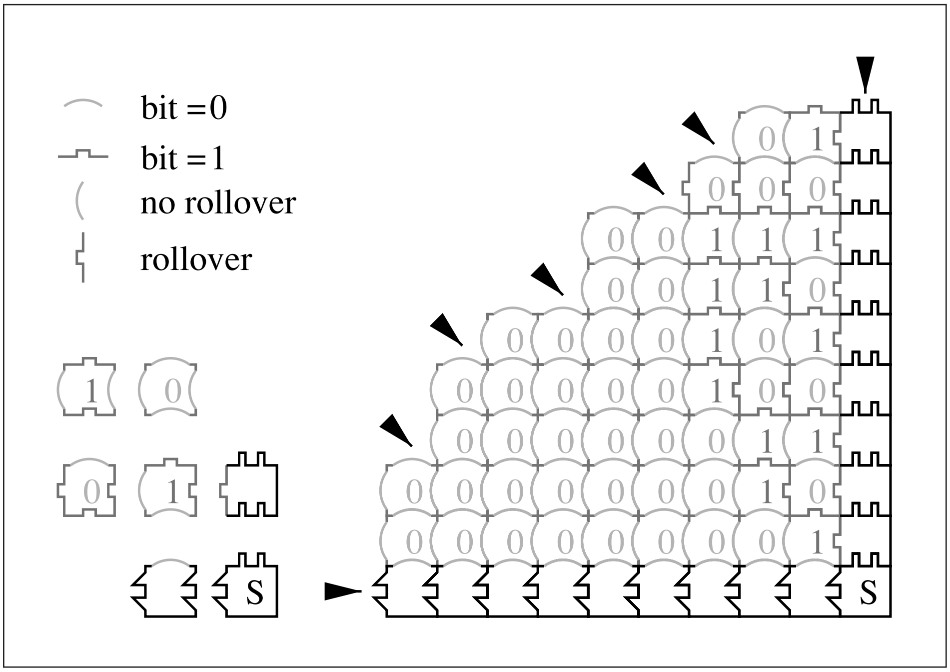

FIGURE 2 A set of seven tiles that implement a binary counter when started with the seed tile *S*. Strength-2 bonds are indicated by tile sides with *two* projections (or indentations); other bonds have strength 1. Arrows indicate sites where a tile may be added at $\tau = 2$.

triangles as large as 8 x 16 have been observed by atomic force microscopy. However, error rates (the frequency with which the wrong tile was incorporated into the crystal) ranged from 1 to 10 percent, and many fragments appeared to have grown independently of the input structure. It is clear that controlling nucleation and finding mechanisms to reduce the error rates are critical challenges for making algorithmic self-assembly practical.

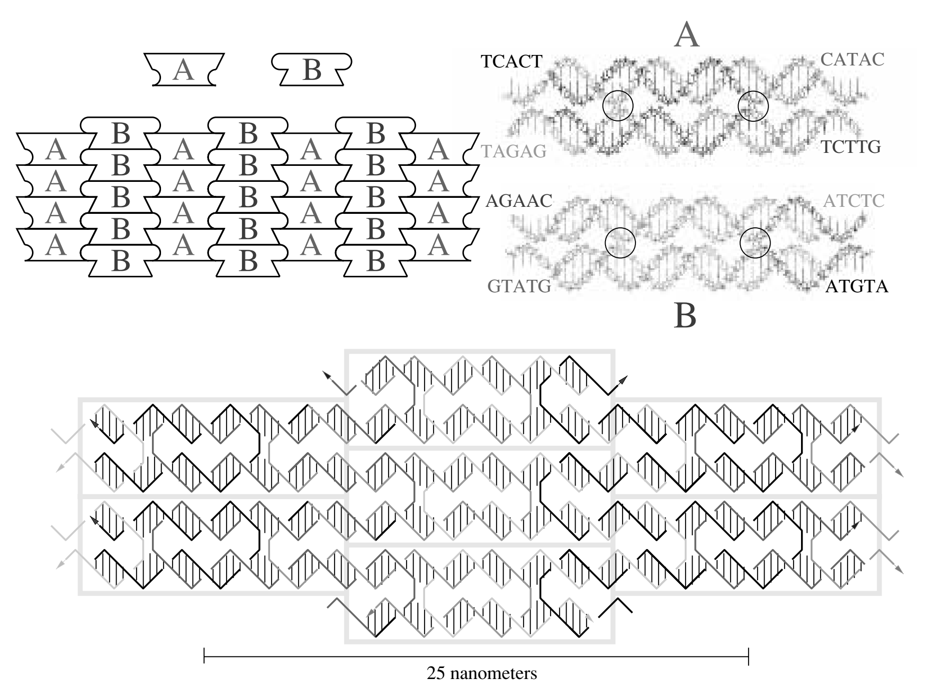

FIGURE 3 DNA double-crossover molecules can implement abstract Wang tiles, producing a two-dimensional lattice of DNA with binding interactions dictated by the DNA sticky ends.

Potential Technological Applications

Combinatorial Optimization Problems

Solving combinatorial optimization problems, in the spirit of Adleman's original paper, was the first application considered for algorithmic self-assembly. Adleman's essential insight is based on the fact that a class of hard computational problems, the NP-complete problems, share a common generate-and-test form—does a sequence exist that satisfies easy-to-check properties X, Y, …, and Z. All known algorithms for NP-complete problems require exponential[3] time or exponential parallelism. The basic idea is to use combinatorial chemistry techniques to simultaneously generate all potential solutions and then to filter them, based on chemical properties related to the information they encode, leaving at the end possibly only a single molecule that has all of the desired properties. If the final solution to the problem is defined by satisfying a small number of simple properties—as is the case for all NP-complete problems—then this approach can be used to find the solution in a short amount of time, if the parallelism is sufficient. That a single cc of DNA in solution at reasonable concentrations can contain 2^{60} bits of information—which can be acted on simultaneously by chemical operations—gives us hope that the parallelism could be sufficient.

By exploiting the situation in which multiple different tiles could be added at a given location—much like Adleman's assembly step that produced all possible paths through a graph—self-assembly can generate a combinatorial set of possible assemblies and then continue growing according to a process that tests the information to see if it has the desired properties. Theoretical schemes have been worked out that use a single self-assembly step to solve the Hamiltonian path problem (HPP) (Winfree et al., 1998b), solve the Boolean formula satisfiability problem (SAT) (Lagoudakis and LaBean, 2000), and perform other math calculations (Reif, 1997). How much computation could be done this way? If assembly were to proceed with few errors, solving a 40-variable SAT problem would require 30 milliliters of DNA at a tile concentration of 1 micromolar and might be completed in a few hours. This "best possible" estimate corresponds to 10^{12} bit operations per second—not bad for chemistry but still low compared to electronic computers.

The sheer speed and flexibility of silicon-based electronic computers make them preferable to DNA computing, even if self-assembly were to proceed without errors. We can conclude, then, that the low-hanging fruit are not to be found in the field of combinatorial search. But the ability of self-assembly to perform sophisticated computations suggests that we are making progress toward our goal of understanding (and

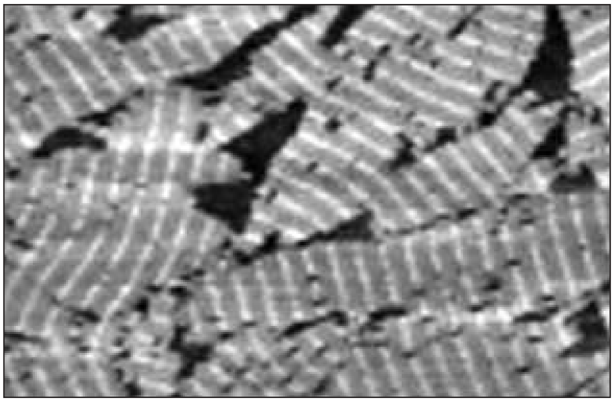

FIGURE 4 Atomic force microscope image of DNA double-crossover crystals. Stripes are spaced at 25 nm; individual 2 x 4 x 13 nm tiles are visible.

potentially exploiting) autonomous biochemical algorithms. A more promising application is suggested by examining how self-assembly is used in biology.

Programmable Nanofabrication

Biology uses algorithmically controlled growth processes to produce nanoscale and hierarchically structured materials with properties far beyond the capability of today's human technology. Does DNA-based algorithmic self-assembly give us access to new and useful technological capabilities? The simplest applications would make use of self-assembled DNA as a template or scaffold for arranging other molecular components into a desired pattern. This could be used for biochemical assays, novel materials, or devices. Seeman has envisioned, for example, using periodic three-dimensional DNA lattices to assist with difficult protein crystallization or to direct construction of molecular electronic components into a memory (Robinson and Seeman, 1987).

The potential of self-assembly for fabricating molecular electronic circuits is intriguing, given the limitations of conventional silicon-circuit fabrication techniques. Photolithography is unable to create features significantly smaller than the wavelength of light, and even if it could, for several-nanometer line widths the unspecified atomic positions within the silicon substrate would lead to large stochastic fluctuations in device function. For these reasons, many researchers are investigating electrical computing devices created from molecular structures, such as carbon nanotubes, in which the location of every atom is well defined. However, an outstanding problem is how to arrange these chemical components into a desired pattern.

DNA self-assembly could be used in a variety of ways to solve this problem: molecular components (e.g., AND, OR, and NOT gates, crossbars, routing elements) could be chemically attached to DNA tiles at specific chemical moieties, and subsequent self-assembly would proceed to place the tiles (and hence circuit elements) into the appropriate locations. Alternatively, DNA tiles with attachment moieties could self-assemble into the desired pattern, and subsequent chemical processing would create functional devices at the positions specified by the DNA tiles. None of these approaches has yet been convincingly demonstrated, but it is plausible that any of them could eventually succeed to produce two- or three-dimensional circuits with nanometer resolution and precise control of chemical structure.

Using self-assembly to direct the construction of circuits as large and complex as those found in modern microprocessors is daunting. The question arises, therefore, of whether there are useful circuit patterns that can be generated by a feasibly small number of tiles. Any circuit pattern that has a concise algorithmic description is a potential target for this approach. Small tile sets have been designed for demultiplexers, such as the ones necessary to access a RAM memory (shown in Figure 5), and for signal-processing primitives, such as the Hadamard matrix transform (Cook et al., in press). Regular gate arrays, such as those used in cellular automata and field programmable gate arrays (FPGAs), are another natural target for algorithmic self-assembly of circuits.

Many technical hurdles will have to be overcome before algorithmic self-assembly can be developed into a practical commercial technology. It is not clear if real circuits will ever be built this way, but the sheer range of possibilities opened up by algorithmic growth processes suggests that algorithmic self-assembly will be used in the future for technologies that place molecular components in a precisely defined complex organization.

Summary and Prospects

DNA-based self-assembly appears to be a robust, readily programmable phenomenon. Periodic two-dimensional crystals have been demonstrated for tens of distinct types of DNA tiles, illustrating that in these systems the sticky ends drive the interactions between tiles. Several factors limit immediate applications, however. Unlike high-quality crystals, current DNA tile lattices are often slightly distorted, with the relative position of adjacent tiles jittered by a nanometer and lattice defect rates of 1 percent or more. Some DNA tiles designed to form two-dimensional sheets appear to prefer tubes, for better or worse. Furthermore, procedures have yet to be worked out for reliably growing large (greater than 10 micron) crystals and depositing them nondestructively on the substrate of choice.

Although one- and two-dimensional algorithmic self-assembly has been demonstrated, per-step error rates between 1 and 10 percent preclude the execution of complex algorithms. Recent theoretical work has suggested the possibility of error-correcting tile sets for self-assembly, which, if demonstrated experimentally, would significantly increase the feasibility of interesting applications. A second prevalent source of algorithmic errors is undesired nucleation (analogous to programs starting by themselves with random input). Thus controlling nucleation, through careful exploitation of supersaturation and tile design, is another active topic of research. Learning how to obtain robustness to other natural sources of variation—lattice defects, ill-formed tiles, poorly matched sticky-end strengths, changes of tile concentrations, temperature, and buffers—will also be necessary.

Presuming that algorithmic self-assembly of DNA can be made more reliable, it then becomes important that we understand the logical structure of self-assembly programs and how that structure relates to and differs from existing models of computation. At the coarse scale of what can be computed—at all—by self-assembly of DNA tiles, there is a natural parallel to the Chomsky hierarchy of formal language theory. Recent theoretical work by Adleman, Goel, Reif, and others, has focused on two issues of efficiency: (1) the kinds of shapes and patterns that can be assembled using a small number of tiles; and/or (2) the kinds of shapes and patterns that can be assembled with rapid assembly kinetics.

To what extent has this investigation enlightened us about how information and algorithms can be encoded in biochemical systems? First, it is intrinsically interesting that self-assembly can support general-purpose computation, although it looks very different from conventional electronic computational circuits. At first glance, other biochemical systems, such as *in vivo* genetic regulatory circuits, appear to have a structure more similar to conventional electronic circuits. But we should be prepared for differences that dramatically alter how the system can be efficiently programmed. Ever-present randomness, pervasive feedback, and a tendency toward energy minimization are unfamiliar factors for computer scientists to consider. Nevertheless, functional computation can be hidden in many places!

Thus, DNA self-assembly can be seen as one step in the quest to harness biochemistry in the same way we have harnessed the electron. Electronic computers are good at (and pervasive at) embedded control of

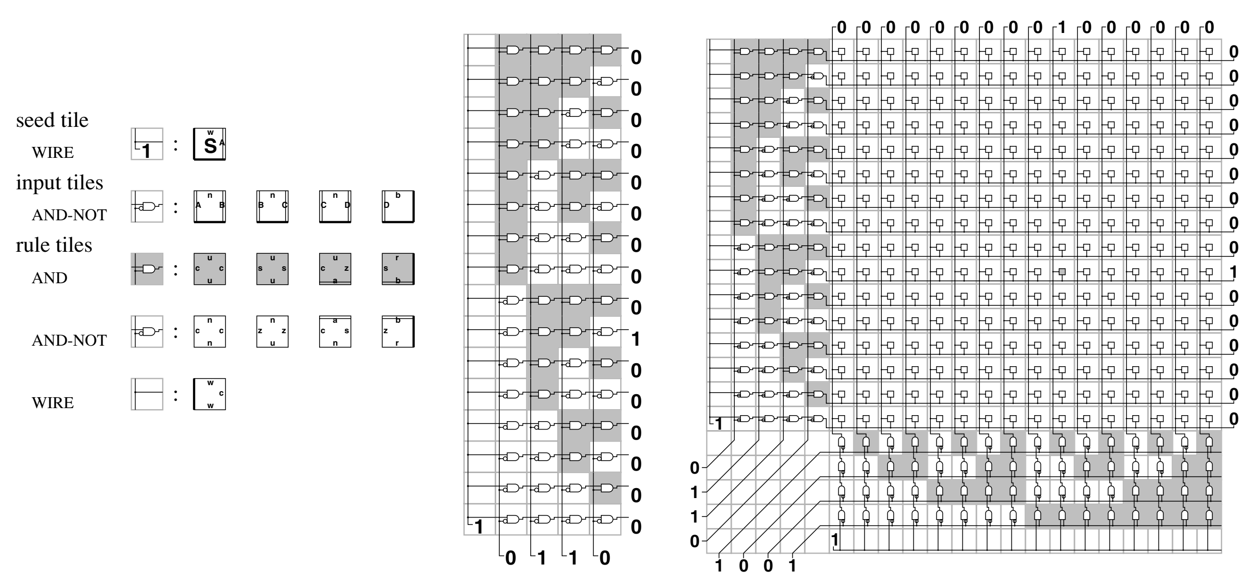

FIGURE 5 Using self-assembly of DNA tiles to create a molecular-scale pattern for a RAM memory with demultiplexed addressing. The tile set is closely related to the binary counter.

macroscopic and microscopic electromechanical systems. We don't yet have embedded control for chemical and nanoscale systems. Programmable, algorithmic biochemical systems may be our best bet.

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Endnotes

[1] Turing machines, invented by Alan Turing in 1936, are extremely simple computers that consist of a finite-state compute head that can move back and forth on an infinite one-dimensional memory tape. Turing showed that these machines are universal in the sense that they can perform any computation that can be performed by any other mechanical device—there is no fundamental need to use a more complicated kind of computer!

[2] The n^{th} bit of the cumulative XOR gives the parity of the first n bits of the input sequence.

[3] Exponential in the length of the problem description, in bits.

Someday we may be able to program cell behavior as easily as we program computers.

Challenges and Opportunities in Programming Living Cells

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With recent advances in our understanding of cellular processes and DNA synthesis methods, we can now regard cells as *programmable* matter. Cells naturally process internal and environmental information in complex fashions and interact with neighboring cells to achieve coordinated behavior. Through genetic engineering, we can now equip cells with sophisticated capabilities for gene regulation, information processing, and communication. These new capabilities serve as catalysts for *synthetic biology*, an emerging engineering discipline to program cell behaviors as easily as we program computers.

Synthetic biology will benefit a wide variety of existing fields and enable us to harness cells for applications that are not feasible today. Applications include tissue engineering, molecular fabrication of biomaterials and nanostructures, synthesis of pharmaceutical products, and biosensing and will surely lead to quantitative insights into the operating principles that govern living organisms. Research so far has focused on building an enabling infrastructure for synthetic biology applications. A particular emphasis has been on constructing prototype synthetic gene networks that perform digital computation, analog computation, signal processing, and communications. In this paper, I will describe the building blocks for these genetic circuits, several intracellular and intercellular prototype genetic circuits that have been implemented recently, some of the challenges in designing such circuits, and the long-term significance of this work.

Synthetic Gene Networks

Genetic circuits are collections of basic elements that interact to produce a particular behavior. These elements include: DNA regions where RNA polymerase molecules bind and initiate *transcription* of DNA into messenger RNA (mRNA); mRNA sequences where ribosomal RNA molecules bind and initiate *translation* of mRNA into proteins; proteins that regulate the activity and production of other proteins; DNA regions that terminate transcription; and motifs that determine protein and mRNA stability. Each element serves a particular function that helps accomplish the overall behavior of the genetic circuit.

The basic elements can be grouped into units (or *devices*) that perform logic operations. For example, Figure 1 shows a logic unit that implements the digital NOT operation using the biochemical reactions of transcription, translation, and protein decay. Based on this mechanism, we have constructed and tested synthetic gene networks with units that implement the NOT, AND, and IMPLIES logic functions (Weiss, 2001; Weiss and Knight, 2000). In addition, we also proposed and modeled a biochemical NAND gate that consists of two NOT gates whose outputs are connected with a wire-OR (Weiss et al., 1999). Theoretically, any arbitrary digital logic function can be implemented with genetic circuits using these gates.

By constructing biochemical logic circuits and embedding them in cells, one can extend or modify the behavior of cells. Consider how computer designers program the behavior of computers or robots by fabricating silicon-based logic circuits. To program cells in an analogous way, the genetic circuit designer constructs a DNA sequence that encodes a particular circuit and then embeds this DNA molecule in cells (a process called transformation). Typically, the purpose of this network is to regulate precisely the production of proteins. Because proteins essentially perform all the "work" and information processing in the cell, cell behavior can be programmed by controlling when and under what conditions proteins are produced and degraded in the cell.

To date, several small synthetic gene networks have been built that accomplish specific genetic regulatory functions *in vivo*: the autorepressor (Figure 2a), in which a repressor regulates its own production to reduce noise in gene expression (Becskei and Serrano, 2000); the toggle-switch (Figure 2b), in which two repressors inhibit each other's production to achieve a bistable system (Gardner et al., 2000); the repressilator (Figure 2c), in which three repressors are connected in a ring topology to produce repeated oscillation (Elowitz and Leibler, 2000); the genetic clock and toggle switch constructed from transcriptional repressors and activators (Atkinson et al., 2003); and our synthetic gene networks used for engineering digital logic gates and circuits in cells (Weiss and Basu, 2002; Weiss et al., 1999).

Despite their logically simple functions, the difficulties in building these networks revealed that many challenges will be faced in building circuits of increasing complexity. For example, designers of genetic circuits will have to cope with the significant noise inherent in gene expression (Becskei and Serrano, 2000; Elowitz et al., 2002; McAdams and Arkin, 1997) and will have to match carefully the

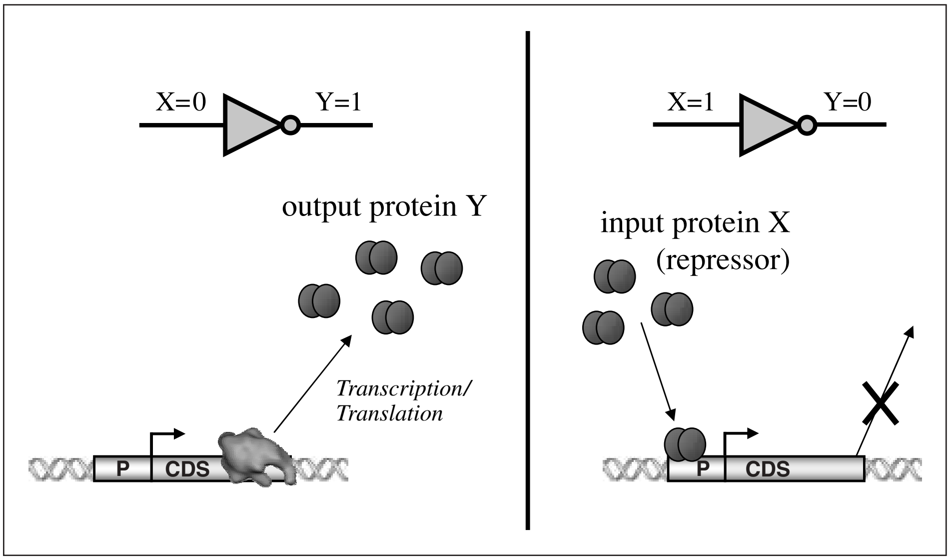

FIGURE 1 A simplified view of the two cases for a biochemical inverter, a logic device whose output value is always the inverse of its input value. The concentration of two particular proteins represent the input and output logic signals. In the first case (left), input protein X is absent, and the cell transcribes the coding sequence for output protein Y (labeled CDS). In the second case (right), input protein X is present and binds specifically to the gene at the promoter site (labeled P), preventing the cell from expressing output protein Y.

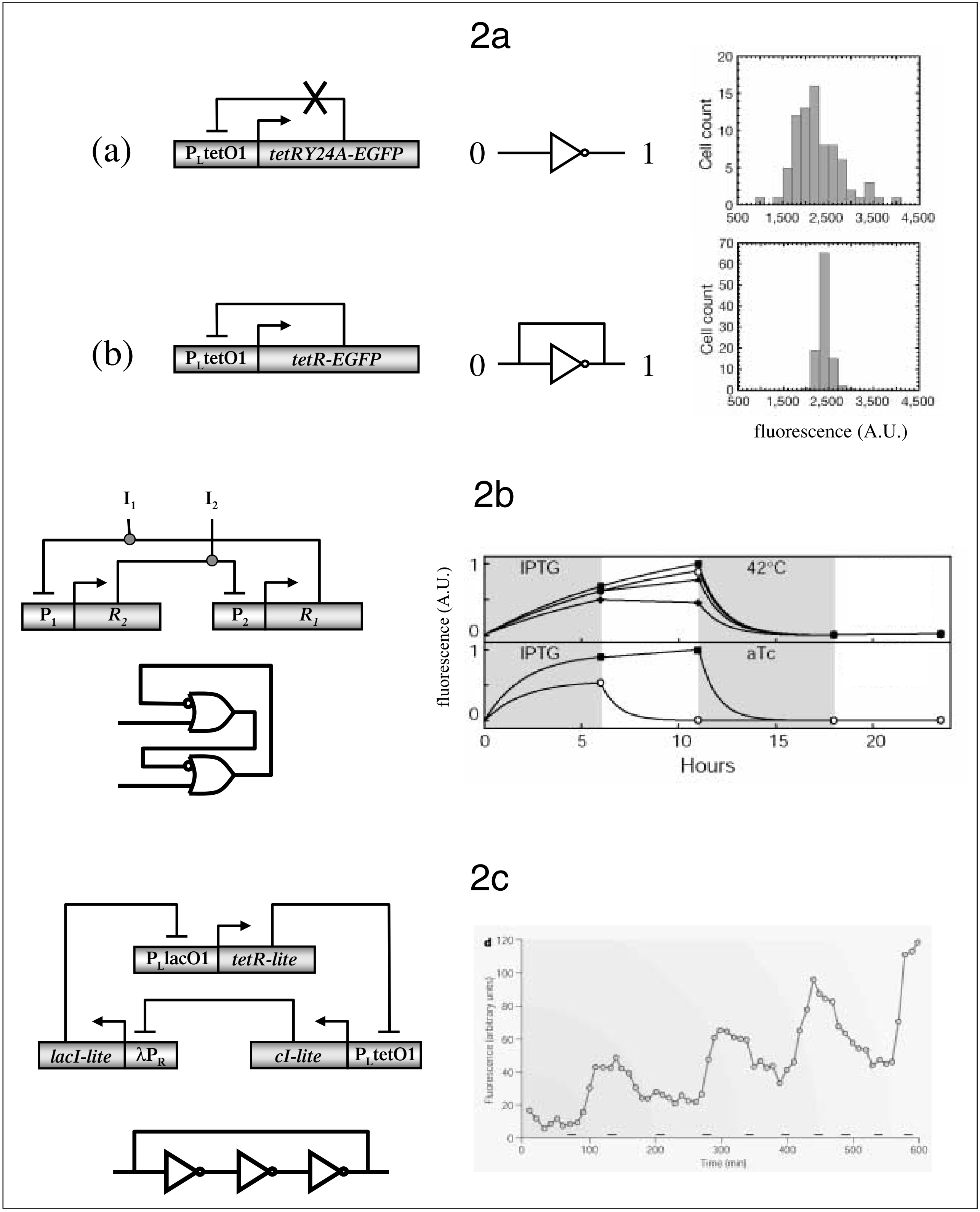

FIGURE 2 An overview of three synthetic gene networks, their corresponding logic circuits, and experimental behavior. These networks have been implemented to demonstrate specific genetic regulatory tasks. 2a. The auto-repressor circuit reduces variations in gene expression (Becskei and Serrano, 2000). 2b. The toggle switch circuit is a bistable system (Gardner et al., 2000). 2c. The repressilator circuit exhibits periodic oscillation in gene expression (Elowitz and Leibler, 2000).

"impedances" of constituent devices to achieve compound circuits that operate properly and reliably (Weiss and Basu, 2002). Because these circuits operate in the context of a living organism that already has an existing "program," understanding the interactions of the exogenous circuit with the endogenous elements will be critical. When designing these circuits, such interactions will have to be minimized to avoid undesired cross talk and interference with normal cellular processes. The exception to this design rule applies when control over endogenous cell behavior is intentional and desired (e.g., controlling cellular metabolism or growth).

Communication and Signal Processing

Intercellular communication allows individual cells to coordinate their behavior and accomplish sophisticated tasks they simply cannot perform alone. In higher level organisms, such as mammals, eukaryotic cells send and receive signals to perform a wide range of activities, from differentiation and growth during embryogenesis to immune and stress responses during adult life. However, cell-to-cell communication is not exclusive to higher level organisms. Bacterial cells, for example, are known to regulate gene expression based on their own cell density by secreting and then detecting concentrations of unique biochemical signals in a behavior known as *quorum sensing* (Bassler, 1999). This coordinated behavior gives bacterial cells a competitive advantage both as pathogens and in symbiotic relationships with their hosts.

To explore potential applications that would benefit from coordinated, multicellular behavior, we have begun to integrate communication capabilities with various synthetic genetic regulatory and information-processing networks. Toward this end, we first programmed *Escherichia coli* cells to communicate with each other by connecting several transcriptional regulatory elements with previously unrelated signaling elements from the marine bacterium *Vibrio fischeri* (Weiss and Knight, 2000). In the experimental system, we externally induced "sender" cells to synthesize the production of a small molecule ($30C_6HSL$) that then diffused outside the cell membrane and entered the cytoplasm of nearby "receiver" cells. The receiver cells responded to this chemical message by expressing a green fluorescent protein that was visible under a microscope (Figure 3). We are now extending this work to achieve programmed, two-way communications by constructing new circuits that use multiple signal synthesis and response elements from various bacterial sources. Two important challenges in engineering sophisticated and robust, multisignal, cell-to-cell communication networks will be matching response sensitivities and reducing cross talk between the signals.

Cells naturally analyze cell-to-cell communication and various environmental conditions with elaborate signal-processing circuitry that includes both digital and analog components. The ability of cells to detect and subsequently react to environmental and internal signals is a principal characteristic of many biological phenomena. Examples include the movement of bacteria toward higher concentrations of nutrients through chemotaxis, the release of fuel molecules in response to hormones that signal hunger, and cell differentiation during embryogenesis based on

FIGURE 3 Time-series fluorescence images illustrating the response of colonies of engineered receiver cells to communication from nearby sender cells on a petri dish.

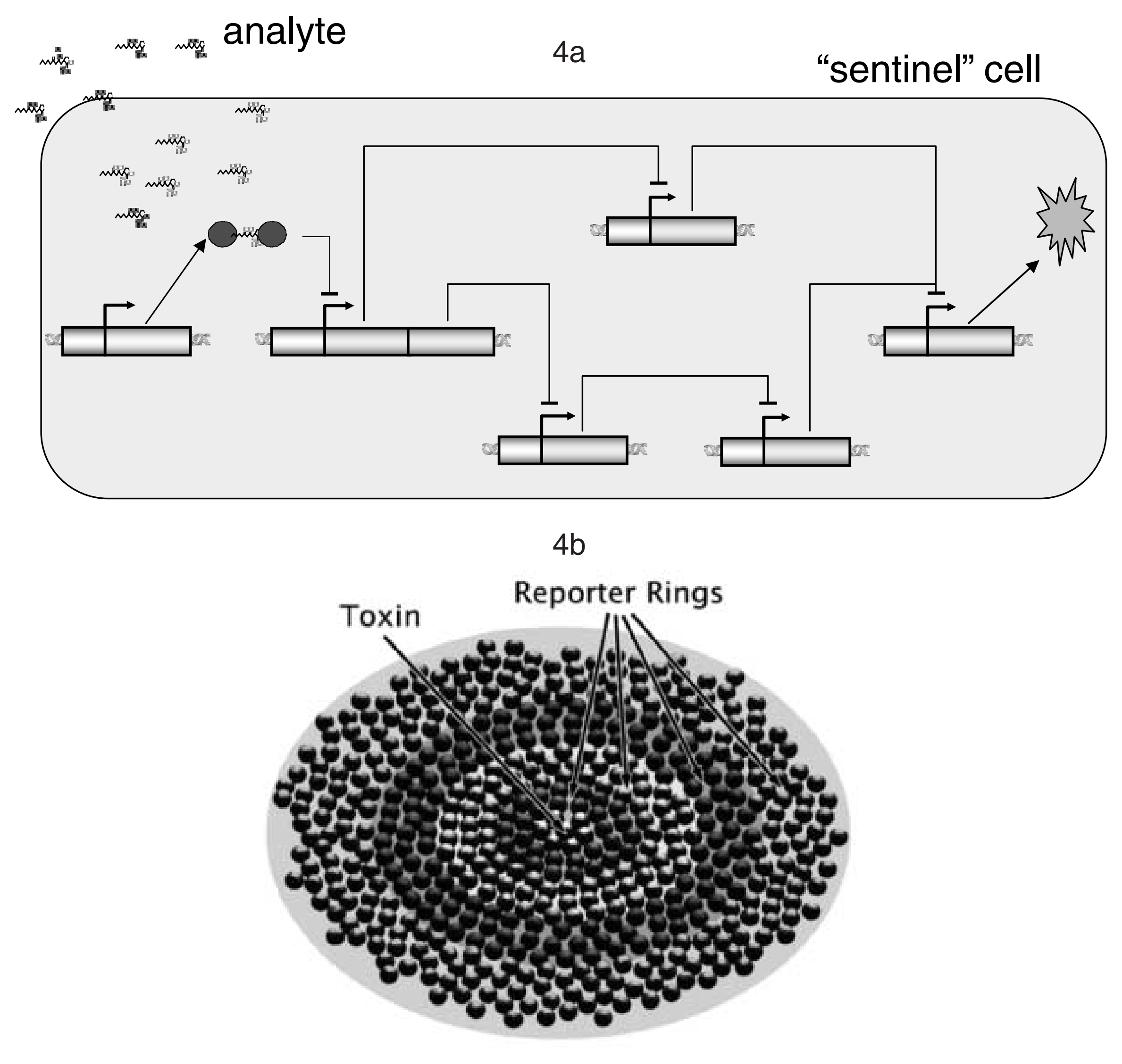

FIGURE 4 4a. Chemical-source pinpointing can be accomplished using cells with a genetic circuit that expresses a green fluorescent protein only when a given analyte concentration falls within a particular range. Because the chemical concentration is highest at the source and forms a gradient as the distance from the chemical source increases, cells with this circuit will form a fluorescent ring around the source. 4b. Given a small library of circuits that can detect different chemical concentration ranges with unique fluorescent colors, cells will form separate rings centered on the source that result in a bullseye pattern.

chemical gradients. To extend a cell's ability to respond to internal and environmental stimuli beyond the digital realm, we began to engineer analog signal-processing capabilities using synthetic gene networks. In our laboratory, we have built genetic circuits that enable cells to detect various chemical concentrations (below and above prespecified thresholds or only within certain ranges) and other circuits that allow cells to respond to multiple environmental signals (Basu et al., in press; Weiss et al., 2003).

As a prototype for exploring issues in engineering signal-processing capabilities, we designed a new genetic *chemical-source pinpointing* circuit. The circuit is able to detect the presence of a particular extracellular molecule and then distinguish between various chemical concentrations of the molecule (Basu et al., in press). Consider a toxin analyte whose location or even presence in the environment is unknown. The analyte is secreted from a particular pathogen and forms a chemical gradient centered on the source. A potential method of determining the location of the pathogen is to spread engineered sentinel cells in the

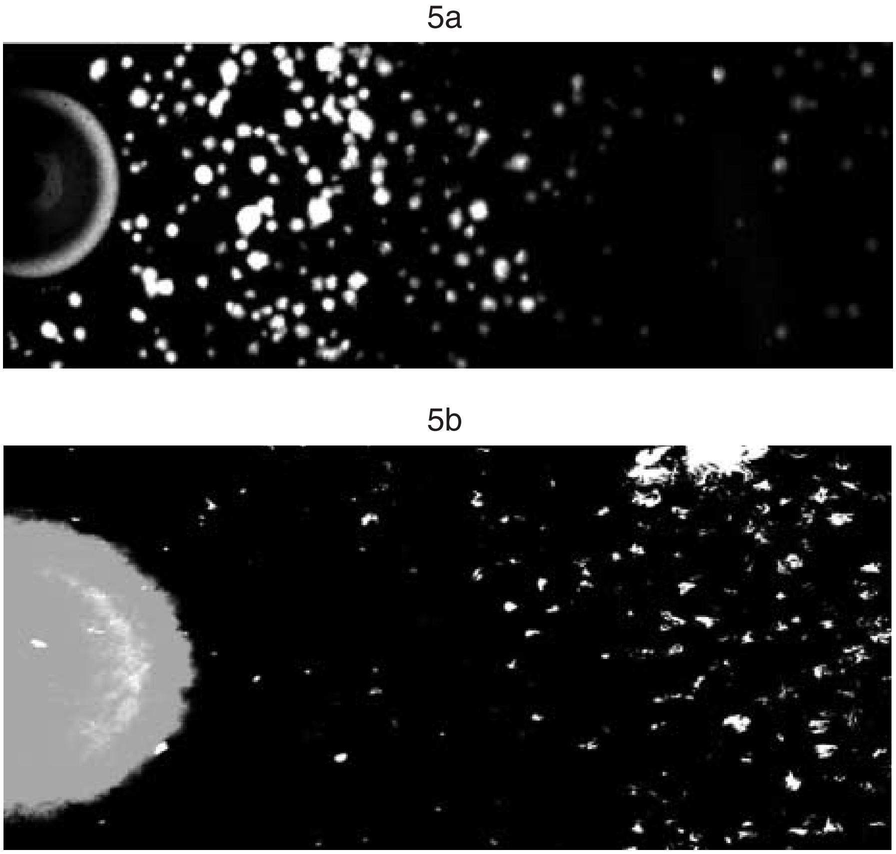

FIGURE 5 Fluorescence microscope images of "sentinel" bacterial cells programmed to detect whether the concentration of a chemical secreted by another type of bacteria is above or below particular thresholds. The bacteria that secrete the biochemical are fluorescing in red, while the sentinel bacteria scattered throughout the entire viewing area are fluorescing in yellow when the prespecified detection conditions are satisfied. 5a. Concentration above a high threshold. 5b. Concentration below a low threshold.

suspected environment that can detect prespecified chemical concentrations. For a given concentration range, these cells will fluoresce in a ring pattern around the source. If the cells are engineered to detect multiple ranges distinguishable by different fluorescent colors, a bullseye pattern will emerge with several concentric rings around the analyte source (Figure 4).

The source-pinpointing circuit consists of several components that first detect the external analyte concentration and then determine whether the concentration falls above a prespecified low threshold and below a high threshold. Figure 5 shows two separate experiments of "sentinel" bacterial cells that have been programmed to respond to either low or high concentration thresholds of a biochemical secreted from nearby sender cells (Basu et al., in press). By combining and inverting the low and high threshold outputs, one can realize a circuit that responds with a high fluorescent output only when the analyte concentration is within the prespecified range. With the aid of simulation tools, we have also been able to fine tune the threshold responses of these circuits by modifying the DNA sequences of chosen genetic elements. An important long-term goal for this type of research is to be able to tune the responses of genetic circuits with the same predictability and reliability as we can when we design electrical devices. By combining this type of analog information processing with digital computation and programmed cell-to-cell communication, we may be able to create a flexible and powerful engineering discipline for programmed cell behaviors.

Key Challenges

The initial modeling and experimental efforts in this field have generated a great deal of excitement but have also revealed many challenges that must be faced. Some of the significant challenges are described below.

Programming complex behavior will require the assembly of a large, well characterized library of intracellular and intercellular components. The library should include elements for regulating transcription and translation, as well as elements for regulating protein-to-protein interactions, such as phosphorylation-based signal-transduction cascades. Most of the library elements must exhibit minimal cross talk and must not affect the host's behavior. However, an important subset of this component library should be devoted to interfacing with the host to control desired cellular functions, such as the production of specific enzymes during predefined conditions, control over cell replication, and programmed secretion of various chemicals.

Designing operational and efficient genetic circuits will *require models and simulation tools that can provide accurate quantitative predictions of circuit behavior.* Engineered genetic circuits operate within a highly complex environment that is not well characterized and whose effects on the operation of the circuit have not been quantified. Models are still unable to predict the precise concentration averages and population statistics of the molecular components of even relatively simple systems. Solutions to this challenge will require more precise kinetic rates for describing the relevant biochemical reactions, models that incorporate additional cellular states (e.g., accurate RNA polymerase and ribosomal RNA levels), accurate predictions of noise in the biochemical reactions, a physical model of the cells and their surroundings, and potentially completely different modeling techniques. Furthermore, as the complexity of engineered circuits increases, they begin placing a significant metabolic burden on the host. Molecular interactions between the exogenous components and the endogenous cellular circuitry can also affect host behavior. Effects on the host's environment must be understood and modeled to design complex synthetic circuits.

Genetic circuits must integrate specific components or network motifs that make them robust to fluctuations in the kinetics of biochemical reactions. Gene expression tends to be noisy because of the stochastic nature of the constituent biochemical reactions (Elowitz et al., 2002; McAdams and Arkin, 1997). In addition, fluctuations in environmental conditions, such as temperature and nutrient levels, affect cellular metabolism and consequently the operation of genetic circuits. Circuits that achieve reproducible, reliable behavior must do so despite components whose behavior fluctuates considerably. Mitigating the effects of gene expression noise will probably require a solution that incorporates positive and negative feedback loops.

A major bottleneck in genetic circuit engineering is the difficulty of synthesizing DNA constructs. Anecdotal evidence suggests that the construction of new strands of DNA consumes a significant portion, if not most, of the time spent in circuit engineering. Currently, several ongoing efforts are trying to remove this bottleneck by using various *de novo* DNA-synthesis methods.

Genetic-circuit design will require novel approaches that may be fundamentally different from existing computer-circuit design methodologies. In constructing our circuits, we have used "rational" design in which detailed models are used to guide the circuit engineering, helping to select appropriate components and suggesting how to mutate them, when necessary, to achieve correct circuit behavior (Weiss and Basu, 2002). We have also used another technique called directed evolution to optimize circuit behavior (Yokobayashi et al., 2002). Building on nature's fundamental principle of evolution, this unique process directs cells to mutate their own DNA until they find gene network configurations that exhibit the desired system characteristics. Because our understanding of cellular processes is incomplete, efficient circuit design will most likely require a combination of rational design and directed evolution, or perhaps some other completely different approach.

Long-Term Significance

The field of synthetic gene networks is still in its infancy. Researchers are currently trying to build small genetic-regulatory systems that exhibit a particular behavior reliably and predictably. Solving the existing challenges in building complex genetic circuits will take considerable effort. However, once the major challenges are solved, the construction of synthetic gene networks will enable us to direct cells to perform sophisticated *digital* and *analog* functions, both as individual entities and as part of larger cell communities. An engineering discipline to program cell behaviors and its associated tools will advance the capabilities of genetic engineering and allow us to harness cells for a myriad of new applications. As a result, someday we will be able to modify and extend the behavior of cells in almost arbitrary ways. Because this technology will allow us to modify the instructions that govern the capabilities of organisms that live around us, as well as our own bodies' instructions, it has tremendous potential for increasing our control over the environment and our surroundings and improving our quality of life.

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NAE News and Notes

NAE Newsmakers

In late October, President Bush announced the winners of the National Medals of Science and National Medals of Technology, 14 of whom are members of the National Academies.

The **National Medal of Science**, established by Congress in 1959, is the government's highest honor for science and engineering. The award is administered by the National Science Foundation. This year's winners include **Leo L. Beranek**, an NAE member, and **Richard L. Garwin**, a member of NAS, NAE, and IOM. Leo L. Beranek, retired director, BBN Technologies, was honored for "his leadership, dedication, and contributions to the art and science of acoustics; for co-founding one of the world's foremost acoustical research and consulting firms; and for sustained contributions to scientific societies and civic organizations." Richard L. Garwin, Philip D. Reed Senior Fellow, Science and Technology, Council on Foreign Relations, was chosen "in recognition of his research and discoveries in physics and related fields, and of his longstanding service to the nation by providing valuable scientific advice on important questions of national security over half a century."

The National Medal of Technology, established by Congress in 1980 and administered by the U.S. Department of Commerce, is the government's highest honor for technological innovation. This year's winners include NAE members **Magnus G. Craford**, **Russell D. Dupuis**, **Haren S. Gandhi**, **Nick Holonyak, Jr.**, and **Carver A. Mead**. Drs. Holonyak and Mead are also NAS members.

Haren S. Gandhi, Ford Motor Company, Dearborn, Michigan, a pioneering researcher in automotive technology to improve the environment, was honored for "research, development, and commercialization of automotive exhaust catalyst technology, shaping the industry from its very beginning and continually pushing to improve the quality of the air we breathe. Dr. Gandhi has also led the automotive industry in ensuring the judicious use of precious metals, including conservation measures such as recycling of spent converters and technological advances in precious metal utilization."

Nick Holonyak, Jr., Microelectronics Laboratory, University of Illinois at Urbana-Champaign, Urbana, Ill.; **Magnus G. Craford**, LumiLeds Lighting, San Jose, California; and **Russell D. Dupuis**, Georgia Institute of Technology, all inventors and innovators in LED technology, were honored for their "contributions to the development and commercialization of light-emitting diode (LED) technology, with applications to digital displays, consumer electronics, automotive lighting, traffic signals and general illumination."

Carver A. Mead, California Institute of Technology, Pasadena, California, a pioneer in microelectronics, teacher, and entrepreneur, was selected for his "pioneering contributions to the microelectronics field, that include spearheading the development of tools and techniques for modern integrated-circuit design, laying the foundation for fabless semiconductor companies, catalyzing the electronic-design automation field, training generations of engineers that have made the United States the world leader in microelectronics technology, and founding more than 20 companies."

At the NAE Annual Meeting on October 12, Dr. Mead was also awarded the NAE **Founders Award** for his pioneering contributions to the field of microelectronics (see p. 56). **Robert A. Frosch** of the Kennedy School of Government, Harvard University, received the **Arthur M. Bueche Award** for his work in industrial ecology and his contributions to public policy (see p. 54).

The Society of Women Engineers (SWE) conferred the 2003 SWE **Rodney D. Chipp Memorial Award** on **Nicholas M. Donofrio** for his exemplary commitment, impassioned leadership, and tireless devotion to the acceptance and advancement of women in engineering, science, and technology. Mr. Donofrio was also cited for his ardent advocacy of mathematics and science education.

Anthony G. Evans has been awarded the **Nadai Medal** presented by the American Society of Mechanical Engineers (ASME International). Established in 1975, the Nadai Medal is awarded for contributions to the field of engineering materials.

Mischa Schwartz was awarded the 2003 **Okawa Prize** by the Japan-based Okawa Foundation for Information and Telecommunications for his contributions to telecommunications and engineering education. The prize consists of a certificate, a gold medal, and a cash award of 10 million yen. The award ceremony took place November 27 in Tokyo.

2003 Annual Meeting

NAE members, foreign associates, and guests gathered in Washington, D.C., this October for the 2003 NAE Annual Meeting. The meeting began on Saturday, October 11, with the orientation of new members. This was followed by the NAE Council Dinner honoring the 74 new members and seven foreign associates.

The public session on Sunday, October 12, was opened by NAE Chair **George M.C. Fisher**. President **Wm. A. Wulf** then addressed the group. Dr. Wulf announced the start of a new annual program to recognize members elected 25 years ago. This year, members who had been elected from 1965 to 1978 were sent special invitations to attend the meeting and were honored with lapel pins commemorating their years of membership.

NAE President Wm. A. Wulf addressed the gathering to set a context for the sessions that followed. The focus of his talk was the reform of engineering education (see p. 49). The induction of the NAE Class of 2003 followed President Wulf's address.

The program continued with the presentation of the 2003 Founders Award to **Carver Mead** and the Bueche Award to **Robert A. Frosch**. Dr. Mead, the Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, at the California Institute of Technology, was recognized for his "visionary contributions in the field of microelectronics, including VLSI technology and computational neural systems." Dr. Frosch, senior research fellow at the Belfer Center for Science and International Affairs, John F. Kennedy School of Government at Harvard University, received the Bueche Award for advances in aerospace and automotive technology and industrial ecology and for administration of R&D in industry, government, and academia.

After a break, the two recipients of the Lillian M. Gilbreth Lectureships, which recognize outstanding young engineers, presented talks. The first speaker, Dr. Roy Want, principal researcher at Intel Research, spoke about personal servers and the limits of personal computing. The second speaker, Dr. Stephen van Enk, member of the technical staff at Lucent Technologies, spoke about quantum cryptography.

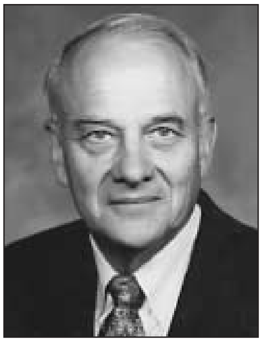
After the Gilbreth Lectures, President Wulf introduced *A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives*, a new book sponsored by NAE. **Henry Petroski** presented a review of the book, and **Roland Schmitt** read his contribution to the chapter on household appliances. Dr. Wulf then acknowledged **Robert A. Pritzker**, whose donation had made publication of the book possible. A reception honoring the awardees, new members, and anniversary members followed in the Great Hall.

The Annual Business Session on Monday morning was followed by a symposium entitled "Celebrating 100 Years of Aviation: Building on the Legacy of the Wright Brothers." Speakers included **C. Dan Mote**, president and Glenn Martin Institute Professor of Engineering, University of Maryland; Richard Hallion, Air Force historian; Robert Walker, chair of Wexler & Walker Public Policy Associates; Daniel P. Mooney, vice president of product development for Boeing Commercial Airplanes; **Meyer Benzakein**, general manager, Advanced Engineering, GE Aircraft Engines; and **Alan H. Epstein**, R.C. Maclaurin Professor, Massachusetts Institute of Technology. On Monday afternoon, members and foreign associates participated in NAE section meetings at the Keck Center, the new Academies building.

The final event of the meeting was the annual reception and dinner dance, once again held at the J.W. Marriott Hotel. Entertainment was provided by the Capitol Steps, and music was provided by the Doc Scantlin Orchestra.

The next annual meeting is scheduled for October 3–5, 2004.

President's Remarks



Wm. A. Wulf

These remarks were delivered October 12, 2003, at the NAE Annual Meeting.

My practice each year has been to set the context for the Annual Meeting by addressing an issue of importance to engineering. When deciding on a topic this year, I realized that, even though I have taken a proactive position on NAE's involvement in reforming engineering education, and even though I have spoken about it all over the country and written about it in journals, including *The Bridge*, I have never spoken about it to NAE members. Today I hope to communicate to you the urgent need for changing engineering education and to tell you what steps the academy has taken to promote reform.

There are lots of problems in the world, and engineering education isn't the only one NAE could focus on. I believe, however, that unless we have an adequate supply of gifted and creative engineers, we will not be able to solve the most substantive problems facing our planet. We will not be able to provide the benefits to the developing world that we have in the developed countries. Frankly, we will not even be able to maintain our current quality of life. The preparation of the next generations of engineers is, in my view, of the utmost importance.

I want to make three introductory comments before I launch into the main part of my talk. The first one is a caveat. I know that many schools are working on improving engineering education, but I am going to paint with a very broad brush in my talk; I am going to create a cartoon. If we look down from 30,000 feet, the center of gravity of engineering education does not seem to have moved very much since I was a student. From this height, we can't see encouraging "points of light," but I think we can get a correct overall picture.

Second, a word about my view of what an engineer does—namely "design under constraint." I am particularly fond of Theodore Von Karmen's remark contrasting science and engineering. Science, he said, is about understanding nature, understanding what is. By contrast, engineering is synthetic; it is about creating what has never been. Think about it! Creating what has never been. I believe engineering is enormously creative. It is design constrained by cost and size and weight and heat dissipation and power consumption and ergonomics and environmental impact and reliability and safety and on and on. Creating elegant designs under those constraints is one of the most creative activities I know of. Engineering is not "just applied science." To be sure, our knowledge of nature is one of the constraints we work under. But it is not the only one, not the hardest one, and, in my experience, almost never the limiting one.

Third, the practice of engineering is changing. Indeed, that is why I feel a sense of urgency about reforming engineering education. As global competition increases, we must engineer in a global cultural and business context. New designer materials, for which you can prespecify the properties you want, makes the design space infinitely larger. Information technology will be part of every product manufactured in the future—it will simply not be cost effective to build "dumb" products any more. These and other forces have irreversibly changed engineering, and, if anything, the pace of change is accelerating. To be competitive in a globalized economy, to ensure that the quality of life in this country continues to improve, we must educate engineers for the jobs that will be, not the jobs that are or were.

Now that I've set the context, I want to make four points: (1) why I feel a sense of urgency; (2) what has to change; (3) why things aren't changing (faster); and (4) what NAE is doing to bring about change.

An Urgent Need for Change

First, why do I feel a sense of urgency? Let me tell you a bit about my personal history. After I got my Ph.D., I taught at Carnegie Mellon University for 13 years. I then founded, and was CEO, of a company for almost 10 years. Then, after a short detour through the National Science Foundation, I returned to teaching, at the University of Virginia. The interlude in industry really shaped my views about the need for reforming engineering education. On returning to academe, I was struck by two things. First, the engineering curriculum was pretty much the same one I had experienced 40 years before. Second, it had little relation to what I had experienced in industry.

Of course, many things are changing simultaneously; there is a mosaic of individual changes. Like any mosaic, if you are too close to it, it is hard to see the overall pattern. If you stand back far enough, an overall image emerges, in this case an image of startling change. That is why I feel a sense of urgency about changing engineering education.

Necessary Changes

So what has to change? The first things most people mention are curriculum and pedagogy. Many reports—from NAE, from the American Society for Engineering Education, from the National Science Foundation, from the Engineering Dean's Council—speak to these issues. So, I won't. Time is too precious.

The next thing that comes to my mind is diversity, a subject about which I am very passionate. The usual arguments for diversity in the engineering workforce are about equity and the demographics of our population, which is less and less white male. But I think there is a much more powerful argument for diversity. We will engineer better with a diverse workforce. We will find better, more elegant solutions to engineering problems if we work with a diverse team.

That may startle you, but remember, as I said earlier, engineering is profoundly creative. Researchers in psychology have looked into the nature of creativity. Although there is no absolute unanimity on the subject, there is a strong consensus that creativity is simply making unexpected connections between things you already know, between life experiences you have already had. Men, women, underrepresented minorities, and the handicapped experience life differently. Almost by definition, the life experiences of a diverse team are more varied and thus offer greater opportunities for making unexpected connections.

I could go on about diversity, but I want to touch on other things that have to be changed: the decreasing retention rate; the notion of the baccalaureate as the first professional degree; the system of faculty rewards; and the lack of technological literacy in the general population. I could talk for an hour about each of these, but I can only touch on them lightly today.

The retention rate is, frankly, a disgrace! Depending on the data you use, only about half of the students who enter engineering programs finish in engineering. For a long time, I believed the comfortable myth that we were flushing out poor students. Unfortunately, because I am an engineer, I have to believe the data. And the data say that the students who leave are every bit as good as the ones who stay. They have the same GPAs, the same SAT scores, the same scores in math and physics. They had the same standing in their high school classes. We are not flushing out poor students. The comfortable myth I wanted to believe in is just that, a myth.

If you are concerned, as I am, about the continuing decline in the number of students entering engineering and, consequently, the number finishing engineering, the simplest way to fix the problem is to reduce the dropout rate. Fortunately, as a number of schools have shown, this is quite feasible. It is not preordained that we have to lose half of our engineering students.

Now let's talk about the baccalaureate as the first professional degree. Unlike engineering, most professions—business, law, medicine—do not consider the baccalaureate the first professional degree, which in my opinion, is a misrepresentation to both students and employers. Trying to squeeze 10 pounds of material (the engineering curriculum) into a five-pound sack (a four-year course of study) just doesn't work. On one hand, companies must generally provide one or two additional years of training to new graduates. On the other hand, liberal education is squeezed out; there is no space in the curriculum for the social studies, languages, and management material modern engineers need to know.

When we talk about reducing the curriculum, somebody always says we have to "focus on the fundamentals." Everybody agrees on that, but not everyone agrees on what the fundamentals are. The last major change in the engineering curriculum (made just after World War II) morphed engineering into what is now called the "engineering science" model. Physics and continuous mathematics are the core fundamentals of that model.

In the meantime, engineering has been changing. Information technology (IT) will be a part of every product and process in the future, and discrete mathematics, rather than continuous mathematics, is the language of information technology. It is a new fundamental. Biological materials and processes are a bit behind information technology in terms of their impact on engineering practice, but they are catching up fast. Biology and chemistry, organic chemistry and molecular biology in particular, are also new engineering fundamentals. In addition, engineering is now practiced in a global, holistic business context, and engineers must design under constraints that reflect that context. In the future, understanding other cultures, speaking other languages, and communicating with people from marketing and finance will be just as fundamental to the practice of engineering as physics and calculus.

Obviously we can't just add these new fundamentals to a curriculum that is already overcrowded and still claim that the baccalaureate is the first professional degree. We will have to use a very sharp pencil and make some very hard decisions about what, in fact, is really fundamental to engineering.

Slow Rate of Change

Now let's turn to faculty rewards. I do not want to get into the teaching versus research debate, because I believe good teaching and good research go hand in hand and complement each other. In my admittedly idiosyncratic career, I have very seldom found a good researcher who was not a good teacher, or vice versa. There probably are some, but they are not the norm. Recall my description that engineers "design under constraint," that engineering is a synthetic, highly creative activity. Now, please picture your home campus. What other creative activities do not require their faculties to perform? Art? Music? If you don't believe engineering is creative in the same way as music or art, think about performance-oriented professions. Lawyers and doctors are expected to perform. Can you imagine a medical school in which the doctors were discouraged from treating patients? Would you want to be treated by a doctor who was trained at such a university?

Yet, we actively discourage engineering faculty from practicing engineering. The promotion and tenure criteria for engineering faculty are the same as for science faculty—research, teaching, and service. Nowhere in that list is the creation of a product that someone will buy or an addition to the enduring infrastructure of our country.

Of course, what you measure is what you get. So, for the most part, our engineering faculty are superb engineering scientists; but they are not necessarily superb practitioners of the engineering discipline. At most engineering schools, it is hard to hire or promote an individual whose record rests on having produced a product in industry, as opposed to publishing papers in journals. Please understand, I am not criticizing my faculty colleagues. In fact, I "are one." I am criticizing a system that doesn't allow us to complement traditional faculty with people whose experience in the practice of engineering would be of enormous value to students. To close the loop, the faculty decide on the curriculum. Therefore, it is not surprising that many CEOs in industry are critical of current engineering graduates.

So why haven't things changed faster? I honestly don't know the answer, but I have a hypothesis—namely, that most faculty do not believe change is necessary. They are following the time-tested adage—"if it ain't broke, don't fix it." Unless you've gone through the cycle of academia to industry to academia that I have, and unless you are standing back far enough from the mosaic of change, it may not be obvious that things are broke.

Lack of Technological Literacy

Most recently, I have been a professor at the University of Virginia, which was founded by Thomas Jefferson, who was enormously proud of the university. Only three things are listed on his tombstone—and founding the University of Virginia is one of them (no mention of his being president of the United States). As Jefferson wrote many times, he believed you could not have a democracy without informed citizens.

Oops! We have a society profoundly dependent upon technology, profoundly dependent on engineers who produce that technology, and yet profoundly ignorant of technology. I see this "up close and personal" almost every day. I deal with members of our government who are very smart but don't even understand when they need to ask questions about the impact of science and technology on public policy.

Every person with a liberal education must become more technologically literate. Notice I said technologically literate, not scientifically literate. It is not enough to be able to name the branches of flora and fauna, which is what our typical high school biology courses cover. Everyone needs to know something about the process by which the knowledge of science is used to find solutions to human problems. Everyone needs an understanding of the larger innovation engine that creates the wealth from which everyone benefits.

Engineering schools have not usually offered courses in technological literacy. But I can guarantee you that nobody from the English department will come to the engineering school and ask for such a course. We engineers will have to take the initiative.

NAE's Efforts to Promote Change

As I noted before, many reports have been published on curriculum and pedagogy, and I don't think NAE can add anything unique to them. The National Science Foundation has supported innovations in engineering curriculum, for example, support for centers of engineering education. I don't think we have much to contribute there either. But before NSF activities can be widely adopted or the recommendations in reports acted upon, faculty will have to agree that change is needed. NAE has decided that we can make a contribution there! The activities we are engaged in are intended to say: "The National Academy of Engineering believes change is needed, and we value people who contribute to that change."

At NAE, we talk about my four-legged stool to affect change. Leg number one of the stool is to do what we always do—create a committee to conduct a series of workshops, studies, symposia, and so on, to focus attention on the need for change. Second, we have made contributions to engineering education a basis for election to NAE membership. How could we hold our heads up if we said NAE values contributions to engineering education, but you can't be elected a member based on such a contribution?

Third, in addition to the two $500,000 prizes for the practice of engineering, the Draper Prize and the Russ Prize, we now award a third $500,000 prize, the Gordon Prize, for contributions to engineering education. I'm sorry Bernie Gordon wasn't able to be here today, because I would have liked him to receive your applause. About three years ago, he gave us an endowment that allowed us to fund the prize every other year. He called it "the best thing I have ever done." Last fall, he decided to increase the endowment so the prize could be given annually. So, beginning this February, we will award the Gordon Prize every year.

Finally, NAE has established a Center for the Advancement of Scholarship in Engineering Education (CASEE), which will complement, not compete with, the NSF centers. CASEE will support a group of fellows, National Academy of Engineering Fellows in Engineering Education, who will be at the forefront of education research.

Conclusion

Our society is dependent upon technology created by engineers. Engineering is changing rapidly, and I believe engineering education has to change even faster for us to maintain our quality of life. We've studied it to death. We know what to do. So let's get on with it!

Thank you.

NAE Anniversary Classes Honored at Annual Meeting

2003 NAE Anniversary Class

At the 2003 Annual Meeting in October, NAE invited "anniversary" class members of 25, 30, and 35 years to celebrate their service to NAE, the first year NAE has recognized anniversary classes. NAE plans to continue this practice every year at the annual meeting. This year, 49 members and two foreign associates of the anniversary classes were present to receive special commemorative pins marking their 25, 30, and 35 years of membership. The collective achievements of the anniversary members have impacted people worldwide. Their accomplishments include instrumental contributions during the early stages of the space program, advances in computer technology, electronics, heat transfer, and advanced materials, and numerous other developments.

NAE was founded in 1964 by a group of 25 engineers, one of whom was **William L. Everitt**. This year, his grandson, **Randal E. Bryant**, was inducted into the Class of 2003. **H. Guyford Stever**, a member of the first class of 46 members, elected in 1965, was also present.

Engineers are fortunate to be in a profession that makes a profound impact on society on many levels. The engineering expertise and achievements of every NAE member are valuable to the lifeblood of the organization. NAE members make it possible to provide proactive, authoritative, unbiased advice to the nation in all technological matters. This is what sets NAE apart as a professional engineering membership organization. NAE will continue to recognize the extraordinary dedication of members in years to come.

2003 Bueche Award Presented to Robert A. Frosch

(Left to right) George M.C. Fisher, Robert A. Frosch, Wm. A. Wulf, Delores M. Etter.

The 2003 Bueche Award was presented to Robert A. Frosch, senior research fellow at the Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, "for a career of advances in aerospace and automotive technology, and industrial ecology; and for administration of R&D in industry, government, and academia." These remarks were delivered on October 12, 2003, during the NAE Annual Meeting.

Mr. Chairman, Mr. President, colleagues and friends, family, ladies and gentlemen, and, as they say at the circus, children of all ages:

It is a tremendous honor for me to receive the Bueche Award. I greatly respected Art Bueche for his accomplishments and for his service to the engineering profession and to society, and the award named for him has special meaning to me. It will also be a great honor and pleasure to find my name on the list of Bueche awardees with my distinguished predecessors, whom I know, like, and revere. I even revere those I know and like.

It is especially important and interesting for me to be honored by this academy, not only because of what it is and who its members are and because I have been associated with the National Academies and the activities of the National Research Council for a long time, but also because I was nearly a founder of this institution. The late Eric Walker asked me if I wanted to join a few people trying to found a U.S. national academy of engineering, but I passed, largely because I did not then think of myself as an engineer. By the time I was elected a member some years later, I had a better appreciation of what I did professionally and what technology and engineering meant. By then I realized I was dealing with scientific, technological, social, and global problems—and that entire technological systems and organizations were the working ingredients and materials of my work. I say this not to claim too much but to note that these systems tend to be similar at all scales. The principles of good science and engineering are applicable at all scales at which one may be called upon to practice the profession of engineering.

As my perceptions of myself have changed over the 50-plus years of my professional career, so have the problems addressed by scientists, engineers, and technologists. Our concerns have increased in scope and complexity, or at least, we are now much more aware of their complexities. When the late Senator Patrick Moynihan left the White House staff, where he had been advisor on domestic affairs, he said that Washington, D.C., was full of simplifiers, people who could tell you how simple a problem really was. He said he hoped someday there would be more "complexifiers" inside the Beltway, people who could tell you how complex problems really were. Increasingly, engineers must be complexifiers. We must not only recognize the complexities and ramifications of the problems we face, but also invent ways to deal sensibly with these extremely complex problems.

Increasingly, units of technology and engineering include the whole environment in which they are embedded—from the human-made environment of a city to the "natural" environment of an ecosystem, a natural region, or the whole planet. People, like other organisms, for example, microorganisms, termites, and ants, have had, and continue to have, major effects on local, regional, and global environments. These effects are both purposeful—the effects of growing and building what we need and want—and inadvertent—the effects of our actions on the places and surroundings in which we grow and build. However, we have the capacity to take these effects into consideration, to think about the implications of what we do and design systems that address the possible effects. We need to make concerted efforts to develop technical methods for dealing with extremely complex systems, especially systems that involve combinations of technological systems, natural systems, and human systems.

In response to the complexification and globalization of our tasks, and of the means we must devise to deal with such tasks, it is more important than ever that we aim for the ideals of Art Bueche and the Bueche Award, especially the ideal of working in close cooperation with the academic, governmental, and industrial branches of the scientific, engineering, and technological professions. It is no longer sufficient, if it ever was, for technologists to be tools of policy—"on tap, but not on top." We don't have to be necessarily on top, but we should be fully engaged, early on and continuously, in policy issues that have technological components.

It is not enough for us to "stick to the science." Most policy systems and issues have technological aspects and components, even systems that are not considered technological. Take financial accounting systems; it is important to note that many scientists and engineers are experts in the collection, handling, and testing of data and that financial data are only data about a human system. Or take voting systems. We know something about the mechanics and mathematics of proposed voting systems and quite a lot about whether any system of data and evidence can provide 100 percent certainty about a legal or other conclusion.

In a democracy, the technical aspects of an issue should not necessarily be the determining factors, but the people who make decisions should not avoid, and should not be allowed to avoid, taking into account the likely technical consequences of their decisions. I believe our profession should find appropriate ways to make known the technical consequences of public, regional, and global choices and to make clear the inevitable uncertainties about those consequences. We need a better seat at the table. At the very least, we must become helpful critics at the policy and implementation table. For some years, I have regretted that in 1897 the Indiana state legislature did not pass legislation that a totally absurd value (apparently: $16/\sqrt{3} = 9.2376\ldots$) would be the legal value of π for the state. Passage of the law was narrowly averted by the accidental presence of a professor of mathematics from Purdue, who happened to be there lobbying for university appropriations. Had the bill become law, its consequences might have drawn considerable attention to the necessity of making careful decisions involving scientific and engineering matters.

I have many people to thank for my accomplishments. In the course of my life, I learned a great deal, first from my wonderful parents and then from a series of exceptional teachers in the schools I was lucky enough to attend. In the kind of work I have been fortunate enough to do, one accomplishes nothing alone. During my career, I have learned from, and worked for and with, many wonderful bosses and mentors in many exceptional organizations. Those organizations and I also benefited from many colleagues who worked with and for me, who did the real work, and who taught me how to help them do so. It would be impossible to mention all of their names, but I have been very lucky to have had many wonderful colleagues.

The Taoist work attributed to Lao Tzu, who may or may not have existed, expresses this same idea. This translation (one of many) of a stanza is by the American poet Witter Bynner:

> *A leader is best*
> *When people barely know*
> *he exists,*
> *Not so good when people obey*
> *and acclaim him,*
> *Worst when they despise him.*
> *"Fail to honor people,*
> *They fail to honor you."*
> *But of a good leader, who*
> *talks little,*
> *When his work is done, his*
> *aim fulfilled,*
> *They will say, "We did this*
> *ourselves."*

In addition to the colleagues who were my partners, I want to thank my family, my wife Jessica and my daughters Elizabeth and Margery, who put up with my absences, both when I was working elsewhere and when I was there but occupied in my own head so that I might just as well have been elsewhere. That was not strictly necessary, but, unfortunately, it is my personality and my way of working. They have my deep love and also my gratitude. I would also like to thank our grandchildren, Jonah and Lael, for their love, and for being Jonah and Lael.

Finally, you probably noticed the last phrase of my salutation—children of all ages. That salutation was not intended to be disparaging, but rather to remind us all that professional success is a matter of having fun in the exercise of one's talents and capabilities. I have been lucky enough to have had, and to continue to have, professional fun. In the Talmud, it is said: "You may not expect to complete the work, but you may not take your hand from it, either." Thank you!

References

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Bynner, W. 1980. The Way of Life, According to Lao Tzu. New York: Perigee Books, G. P. Putnam's Sons.

2003 Founders Award Presented to Carver A. Mead

(Left to right) George M.C. Fisher, Wm. A. Wulf, Carver A. Mead, Delores M. Etter.

The 2003 Founders Award was presented to Carver A. Mead, Gordon and Betty Moore Professor of Engineering and Applied Science, Emeritus, California Institute of Technology, for "visionary contributions in the field of microelectronics, including VLSI technology and computational neural systems." These remarks were delivered on October 12, 2003, during the NAE Annual Meeting.

It is wonderful to be here with old friends and new friends. I very much appreciated Bill's talk earlier about engineering education, something into which I have put a large part of my life.

My students have asked me what the difference is between engineering and science, often when we were out in the research laboratory trying to figure out what was true. I always told them that "engineering is the stuff that works out in practice." When you are doing research, you really don't know what will work out. Of course, things that don't work in the lab don't work in the real world, but things that do work in the lab often take a long time to work out in the real world. In my experience, it takes about 20 years from the time we can do something routinely in the research lab until it becomes common industrial practice. If you think about it, that is really too long. That length of time includes the time it takes students to learn how to do something, to have confidence in their ability to do it, to get out into companies, to rise through the ranks and become decision makers in the companies, and then to decide to use those techniques to contribute to real-world solutions. I think we are developing faster ways to get knowledge from our research universities into industrial practice, and there has been progress. But there needs to be a lot more.

Bill didn't mention one of the most fundamental problems in engineering education, so let me touch on it briefly. The amount of fundamental knowledge being generated by the research community is doubling every few years. Yet, we have only 16 to 20 years to train a student to be a member of the engineering workforce. The explosive growth in the number of facts, in the amount of information that it takes a student to master a technological field, and the limited number of years to educate students creates a fundamental issue. The default solution, of course, is specialization. We keep teaching more and more about less and less until finally we are teaching everything about nothing! That is one solution, but I don't think it will make for a viable society in the long term.

Another, much slower and more imperceptible process, will make for a viable society. That process is the quest to see facts, not as isolated facts but as part of constellations of facts, to see any given fact as an aspect of a much larger fact. Science and engineering share the quest for a viewpoint into which facts can be integrated effortlessly, and things that were hard to remember become obvious. Fire is a chemical reaction, not a separate element. The planets revolve around the sun under the influence of gravity, not by the action of a flock of invisible angels. The atoms of all elements are made up of protons, neutrons, and electrons. These same electrons are the carriers of electric current. Electricity and magnetism are two manifestations of the same underlying properties of electrons.

We have come to take these insights for granted, and we seldom honor the ongoing process of unification and simplification that led to them. I have spent a lot of my energy through the years trying to build frameworks of understanding that make otherwise obscure facts obvious. In my view, it is the only sustainable route to a bright future. In a very deep way, it is a fundamental quest that makes us uniquely human. I am very honored to receive the Founders Award today, and I accept it as honoring the process of building frameworks of understanding that make otherwise obscure things obvious.

Call for Nominations for 2004–2005 Awards

For more than 40 years, NAE has recognized outstanding engineers for the development of (or involvement in) engineering innovations or processes that have greatly improved people's lives. NAE awards five prizes and bestows more than $2.5 million biennially for achievements in engineering and engineering education. We invite you to help us continue this tradition by nominating outstanding engineers for the next prize cycle.

The Founders Award and Arthur M. Bueche Award are presented annually at the NAE Annual Meeting. The Founders Award is awarded to an NAE member or foreign associate who has upheld the ideals and principles of NAE through professional, educational, and personal achievement and accomplishment. The Bueche Award is awarded to an engineer who has been actively involved in determining U.S. science and technology policy, promoting U.S. technological development, and improving relations between industries, government, and universities.

The Charles Stark Draper Prize, awarded annually in February during National Engineers Week, is a $500,000 cash prize honoring an engineer whose contributions have significantly improved the quality of life, made it easier for people to live freely and comfortably, or provided access to information. The Fritz J. and Dolores H. Russ Prize, awarded biennially (in odd numbered years) in February during National Engineers Week, is a $500,000 cash prize honoring bioengineering achievements worldwide that have improved the human condition or had a significant impact on society.

Beginning in 2004, NAE will present the Bernard M. Gordon Prize for Innovation in Engineering and Technology Education every year in February during National Engineers Week. The Gordon Prize includes a $500,000 cash prize (half awarded to the recipient[s] and half to the institution). The Gordon prize honors technology educators whose innovative programs have strengthened the engineering workforce by cultivating students' communication skills, creativity, and teamwork.

Nominations for the 2004 Founders and Bueche awards and the 2005 Draper, Russ, and Gordon prizes will be accepted January 2, 2004, through April 12, 2004. Members and foreign associates will receive nomination materials by mail. Nonmembers who wish to submit nominations can obtain materials from Kimberly West at (202) 334-1628 or *kwest@nae.edu* or download them from our website *www.nae.edu/awards*. Mail or fax your nomination to: NAE Awards, National Academy of Engineering, 500 Fifth Street, N.W., NAS 308, Washington, DC 20001. Fax: (202) 334-1595.

U.S. Frontiers of Engineering Holds Meeting in September

NAE President Bill Wulf talks with Chester Kennedy (Lockheed Martin) and Karen Burg (Clemson University) during a break.

NAE hosted the ninth U.S. Frontiers of Engineering (FOE) meeting at the Beckman Center in Irvine, California, September 18–20. The approximately 100 engineers who attended the symposium heard talks on four topics: environmental engineering; fundamental limits of nanotechnology; counterterrorism technologies and infrastructure protection; and biomolecular computing. The talks in the environmental engineering session illustrated the interface between engineering and natural sciences, resource economics, systems analysis, and risk management. Speakers discussed how an understanding of microbial mineral respiration could inform the remediation of contaminated environments and/or generate electricity, the interface between water-resource engineering and economics and public policy, and how life-cycle analysis can be used to address sustainability issues.

Nanotechnology has been a topic at several past FOE meetings, but this year the focus was on the fundamental limits of nanotechnology. The speakers addressed prospects for nanotechnology in top-down approaches applied to silicon microelectronics; limits in the bottom-up approach to molecular electronics; the limits of storage in magnetic materials; and limitations imposed by the behavior of thermal systems at very small length scales.

Presentations in the session on counterterrorism technologies and infrastructure protection addressed chemical and biological threats, as well as threats to infrastructure systems (e.g., power distribution, telecommunications, and transportation) that depend on computing systems for their control and operation. The presentations covered biocatalytic decontamination/demilitarization, engineering problem-solving approaches for dealing with biological terrorism, and software and network security.

The symposium concluded with a session on biomolecular computing, also called DNA computing, biocomputing, and molecular computing. The primary goal of research in this field is to determine the potential of molecules, such as DNA, for massively parallel computation. Talks covered some promising areas in the field: computation based on DNA self-assembly; molecular breeding of DNA sequences by DNA shuffling; and programmable biological cells.

Breakout sessions were held on the second afternoon of the meeting to encourage discussion among small groups of participants. The discussions were focused on several questions related to the dynamic between the engineering profession and the general public, specifically, public understanding of engineering and engineering outreach to the general public: why engineering should matter to the public and why public understanding should matter to engineers; what engineering can do to make the world safer; the proper balance between the free

Luis Nunes Amaral (Northwestern University) raises a question following one of the talks.

flow of information and national security in a free, technologically sophisticated society; and how the engineering profession can be made more representative of the country as a whole. Summaries of the breakout discussions will be included in the upcoming FOE book.

The dinner speaker this year, **William F. Ballhaus, Jr.**, president and CEO of the Aerospace Corporation, gave a talk entitled "The Most Important Lessons You Didn't Learn in Engineering School." **Pablo P. Debenedetti**, Class of 1950 Professor and chair, Department of Chemical Engineering, Princeton University, chaired the organizing committee and the symposium.

Funding for the 2003 U.S. FOE symposium was provided by the Air Force Office of Scientific Research, Defense Advanced Research Projects Agency, U.S. Department of Defense (DDR&E-Research), National Aeronautics and Space Administration, Eastman Kodak, Microsoft Corporation, ATOFINA Chemicals, Inc., Cummins, Inc., Science Applications International Corporation, Air Products and Chemicals, Inc., Millipore Corporation, GE Foundation, and Dr. John A. Armstrong and other individual donors.

NAE has hosted the U.S. Frontiers of Engineering meeting annually since 1995; bilateral programs are also held with Germany and Japan. All of the FOE meetings bring together outstanding engineers from industry, academe, and government at a relatively early point in their careers; all participants are 30 to 45 years old. FOE provides an opportunity for these young engineers to learn about developments, techniques, and approaches at the forefront of research in many fields, which has become increasingly important as engineering has become more and more interdisciplinary. The meetings also facilitate contacts and collaborations among the next generation of engineering leaders.

Extended summaries of the presentations and breakout sessions will be published in February 2004. The 2004 symposium will be held September 9–11 at the Beckman Center. For information about the symposium series or to nominate an outstanding engineer to participate in a future meeting, contact Janet Hunziker, NAE Program Office, (202) 334-1571 or *jhunziker@nae.edu*.

Randy Atkins Wins Academies Award

Randy Atkins

On the morning of October 7, 2003, staff from all over the National Academies gathered in the auditorium of the National Academies building to recognize the extraordinary work of their colleagues. The event began with a humorous look at some forgettable projects from the past. However, the tone became suitably dignified when the three presidents presented the awards acknowledging serious work by individuals and groups that has impacted the entire organization and beyond.

Randy Atkins, NAE senior program officer for media/public relations, received a Distinguished Service Award. William Colglazier, chief operating officer of the National Research Council (NRC) and executive officer of the National Academy of Sciences and the NRC, read the citation: "Since joining the NAE, Randy's outreach in print, radio, and television media have increased the NAE's public exposure to levels never seen before. Mentions of NAE have doubled year after year, and attention to NAE's major prizes has reached an all-time high. He has made a remarkable contribution to the public recognition of the NAE and the engineering community."

Ethics Workshop Energizes Engineers

On October 14 and 15, 2003, more than 150 engineers and ethicists participated in an NAE workshop "Emerging Technologies and Ethical Issues." The workshop began with presentations on technologies in the rapidly developing fields of sustainability (or earth systems engineering), nanotechnology, neurotechnology, and energy. Balancing future possibilities with ethical questions about how to develop and use these technologies raises many issues: cultural constructs surrounding sustainability; health risks of nanomaterials; prophylactic treatment of psychiatric susceptibilities predicted by brain imaging; and maintaining professional objectivity when addressing a politicized topic like nuclear energy.

One speaker, **John Ahearne**, director of the ethics program at Sigma Xi, summarized the role of engineers. "The technology professional has a responsibility to do rigorous analysis with complete objectivity," he said. "Many citizens do not have the background, the resources, the time, or the interest to dig deeply into technical issues. The public must rely on the professionals, who therefore carry a heavy burden."

In the afternoon session, which included talks on state-of-the-art approaches to ethical issues, Ed Harris, associate professor in the Department of Philosophy at Texas A&M University, described a methodology for analyzing and resolving issues in engineering ethics that focuses on four aspects of a situation: factual, conceptual, application, and moral. The key to ethical analysis, according to Harris, is "to locate or isolate the locus of ethical disagreement." Other speakers presented academic theories and described new tools for analyzing risks and responsibilities and codes of ethics endorsed by engineering societies.

Addressing ethical issues raised by complex systems requires an ongoing discussion among engineers in many disciplines, as well as between engineers and ethicists. Participants had many opportunities to enter into discussions during question and answer periods following each presentation, during afternoon breakout sessions, and throughout the workshop. As NAE President **Bill Wulf** noted, "I was struck by the fact that, as always, there were little clumps of people talking to each other, and virtually every one of them was a mixture of engineers and ethicists. I detect a genuine desire to communicate."

The last major activity of the day was a film, "Incident at Morales," developed by the National Institute for Engineering Ethics, that raised issues of responsibility for decisions in a corporate setting. In the film, budget cuts prompt a design engineer at a chemical plant to consider options that could threaten environmental and workplace safety. The discussion that followed touched on both the ethical issues and the effectiveness of films and other "tools" for developing a sensitivity to ethical issues.

The next morning, workshop participants took up the subject of incorporating ethics into the education of future and practicing engineers. Vivian Weil, director of the Center for the Study of Ethics in the Professions at Illinois Institute of Technology, described a workshop for professors at her institution, "Engineering across the Curriculum," on integrating ethics into their courses. Stephanie J. Bird, editor of *Science and Engineering Ethics*, described two ways of building ethics into engineering education. First, ethics can be a component of a project; for example, ethics can be included in the presentation of research findings by students in the summer Research Experiences for Undergraduates (REU) Program. Second, engineering practice workshops can bring together young and experienced engineers to discuss ethical issues; successful workshops involve senior professionals in discussions explicitly about ethics.

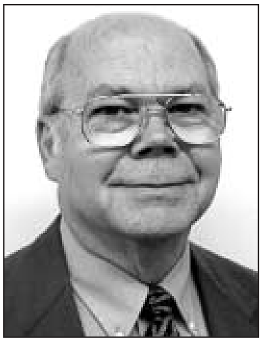
In closing remarks, workshop steering committee chair Deborah Johnson, Anne Shirley Carter Olsson Professor of Applied Ethics at the University of Virginia, suggested that not enough attention is paid to engineering ethics. "There really is a gap in our understanding of how to deal with macro-ethical issues," said Johnson. "We're much more comfortable with and know much more about how to think about the micro-issues. It's not just that we don't know about the macro-issues, but we don't know about the connections between the micro- and the macro-."

For more information about the workshop or to hear audio presentations, visit the NAE website at *www.nae.edu*. A proceedings of the workshop presentations will be published in spring 2004.

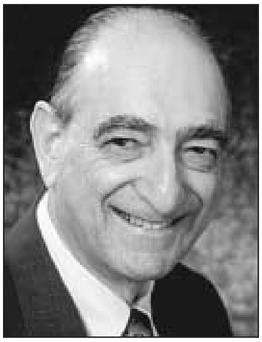
CASEE Senior Fellows, Scholar in Residence, and Intern Focus on Engineering Education

In keeping with NAE's initiative to promote the reform of engineering education, the NAE Center for the Advancement of Scholarship on Engineering Education (CASEE) now has three senior fellows (working from their home institutions), one scholar in residence, and a student intern.

Senior Fellows in Engineering Education



Donovan Evans



Myron Tribus

Karan L. Watson

Donovan Evans, Emeritus Professor in the Department of Mechanical and Aerospace Engineering at Arizona State University (ASU) in Tempe, Arizona, will provide a status report on the development and implementation of concept inventories in engineering education. The concept inventory method, which measures students' understanding of important concepts, has been used to assess undergraduate learning for more than 15 years and is credited with stimulating educational reform in physics, biology, and geology.

Dr. Evans was the founding director of the Center for Research on Science, Mathematics, Engineering, and Technology, a joint venture of the ASU Ira A. Fulton School of Engineering, College of Liberal Arts and Sciences, and College of Education. Previous to that, he was the founding director of the Center for Innovation in Engineering Education, in what was then the College of Engineering at ASU. Dr. Evans is a member of Pi Tau Sigma (the mechanical engineering honor society), Tau Beta Pi (the engineering honor society), the American Society of Mechanical Engineers, and the American Society for Engineering Education.

Myron Tribus, a consulting engineer in private practice and an NAE member, has written extensively on how the management principles of **W. Edwards Deming** and the teaching-learning principles of Reuven Feuerstein can be applied to K-12 education. He is now working on the application of these principles to engineering education. Edwards Deming, a statistician often called the father of the quality movement, developed management principles that contradicted conventional wisdom but have proven effective in reducing costs, improving quality, and increasing customer satisfaction. Reuven Feuerstein, an Israeli psychologist and innovator in education, developed methods of cognitive modifiability that help people act more intelligently. Dr. Tribus believes that the combined principles of Deming and Feuerstein can lead to an innovative approach to teaching and learning that will increase the joy of learning and lead to engineers who are better prepared to face complex, real-world situations.

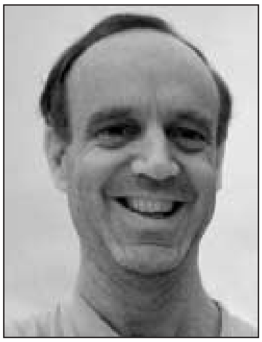
Dr. Tribus retired from an 11-year career at MIT as director of the Center for Advanced Engineering Study. He was senior vice president for research and engineering for the Xerox Corporation and, for two years, assistant secretary for science and technology in the U.S. Department of Commerce. For eight years, he was dean of the Thayer School of Engineering at Dartmouth College, where he introduced the unified engineering curriculum and led the faculty in developing a curriculum based on engineering design and entrepreneurship.

Karan L. Watson is associate provost and dean of faculties, as well as professor of electrical engineering, at Texas A&M University. Dr.

Watson's work has focused on increasing the participation of underrepresented populations—particularly women and minorities—in engineering. Dr. Watson believes that a diverse workplace provides a stimulating environment for workers and that conflicts about diversity should be discussed and resolved openly. As an NAE senior fellow, she will survey instructional and institutional strategies that encourage diversity among people, learning styles, and perspectives. She will also consider how these strategies can contribute to the formulation and solution of engineering problems.

Dr. Watson has been involved in the Women and Engineering Program Advocates Network and the National Association of Minority Engineering Program Administrators and is principal investigator for the Texas Alliance for Minority Participation. She is the recipient of many national awards, including the Minorities in Engineering Award, the United States President's Award for Excellence in Science and Technology Mentoring, the American Association for the Advancement of Science Mentoring Award, and the Women in Engineering Programs and Advocates Network's Founders Award.

CASEE Scholar-In-Residence



Myles Boylan

Myles Boylan, a program officer with more than 19 years of experience at the National Science Foundation (NSF), joined CASEE in October 2003 as a 12-month scholar-in-residence. Dr. Boylan will be working on two projects. First, he will develop a method of classifying projects and studies for improving or examining an aspect of undergraduate engineering education as a basis for measuring scholarly interest in the engineering community. In the second project, he will develop a format for reporting on CASEE activities and for assessing their value to the engineering community and the nation.

Dr. Boylan is lead program director for the NSF Assessing Student Achievement component and program codirector for the National Dissemination component of the Course, Curriculum, and Laboratory Improvement Program. He joined NSF in 1984 after holding academic appointments at Ohio State University, Case Western Reserve University, and Colby College. His academic research was focused on the process and diffusion of technological innovation in private industry, particularly manufacturing. His instructional innovations included early advocacy and small-group learning. In the early 1990s, Dr. Boylan was executive secretary of a National Science Board subcommittee that assessed national literacy in science, technology, engineering, and mathematics (STEM) and staff leader for a comprehensive study, released in 1996, of the state of undergraduate education in STEM disciplines.

Dr. Boylan earned his bachelor's degree in mathematics from Michigan State University, his master's degree in organizational science from Case Institute of Technology, and his doctorate in industrial economics from Case Western Reserve University.

CASEE Student Intern

Tracy L. Blake

Tracy L. Blake, a Ph.D. candidate in higher education administration at the University of Florida, was an intern this fall at NAE. Ms. Blake's primary focus was on continuing work begun by previous interns to identify best instructional practices in engineering education and to document links between instructional practices and student learning outcomes as a basis for a grant proposal to NSF.

Ms. Blake, a second-year doctoral student, is hoping to teach at a major research institute and perhaps secure a research position in a government organization dedicated to promoting educational excellence. She is interested in mentoring, graduate student education, and policy issues in higher education as they relate to minority access, equity, and outcomes.

Sheila Widnall Inducted into the National Women's Hall of Fame

Sheila Widnall

Sheila E. Widnall, vice president of NAE, was one of 12 women inducted into the National Women's Hall of Fame on October 4. The Honorable Sheila E. Widnall was appointed Secretary of the Air Force in 1993 by President Clinton, the first woman to hold that position. A member of the MIT faculty since 1964 and the first woman to serve as chair of the MIT faculty, Dr. Widnall was influential in increasing the percentage of women undergraduate students from 2 percent to 45 percent; women now constitute a majority in three engineering departments at MIT. Most recently, she served on the NASA commission that investigated the *Columbia* tragedy. NAE President **Wm. A. Wulf** traveled to the induction ceremony in Seneca Falls, New York, to present the award.

Grace Huynh, NAE Intern

Grace Huynh

Grace H. Huynh is currently working toward a Ph.D. in bioengineering in the Joint Bioengineering Graduate Group Program at the University of California-Berkeley and the University of California-San Francisco; she earned a B.S. in interdisciplinary engineering at the University of Washington. Her interest in this field developed during her studies in the Early Entrance Program at the University of Washington (UW), a program that allowed her to enter the university at the age of 14 following a year of intensive Transition School in place of high school. Her graduate research is on the physicochemical properties of phospholipid self-assembled structures and their medical and electronic applications.

At the NAE Grace worked on identifying projects on the state and local levels that keep K-12 science and engineering students abreast of new technologies, inspire them with innovative designs, and encourage them to think critically and creatively. Grace also reviewed websites and conducted focus groups to find ways to improve *Engineer Girl!*, NAE's online website for middle school girls.

Jamie Ostroha, NAE Intern

Jamie Ostroha

Jamie Ostroha, a doctoral candidate in materials science (biopolymers) and engineering at Drexel University, worked with the NAE Committee on Engineering Education on the Engineer 2020 project. Upon completion of her Ph.D. program, she hopes to work on educational policy issues that promote science and technology education among children and young adults. As a Christine Mirzayan Intern, Jamie hopes to affect changes in policy to bring science and technology education to more students, improve the learning of science in general, and improve the education of teachers of science and technology. Jamie is actively involved in educational outreach programs at Drexel, where she works with high school students and college freshmen and participates in a teacher-training program for middle schools.

Calendar of Meetings and Events

2003

December 5–6	Committee on Membership Meeting Irvine, California
December 11	NRC Governing Board Executive Committee Meeting
December 18–19	Assessing Technological Literacy Committee Meeting

2004

January 20	EngineerGirl! Website Subcommittee Meeting
February 11–12	NAE Council Meeting Irvine, California
February 12	NAE National Meeting Irvine, California
February 24	NAE Awards Dinner/Presentation
February 25	NAE Finance and Budget Committee Conference Call
March 9	NAE Regional Meeting San Jose, California
March 18	NAE Regional Meeting Houston, Texas
April 8	NAE Regional Meeting Philadelphia, Pennsylvania
April 15	NAE Regional Meeting Columbus, Ohio
April 29–May 1	7th German-American Frontiers of Engineering Symposium
May 3–4	Convocation of Professional Engineering Societies

All meetings are held in the National 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

JOHN L. BOGDANOFF, 87, Professor Emeritus, Purdue University, died on July 20, 2003. Dr. Bogdanoff was elected to NAE in 1975 for the introduction of stochastic processes into mechanical and civil engineering analysis.

WILBUR B. DAVENPORT, JR., 83, Professor of Communications Science and Engineering, Emeritus, Massachusetts Institute of Technology, died on August 28, 2003. Dr. Davenport was elected to NAE in 1975 for contributions to communications engineering and education and for leadership in continuing engineering education.

IVAN A. GETTING, 91, President Emeritus, Aerospace Corporation, died on October 11, 2003. Dr. Getting was elected to the NAE in 1968 for the development of radar systems and technical weapons and for his advisory contributions to national agencies.

WERNER GOLDSMITH, 79, Professor of the Graduate School, Mechanical Engineering Department, University of California, Berkeley, and consultant, died on August 23, 2003. Professor Goldsmith was elected to NAE in 1989 for outstanding research on impact phenomena in solids, including projectile penetration, rock mechanics, and head and neck injuries.

CHARLES C. NOBLE, 87, U.S. Army (retired), and retired president and chief executive officer, C.T. Main Corporation, died on August 16, 2003. General Noble was elected to NAE in 1981 for new concepts in the control and development of the nation's largest rivers to effect optimum utilization.

BRUCE S. OLD, 89, president, Bruce S. Old Associates, Inc., died on September 3, 2003. Dr. Old was elected to NAE in 1968 for process improvements in iron and steel, metallurgy of nuclear materials, and cryogenics.

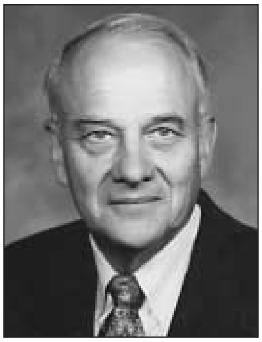
NORMAN C. RASMUSSEN, 75, McAfee Professor of Engineering, Emeritus, and Professor of Nuclear Engineering, Emeritus, Massachusetts Institute of Technology, died on July 18, 2003. Professor Rasmussen was elected to NAE in 1977 for contributions to applied radiation detection, the development of quantitative methods of risk assessment, and nuclear safety.

WILLIAM G. SHEPHERD, 92, Professor Emeritus of Electrical Engineering, University of Minnesota, died on September 5, 2003. Dr. Shepherd was elected to NAE in 1969 for the development of velocity-modulated, reflex-type tubes.

Testimony before Congress

Database and Collections of Information Misappropriation Act of 2003

Excerpts from testimony on September 23, 2003, before the Energy and Commerce Subcommittee on Commerce, Trade, and Consumer Protection, and the Judiciary Subcommittee on Courts, the Internet, and Intellectual Property, U.S. House of Representatives.



Wm. A. Wulf is president of NAE.

I have been asked to testify on behalf of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine (the National Academies) and on behalf of the Association of American Universities, the American Library Association, and the Association of Research Libraries. I am grateful for the opportunity to testify before you today about the draft legislation called the "Database and Collections of Information Misappropriation Act of 2003." The proposed legislation concerns a topic about which the scientific, research, education, and library communities have an abiding interest and continuing concerns. Indeed, this is the third time the National Academies has testified on congressional legislation in this area since 1997. In addition, both the National Academies and its operating arm, the National Research Council (NRC), have published extensively on these issues in the past seven years.

Although I am authorized to speak only on behalf of the organizations I represent here today, the issues I wish to raise with you pertain broadly to our nation's scientific, research, education, and library concerns. And although I do not address directly the important issues raised by this legislation for the commercial sector, which are the focus of other testimony before you, I am cognizant of the broad implications for our nation's economic and social progress.

In my testimony, I will make the following points, which build on previous analyses:

- As a matter of public policy, several key principles must inform the crafting of new legislation in this area:
    1. The public-domain status of factual, non-copyrightable information must be preserved, and any new protection regime should leave a wide buffer zone to ensure that factual information will not be subjected to proprietary claims.
    2. Only significant, proven problems of unfair competition and market failure should be addressed, and negative unintended consequences must be avoided.
    3. A reasonable balance of interests among stakeholders in the information economy should be maintained. Congress should proceed cautiously in creating new protection regimes, because once created, they are virtually impossible to dismantle.
    4. Healthy competition in the information industry should be promoted, and the strengthening of unwarranted monopolies should be avoided.
    5. Exclusive control, either *de jure* or *de facto*, by private parties over information and databases produced by the government must be prevented.
    6. New protection regimes should not create doubt or controversy about the lawfulness of traditional and customary access to and use of factual information for not-for-profit science, research, and education. Effective exceptions must be adopted.
    7. The important role and functions of our nation's libraries must not be undermined.
- The draft legislation includes a number of improvements over previous versions introduced by the House Committee on the Judiciary since 1996.
- There are still major problems and ambiguities in the current draft bill that can and should be addressed, assuming that the creation of a new statutory remedy is still deemed necessary.

- The National Academies and the other organizations represented in this testimony remain committed to helping Congress in its consideration of database protection in a way that is consistent with the principles identified in this testimony and that avoids negative unintended consequences.

Key Principles

1. **The public-domain status of factual, non-copyrightable information must be preserved, and any new protection regime should leave a wide buffer zone to ensure that factual information will not be subjected to proprietary claims.**

As we noted in previous testimony on this issue, access to and use of factual data in the public domain is essential to furthering our understanding of nature, the validation of scientific claims, and the progress of science and our nation's system of innovation. The advent of digital technologies for collecting, processing, storing, and transmitting data has led to an exponential increase in the size and number of databases. A hallmark trait of modern research is obtaining and using dozens, or even hundreds of databases, extracting and merging portions of each to create new databases and new sources of knowledge and innovation.

Not only researchers and educators, but all citizens with access to computers and networks, constantly create new databases and information products for commercial and noncommercial applications by extracting and recombining public-domain data and information from multiple sources. The rapid and continuous synthesis of disparate data by all segments of our society is one of the defining characteristics of the information age. Moreover, the serendipitous nature of research and the need of scientists and others to make transformative uses of non-copyrightable facts are such that one cannot predict when or how a database will be used. The ability of individuals and organizations to use information in a wide variety of innovative ways is also a measure of success of the original data-collection efforts.

Society uses the fruits of research and innovation to expand the world's base of knowledge and applies that knowledge in myriad downstream applications to create new wealth and to enhance the public welfare. Indeed, the policy of the United States has been to support a vibrant research enterprise and to ensure that its productivity can be exploited for national gain. Thus, freedom of inquiry, the availability of scientific and other factual data in the public domain, and the open publication of results are cornerstones of our research system that U.S. law and tradition have long upheld.

The results of these wise policies have been spectacular. For many decades, the United States has been the leader in the collection and dissemination of scientific and technical data and in the discovery and creation of new knowledge. Our nation has used that knowledge more effectively than any other nation to support new industries and applications, such as the biotechnology industry and the discovery of new diagnostics and cures for hereditary and other diseases.

In addition to the critical importance of factual information remaining in the public domain, it is also essential for compelling American values and needs, including First Amendment rights of freedom of expression, the promotion of the information economy, democracy and good governance, and other public-interest uses by consumers and society generally. Therefore, new legislation in this area must be limited to remedying unfair conduct in commerce rather than extending exclusive property rights to factual information itself.

If there is uncertainty or doubt about the effect of potential new legislation, Congress should be careful to err on the side of caution. When the subject matter consists of the fundamental building blocks of knowledge, science, and expression, the cost of overprotection far exceeds the cost of underprotection.

2. **Only significant, proven problems of unfair competition and market failure should be addressed, and negative unintended consequences must be avoided.**

Proponents of new database protection legislation have long argued that the misappropriation of databases is a major problem in the U.S. information industry and that existing methods of protection and remedies are inadequate. We find both assertions to be of dubious validity.

There is little evidence since the last time we testified on this issue before Congress that databases or other collections of information are routinely stolen or that there is massive market failure in the information industry. Indeed, database producers already enjoy a broad range of legal, technological, and self-help methods—many of which have been strengthened in recent years—to protect the fruits of their investments. Available legal remedies at the federal level include traditional copyright law, new rights to prevent the circumvention of technological protection measures granted under the Digital Millennium Copyright Act, and the new Computer Fraud and Abuse Act. Under state law, many jurisdictions have a common law prohibition against misappropriation of "hot news" and a claim for trespass to chattels to protect databases.

Contracts and licenses are now used universally by database owners to make their products available under a range of custom-tailored, restrictive conditions. Technologies that protect digital databases and help enforce the existing statutory and contractual rights of owners are constantly being refined and strengthened, including such methods as encryption, online database access controls, software- and hardware-based trusted systems, and digital object identifiers and electronic watermarks. Indeed, these contracts and technologies are increasingly being used to limit the uses of data and information that would otherwise be permitted by law. Congress should carefully monitor their use and consider whether limits are needed to preserve the balance between access to and the use of factual information and the incentives to invest in the collection of such information, both of which are essential to the vigorous growth of science and knowledge.

Finally, market-based protections of databases through self-help business practices, such as frequent updating and customizing, can make misappropriation more difficult. Taken together, these database protections have helped the commercial database market expand successfully in the United States.

The Academies, the Association of American Universities, the American Library Association, and the Association of Research Libraries nonetheless are committed to helping Congress consider the issues of database protection in a way that is consistent with the principles identified in this testimony and avoids unintended negative consequences. The National Research Council reports referenced at the end of this testimony analyze the far-reaching negative implications for research and innovation that could result from legislation that is overly protective of data and non-copyrightable factual information.

3. A reasonable balance of interests among stakeholders in the information economy should be maintained. Congress should proceed cautiously in creating new protection regimes, because once created, they are virtually impossible to dismantle.

It is essential that Congress promote a healthy balance of the interests of all stakeholders in the information economy and society, including the general public. The trend in recent years has been to increase the breadth, depth, and length of all types of protection of intellectual property. The creation of new statutory rights, particularly for subject matter as sensitive as non-copyrightable factual information, must be done in full cognizance of the interaction of these rights with parallel rights conferred by other statutes to avoid negative synergistic effects. A major concern for the research community, as discussed further below, is the potential negative effect on access to and uses of databases from unbridled, highly restrictive licensing practices, especially through increasingly legitimized adhesion contracts (e.g., shrink-wrap and click-on licenses), in concert with new statutory rights in databases.

Furthermore, history has demonstrated that once intellectual property rights are granted, they are rarely, if ever, reduced or limited. Thus, if there is uncertainty about the effect of a proposed new protection, it is important to err on the side of caution and the preservation of the status quo.

4. Healthy competition in the information industry should be promoted, and the strengthening of unwarranted monopolies should be avoided.

The promotion of competition is primarily an economic issue of direct interest to our colleagues in industry, but the benefits of competitive prices and high quality accrue to the public. It is important, nonetheless, to emphasize that a preponderance of scientific databases are produced by sole sources, in both the public and private sectors. For example, the vast majority of observational data sets of phenomena in the natural world, as well as all unique historical factual compilations, can never be recreated independently and are therefore frequently available only from a single, original source. In other cases, scientific databases are *de facto* unique natural monopolies because the cost of producing the data and the potential market will not support multiple sources. Even when data that are similar, but not identical, to original research results or observations are available for use in nontechnical applications, researchers and educators are unlikely to consider an inexact replica of a database a suitable substitute if it does not fully meet the original specifications. For this reason, scientific databases are particularly prone to monopoly control. New legislation therefore must not enhance the market power of sole-source providers in any segment of the information industry without adequate public-interest safeguards.

5. **Exclusive control, either de jure or de facto, by private parties over information and databases produced by the government must be prevented.**

Consistent with Principle 1 (above), the public-domain status of government databases and other information products is a key factor in the success of our nation's research enterprise, as well as for other compelling national values and interests. Legislation that confers new rights on the private sector must fully exempt government databases from the scope of protection and avoid the possibility of exclusive capture by private-sector entities.

6. **New protection regimes should not create doubt or controversy about the lawfulness of traditional and customary access to and use of factual information for not-for-profit science, research, and education. Effective exceptions must be adopted.**

Also in keeping with Principle 1 (above), it is important to provide clear immunity for customary noncommercial scientific, research, and educational uses from the database protection statute. Nonprofit institutions should not be required to have expert counsel on intellectual property looking over the shoulder of every scientist and scholar. Customary activities should not be "chilled." Because facts themselves are at issue, the legislation should include an express presumption that customary uses of databases are exempt from liability, and the burden of proof on the plaintiff for demonstrating a violation should be increased.

7. **The important role and functions of our nation's libraries must not be undermined.**

Libraries have traditionally served the important public-interest function of providing access to information for our nation's citizens and have performed essential preservation and archiving activities. Any rights conferred on database owners by new legislation must not undermine the ability of libraries to continue to serve as public-interest intermediaries for access to and the preservation of factual information resources.

Preliminary Comments on the Draft Legislation

We have not had sufficient opportunity to make a comprehensive analysis of the draft "Database and Collections of Information Misappropriation Act of 2003." The issues and competing interests in this legislation are complex and difficult to reconcile. Although the drafting process has been long and difficult, we believe it has led to a deeper understanding of the issues, which was palpably lacking when the first legislative proposal, based on the European Union's database directive, was introduced in 1996. The drafting process has also demonstrated inherent problems in introducing new rights in this constitutionally sensitive area and the importance of addressing the competing legitimate interests of the many stakeholders in the information economy and not just the economic interests of the originators of commercial databases.

Our preliminary analysis of this new version of the legislation is consistent with the views expressed by the major university organizations in the September 9, 2003, letter from Nils Hasselmo, president of the Association of American Universities, to the two cognizant committee chairmen. We conclude that, although improvements have been made since the previous legislative proposals introduced by the Committee on the Judiciary, very significant problems still remain. Moreover, the current draft contains a number of new provisions whose intent and impact are ambiguous, which could have serious unintended consequences for the research and education enterprise.

We appreciate, in particular, several improvements that have been made in response to the concerns expressed earlier by the Academies and other parties to this process. The move toward a standard of liability grounded more in unfair competition law and the elimination of some of the most unacceptable aspects of previous versions of the Committee on the Judiciary's proposed statutes are certainly welcome. Among the specific improvements are the elimination of qualitative substantiality, the effort to link liability to direct competition in the same market as the existing database, the adoption of a knowledge requirement as a condition of liability, and a limitation to databases that require substantial effort to develop. The elimination of criminal penalties and the explicit recognition of the doctrine of misuse as a limiting factor on lawsuits are also positive developments.

Although the draft under discussion addresses some of the concerns we identified previously, many serious problems remain, and new ambiguities have been introduced by the recent changes. We note here only the issues of greatest concern to the scientific, research, education, and library communities consistent with the principles articulated above, and we incorporate by reference additional concerns expressed in the September 9 letter from Nils Hasselmo:

- With regard to the liability standard, the discussion draft could confer perpetual ownership rights in a wide variety of data by virtue of protecting investment based on open-ended maintenance of a database. In addition, the concept of "making available to others" appears to be overly broad, posing a threat to customary collaborative work within or among universities and research institutions. Moreover, minimal harm—even one lost sale or a single lost source of data—could lead to a finding of liability and to a chilling constraint on the use of public-domain factual information, contrary to the values articulated under Principle 1 above.

- As written, the exception for educational, scientific, and research institutions applies only to institutions that are nonprofit and their "making available" is for nonprofit purposes. This would discourage joint research and development activities between nonprofit institutions and corporations. It is especially troubling that the exception can be overridden by a shrink-wrap or click-on license, which would render the exception meaningless—a major concern noted under Principles 3 and 6. Any new legislation must preclude such a possibility. Finally, we continue to urge that the burden of proof of demonstrating that customary not-for-profit scientific, research, and educational uses of factual information are unreasonable should be a heavy burden borne by the plaintiff.

- The scope of the exclusion for government information in the discussion draft is uncertain. It appears that a publisher that incorporates government information in its database could prevent others from making available that government information—even if it is not available from any other source, contrary to Principle 5.

- By failing to address the problem of sole-source databases, the discussion draft increases monopolists' control over competitive uses of information. This is of particular concern in the market for databases used in scientific research and education, as noted under Principle 4. The provision on misuse, which could mitigate harmful conduct of database monopolists, provides no guidance for courts to determine whether misuse has occurred. The misuse provision should specifically address the issue of sole-source databases. H.R. 1858 contained appropriate language in this regard.

We believe progress has been made on this legislation, but clearly the current draft is still not ready to be adopted and would introduce serious problems in its present form for many stakeholders in the information economy, including the scientific, research, educational, and library sectors. In closing, I would like to reiterate that the Academies, and all of the organizations I represent in my testimony today, have tried to play a constructive role in congressional efforts to craft legislation in this complex and sensitive area. We look forward to working with Congress on this issue to develop a consensus on the best way to move forward.

Thank you again for providing us with the opportunity to testify at this hearing.

Recent National Research Council reports published by the National Academies Press are all freely available at *www.nap.edu*:

The Role of Scientific and Technical Data and Information in the Public Domain (2003)

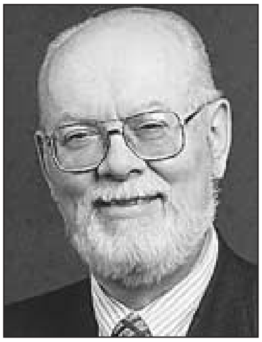
The Digital Dilemma: Intellectual Property in the Information Age (2000)

A Question of Balance: Private Rights and the Public Interest in Scientific and Technical Databases (1999)

Bits of Power: Issues in Global Access to Scientific Data (1997)

Implications of Power Blackouts for the Nation's Cybersecurity and Critical Infrastructure Protection: The Electrical Grid, Critical Interdependencies, Vulnerabilities, and Readiness

Excerpts from testimony of September 4, 2003, before the House Subcommittees on Cybersecurity, Science, and Research and Development and on Infrastructure and Border Security of the Select Committee on Homeland Security.



Paul H. Gilbert is a member of NAE, director emeritus of Parsons Brinckerhoff Inc., and chair of the Panel on Energy Facilities, Cities, and Fixed Infrastructure, Committee on Science and Technology for Countering Terrorism, National Research Council.

Our basic infrastructure systems, which comprise highly integrated, mutually dependent, highly utilized infrastructure components, provide our communities with vitally needed services and support our way of life. They provide electric power, our food supply, our water supply, waste disposal, natural gas, communications, transportation, petroleum products, shelter, employment, medical support and emergency services, and other basic needs. Although all of these elements are essential to our well-being, only one has the unique characteristic that, if it were lost, it would cause all of the others to be either seriously degraded or completely lost. And that, of course, is electric power. Our technically advanced society is literally hardwired to a firm, reliable supply of electricity.

In the past decade, the electric supply system has taken on significantly greater loads (power demands) and has also undergone a makeover—from a highly regulated, vertically integrated utility industry to a partially deregulated, far less unified industry that is not as robust and resilient as it was. On the power-generation side, the industry is essentially deregulated and operating under open-market conditions in which competitive price, low operating costs, and return on investment are rewarded with profits and bonuses. At the same time, the power-transmission sector remains fully regulated.

Taking steps to meet growing demand with new capacity is an undertaking filled with uncertainty about how investments will be paid for. Regulatory bodies are required to see that power is delivered to rate payers at minimum cost. Where possible, operating costs have been reduced by installing automated cybercontrollers, SCADA units, and LANs to perform functions that were previously performed by people. In general, control has been more centralized, spare parts inventories have been reduced, and systems are highly integrated across entire regions.

As a result of these dramatic changes, in-place electrical systems assets today are typically operated very efficiently at close to the limit of their available capacity, and another characteristic of such systems has become apparent. When systems are operated near their capacity, they have little margin within which to handle fluctuations in power or load. Thus, they are vulnerable to being brought down by operating fluctuations that exceed their remaining margins because shutting down is the only way a system element can protect itself from severe damage when load exceeds capacity. But the loss of one piece of the grid, a section of transmission line, for example, does not end the problem. The downed line takes with it the power it was transmitting. Thus, connected power plant, having no connected load, must also shut down. In highly integrated grids, as transmission lines have imbalance problems, more plants sense capacity problems and also shut down. This cascade spreads very rapidly in many directions, and in seconds, an entire sector of the North American grid can shut down. We had a living example of such an event this past month [August], caused by an accident. We were fortunate the power was returned so quickly.

The exact same consequences could easily be caused by an attack by a small, trained terrorist team, as was hypothecated in the National Research Council report, *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism* (2002). The hypothetical attack involves taking out several critical nodes in the grid in the most damaging way. The terror then flows to all of us. Recovery might take weeks or months, not hours or days, and the damage done to people and the economy would be enormous.

The report does not speculate on the extended consequences of such an event, but I have been asked to do so here, and I offer this as personal opinion. Because our critical infrastructure is completely integrated, if the power is out for even a day or two, both the food supply and water supply would soon fail. Transportation systems would come to a standstill. Wastewater could not be pumped away and so would become a health problem. In time, natural gas pressure would decline, and some would lose gas altogether. Nights would be very dark, and communications would be spotty or nonexistent. Storage batteries would have long since been gone from stores, if any stores were still open. Work, jobs, employment, business, and production would be stopped. The economy would take a major hit.

All in all, cities would not be very nice places to be. Some local power grids would get back up, so there would be islands of light in the darkness. Haves and have-nots would become involved. Cities would not be very safe either. Marshal law would likely be declared, and there would be emergency food and water supply relief. We would rally and find ways to get by while the system was being repaired, and in time, the power would come back, tentatively at first, with rolling blackouts, and then in all its glory. After several weeks or months, the cleanup would begin. This is one man's opinion.

We have the means to limit the disaster I just described. The recommendations in Chapter 6 of the report describe actions that would minimize the immediate vulnerabilities of electric power systems and then address longer term solutions. The recommendations (which are summarized below) are as much to the point today as they were when they were published 15 months ago:

- We must immediately mobilize the leadership and then the resources of people and organizations to determine the proper roles of each interested party and then to come together and develop plans.
- Obstacles (e.g., antitrust, liability, and FOIA issues) that deter open discussions among private and governmental parties must be addressed immediately.
- Government should review the institutional and market settings (regulated and deregulated and open free market) for the industry, focusing incentives on what the nation needs to live safely.
- Tools now used by the military to analyze vulnerabilities should be mobilized and, perhaps, transferred to the U.S. Department of Homeland Security for evaluating the grids.
- Coordinated studies should be done to identify the most critical equipment in the respective power systems and to describe protective measures for each.
- Simulation models of these highly complex grids should be done. The models should be capable of identifying the points of greatest vulnerability and reserves of operating capacities.
- Statutory action should be taken to allow recovery crews to enter what would then be a crime scene immediately following an attack to commence repairs and restore service.
- Regulatory bodies must be encouraged to find a way for transmission organizations to define costs for counterterrorism improvements and to recover those costs from their operations or other sources.
- The use of SCADA systems in unprotected configurations should be assessed and expert advice obtained regarding the options available to correct their vulnerabilities.
- Research should be done to address particular system equipment needs. One of the first issues addressed should be the value of modular, universal, extra-high-voltage (EHV) transformers to support rapid recovery of the grid.
- Research should be done on the equipment and technology required for, and the steps involved in, the transition to an intelligent, adaptive power grid.

Much greater detail and substance can be found in Chapter 6 of the report. The unfortunate blackout this past month has drawn attention to the critical need to protect our electric-power infrastructure.

The National Academies Update

International Nuclear Fusion Project

A new National Research Council report, *Burning Plasma: Bringing a Star to Earth*, recommends that the U.S. Department of Energy (DOE) participate in the International Thermonuclear Experimental Reactor (ITER), a project to build a fusion facility for a burning-plasma experiment. The committee also recommends that DOE strengthen its domestic research program on nuclear fusion.

The ITER project was initiated in 1988 by the United States, Japan, the European Union, and Russia (then the Soviet Union). The United States withdrew from the project in 1998, but in the past year the Bush administration has announced, and Congress has affirmed, a willingness to rejoin the project. The current participants—Japan, the European Union, Russia, and Canada—are in the midst of negotiations to choose a site for the ITER facility.

If the United States does not rejoin ITER, the committee recommends that DOE find a way to conduct an experiment with international partners on another basis, and that DOE officials map out a multiyear strategic plan that includes a balanced portfolio of theoretical and experimental research that could be conducted in parallel with ITER. If the United States does participate in ITER, DOE would have to increase its budget for fusion research, which has remained flat in recent years.

The committee was chaired by NAE member **John F. Ahearne**, adjunct scholar, Resources for the Future; adjunct professor in civil and environmental engineering, Duke University; and director, Ethics Program, Sigma Xi. NAE member **Ronald R. Parker**, Massachusetts Institute of Technology, also served on the committee. The prepublication version of the report is available for reading online at *http://books.nap.edu/catalog/10816.html*. For more information, contact the National Academies Press, tel. (202) 334-3313 or (800) 624-6242.

Overhaul of the Air Transportation System

The demand for air travel is expected to double in the next 10 to 35 years. According to *Securing the Future of Air Transportation: A System in Peril*, a new report from the National Research Council and Transportation Research Board, the federal government must make air transportation a national priority and provide strong, focused leadership if it hopes to meet the demand. The government recently established a joint office that involves the Federal Aviation Administration, NASA, U.S. Department of Commerce, U.S. Department of Homeland Security, U.S. Department of Defense, and several other federal agencies to improve cooperation on modernizing the air transportation system.

Aircraft and air-traffic management systems are not being expanded quickly enough to meet the growing demand. As the number of aircraft in the skies increases, more fuel is burned producing more emissions and increasing unwelcome noise. To add to the problem, passengers are becoming increasingly dissatisfied with the cost of air travel and uncomfortable conditions aboard airplanes. In addition, security is a major concern to both travelers and the aviation industry. The committee recommends that these problems be addressed in a coordinated way to meet the conflicting priorities of various stakeholders, such as manufacturers, airlines, pilots, passengers, and government agencies.

The committee concludes that substantial improvements to the air transportation system could be achieved through advances in aircraft design, materials, and structures; for example, modifying the engine and propulsion system could substantially lower noise and emission levels; advanced electronics on board airplanes are expected to improve safety and increase automation in navigation; and the burgeoning field of nanotechnology should lead to the development of stronger materials, more sophisticated control systems, and higher fuel efficiency.

The committee also recommends that computer-based simulations of the entire U.S. air transportation system, incorporating human behavior, aircraft technologies, and economic constraints, be used to develop new operational technologies and concepts. Modeling this complex system will require interdisciplinary research, rather than research segregated by scientific field.

NAE members on the committee were **Eugene E. Covert**, Massachusetts Institute of Technology; **Nancy G. Leveson**, Massachusetts Institute of Technology; and **Herbert H. Richardson**, Texas A&M University System. The prepublication version of the report is available for reading online at *http://books.nap.edu/catalog/10815.html*. For more information, contact the National Acadamies Press, tel. (202) 334-3313 or (800) 624-6242.

New NAE Publications

The following reports have been published recently by the National Academy of Engineering. 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 (800) 624-6242. *(Note: Prices quoted by NAP 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.)*

A Century of Innovation: Twenty Engineering Achievements That Transformed Our Lives. To celebrate a century of innovation, the National Academy of Engineering and a consortium of professional engineering societies present engineering triumphs of the last century. The achievements highlighted in this coffee-table volume encompass many dramatic, highly visible engineering feats, from the first flight at Kitty Hawk to the birth of the Internet. However, the lineup is composed mostly of less spectacular advances that have had truly profound and widespread effects on society. Indeed, most of the achievements profiled in this book are so much a part of our lives that we have come to take them for granted. The stories behind these great achievements renews our appreciation of them.

Topping the list of achievements is electrification, without which more than half of the "Top 20" would not have been possible. Abundant, accessible electric power spurred America's economic development and distributed the benefits everywhere, from cities to farms and from coast to coast. Electrification is a shining example of how engineering has changed the world. We take the likes of air conditioning and refrigeration for granted, even though they have significantly improved our sense of comfort, contributed to our physical health, and extended the shelf life of food. Radio and television provide much more than entertainment—they have profoundly changed the way we view the world and our place in it. The telephone has made the whole planet smaller, a connected place for all of us. Underlying and enabling many of these technologies, old and new, are computers—ranging from room-sized supercomputers to palm-sized, personal devices.

Each chapter is devoted to the history of a specific engineering achievement and features personal reflections by a notable engineer involved in its development. Feature writers include: **Bill Gates**, who brought the personal computer into our homes; **Charles Townes**, inventor of the laser; **Robert Kahn**, one of the originators of the Internet; **Bill Anders**, the Gemini 8 astronaut who took the famous "Earthrise" photograph while in lunar orbit; and **Wilson Greatbatch**, inventor of the pacemaker. Their commentaries capture the excitement, vision, and perseverance that made each achievement a reality. Time lines trace the evolution of each achievement, and dramatic illustrations show how things actually work. Replete with photographs and drawings, this volume brings to life the drama of invention and discovery. Hardback, $45.00.

The Carbon Dioxide Dilemma: Promising Technologies and Policies. In April 2002, a group of experts and researchers met to discuss the current state of carbon sequestration. As we have all been made aware recently, the energy future for the United States could take a number of directions, depending on international politics, technology developments, the health of the economy, and changes in life style. Growing concerns about climate change, partly as a result of greenhouse gas emissions (anthropogenic carbon dioxide), has prompted the research community to seek ways of sequestering carbon dioxide safely for the long term.

The purpose of the meeting was not to find a consensus, but to present a range of options for consideration by the policy community. Options from ocean disposal, terrestrial disposal in old mines, and changing to a noncarbon-based economy to biomass-based approaches have been ongoing for years and are still being debated in terms of their cost, effectiveness, and social impact. Market-based approaches coupled with carbon trading are also under consideration. Another option, the one with perhaps the most real-world experience but that would not be practical in many areas, is using carbon dioxide to enhance oil recovery.

As no single approach seems to hold sway, this volume is meant to be a layman's guide to the discussion. Clearly, much more research will be necessary, especially on how government and partners in the private sector can begin charting a course of action for carbon dioxide sequestration. Paper, $32.00. (Published jointly with the National Research Council.)

Envisioning a 21st Century Science and Engineering Workforce for the United States: Tasks for University, Industry, and Government. U.S. national security and economic status depend primarily on technological dominance. U.S. competitiveness and continued progress depend on a technically trained workforce. There is growing evidence that U.S. dominance in this regard is eroding. Because the federal government now relies heavily on the private sector for much of its research and development, the needs of the federal and private-sector science and engineering workforces are necessarily intertwined, raising the question of responsibility for workforce planning. This paper, written by NAE member Shirley Ann Jackson, president of Rensselaer Polytechnic Institute, reviews options for managing and mitigating risks to the nation's technological advantage. The time has come, she warns, for swift, coordinated action by government, university, and industry to ensure the continued availability of a superior science and engineering workforce. Paper, $12.00.

The Impact of Academic Research on Industrial Performance. A committee of the National Academy of Engineering (NAE) recently completed this study on the benefits of academic research to industry. Drawing on the findings of sector-specific workshops, e-mail surveys, research literature, expert testimony, and committee and panel member expertise, the study assesses the qualitative impact of academic research on five industries—network systems and communications; medical devices and equipment; aerospace; transportation, distribution, and logistics services; and financial services. The report documents the range and significance of academic research contributions to the five industries—comparing the importance of different types of contributions (e.g., research-trained graduates, fundamental concepts and key ideas based on basic and applied research, tools, prototypes, products, and services), the multi- and interdisciplinary nature of these contributions (spanning many fields of engineering, the natural sciences, and the social and behavioral sciences), and the multiple vectors by which academic research is linked to each industry.

The report calls for action to address six cross-cutting challenges to university-industry interactions: the growing disciplinary and time-horizon-related imbalances in federal R&D funding; barriers to university-industry interaction in services industries; the critical role of academic research in the advancement of information technology; the role of academic research in the regulation of industry; the impact of technology transfer activities on core university research and educational missions; and the search for new pathways and mechanisms to enhance the contributions of academic research to industry. The report also includes findings and recommendations specific to each industry.

NAE members on the committee were **Lillian C. Borrone**, Port Authority of New York and New Jersey (retired); **George Heilmeier**, Telecordia Technologies, Inc.; **Jack L. Kerrebrock**, Massachusetts Institute of Technology (retired); **Kent Kresa**, Northrop Grumman, Corporation; **H. Donald Ratliff**, Georgia Institute of Technology; **Robert F. Sproull**, Sun Microsystems Laboratories; and **Morris Tanenbaum**, AT&T Corporation (retired). Paper, $45.00.

Information Technology (IT)-Based Educational Materials: Workshop Report with Recommendations. In the last half-century, we have witnessed the birth and development of a new era—the information age. Information technology (IT), the primary vehicle of the information age, has transformed the workplace and is critical to the development of new knowledge and the creation of wealth. IT has also dramatically influenced our capacity to educate. So far, however, the application of IT in education has been disorganized and uneven. Pockets of innovation in localized environments are thriving, but the promise of open access, greatly enhanced teaching and learning, and large-scale use has yet to be realized. This report identifies critical factors in the development and use of IT-based educational materials and recommends high-priority steps for transitioning from the current fragmented environment to an IT-transformed future in engineering education. The six recommendations include the establishment of a national laboratory for evidenced-based investigations and other activities to ensure interoperability and effective teaching and learning. The report also stresses the need for open architectures and for engaging researchers from many disciplines, including the social sciences, to address the transformation of faculty cultures and the need to engage the users and developers of IT products in activities driven by learning outcomes. Paper, $18.00.

Owner-Authorized Handguns: A Workshop Summary. The feasibility and potential impact of so-called smart handguns has generated considerable public interest and debate. This report summarizes a June 2002 workshop at the National Academy of Engineering that examined three related issues: the state of technology for owner-authorized handguns; the role of product liability in the development and marketing of such firearms; and the potential impact of smart guns on health and crime. Smart-gun technology has the potential to prevent unintended or undesirable uses of handguns, such as accidental shootings; the shooting of police officers by assailants using the officers' own weapons; suicides; homicides with stolen handguns; and other gun-related crimes. However, information presented at the workshop suggests that considerably more research is needed to bring a reliable and commercially viable product to the marketplace. The report also notes that the impact of smart-guns will be influenced by legal issues, human behavior, economic conditions, and other factors. Paper, $18.00.

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