Spring 2008
HEALTH CARE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The
BRIDGE

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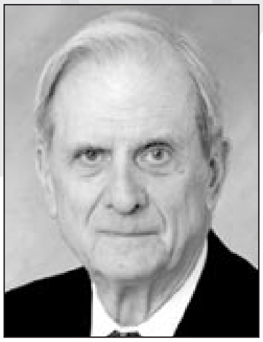
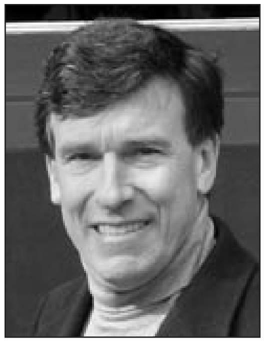
Editor's Note



W. Dale Compton



Proctor P. Reid

Engineering and the Health Care Delivery System

The suggestion that engineers join in the struggle to improve the health care system almost always elicits surprise, even though engineers have been actively involved in bioengineering and biomaterials engineering for years. In addition, publications on using operations-research techniques to model hospital operating rooms and schedule personnel and materials in various medical facilities date back more than three decades. Today, however, the participation of engineers is more important than ever before.

Health care delivery today is in turmoil. Despite rapid advances in medical procedures and the understanding of diseases and their treatment, the efficiency, safety, and cost-effectiveness of the delivery of health care have not kept pace. Improvements in the delivery of services in other industries have simply not been transferred to health care.

The question is why not. Here are a few of the most obvious reasons. For one thing, the third-party reimbursement system is not conducive to a competitive environment in which customers (i.e., patients) can seek out the most cost-effective treatment or provider. Second, health care delivery is still a "cottage industry." Third, very little has been invested in information technology. Fourth, the quality of care delivery and benefits are difficult to quantify. Finally, the annual cost of health care is increasing by double digits. The five papers in this issue, which are based on presentations at the Symposium on Health Care as an Adaptive Enterprise: An Engineering Challenge, at the 2007 NAE Annual Meeting, address several of these issues.

Changing the Health Care Environment

Industries, particularly large, entrenched industries, often find it difficult to change, even when they recognize that change is in their best interest. Therefore, a key driver of change is crisis, a situation that forces an industry either to change or, to put it bluntly, go under. Unlike other industries, however, health care cannot simply go under, so it *must* change. Like other industries, health care must become more efficient, more responsive to patients' (i.e., customers) needs, more flexible, safer, and of higher quality. Industries around the world aspire to achieve the same characteristics.

Health Care as a Cottage Industry

In a so-called cottage industry, many components of the overall system operate as independent agencies. To an engineer, this indicates that the overall system was not designed as a system and does not operate as a system, that no single entity is in charge of the overall system, and that no cost objectives, standards of efficiency, or safety goals have been established for the overall system. In addition, there is little, if any, feedback in terms of measuring overall operating goals.

As systems engineers know, you cannot optimize a large, complex system by optimizing its individual parts, because this does not take into account interactions among the parts. Nevertheless, in the short run, improvements in some components can be made and should be encouraged. For example, systems engineering principles were critical to improving clinical operations—and quality of care—at the Mayo Clinic. Another example is described by Paul Levy, the director of Beth Israel Deaconess Medical Center, who details how process-improvement techniques that have been used in other industries can be applied to some aspects of health care in an academic medical center.

Moving the overall system toward optimization will require many more improvements like these, as well as sharing the lessons learned among providers, empowering patients and encouraging them to take more responsibility for their health care decisions, ensuring that markets for health care services are more transparent and open to new business models, and finding better methods of reimbursement.

Jerry Grossman, director of the Harvard/Kennedy School Health Care Delivery Program, argues in his article that disruptive events, including revolutionary advances in technology and business models, can be effective forces of change in the way an industry performs. Disruptive innovations in the health care sector, he says, are already driving changes in some parts of the system.

Optimizing a Complex, Adaptive System

Bill Rouse, executive director of the Tennenbaum Institute at Georgia Institute of Technology, focuses in his paper on the complex, diffuse nature of health care delivery, which can only be described by a broader definition of "system." Because of the nature of the system in which health care operates, he says, some of the corrective directions engineers usually pursue will not work. A *complex adaptive system* such as health care, he argues, is not amenable to the controls and feedback forces we generally ascribe to a system.

Even though system tools that have been used successfully in many other industries will not suffice to solve all of the operational problems of the health care system, they are the best tools we have to improve the quality and efficiency of care until more powerful tools for optimizing this adaptive system can be developed. For one thing, even if the performance of some parts of the system is optimized, changing the very complex overall system will require strong, effective incentives and other tools for system governance rather than system control. Chris Meyer, chief executive officer of Monitor Networks Inc., describes an approach to change based on natural systems. He argues that the very complex adaptive health care system requires "adaptive management."

Investing in Information Technologies

Although many attempts have been made to increase the use of information technologies (IT) in health care, overall investment in IT is the lowest of any major industry. Thus many places still use paper records, and only a small number of clinicians use physician order entry systems or electronic medical records that are controlled by the patient. In addition, computerized systems are often incompatible, either in hardware or software, making communication difficult, sometimes even impossible.

Steps being taken to overcome these problems include efforts to create a national health information infrastructure and a number of actions, being explored by Congress, to develop a nationwide system of electronic records. Several private-sector consortia, including health care provider organizations, insurers, and technology vendors, are implementing large-scale clinical data exchanges/repositories and personalized health record systems. But there are many barriers to achieving these goals, including the exorbitant cost of these systems, especially for the 80 percent of physicians who work in groups of 10 or fewer.

IT, however, involves much more than computers. For example, wireless communications combined with microelectronic sensors that can remotely sense physiologic parameters may make it possible to monitor and treat patients at home, thus making it possible for chronically ill patients to visit caregivers less often. These advanced IT devices and systems may also improve the quality of treatment of patients in hospitals. It has been said that these systems may someday make every hospital room an intensive care unit.

Educating a New Class of Professionals

Unfortunately, most health care professionals do not even know what questions to ask systems engineers nor what to do with the answers, and vice versa. Most engineers only have contact with the health care system as patients, and few of them understand the constraints under which health care providers operate. In short, these two groups of professionals often talk to each other but seldom understand each other.

Jerry Grossman and the authors of this introduction experienced this firsthand as members of the NAE/Institute of Medicine study committee that published the 2005 report, *Building a Better Delivery System*. The committee comprised an equal number of engineers and health care professionals. Even though no significant disagreements arose and all of the committee members were outstanding professionals, we had great difficulty finding a common language, and thus, great difficulty writing a report that could, and would, be read by both groups.

Based on our own experience, we recognized that we must educate a new class of professionals, which will require a new class of multidisciplinary research and educational centers that bring together engineers and health care professionals in an environment devoted to improving health care. One goal of both medical and engineering education must be that the members of these professions learn from each other, undertake joint research on common problems to develop new or modified tools, and demonstrate these tools to other professionals.

The committee members agreed that both professions need to understand the limitations and opportunities of the other. Although it will be difficult to add interdisciplinary material to present curricula, we dare not continue to ignore the crisis in our health care system.

Only in the area of biomedical engineering have engineers, scientists, and medical practitioners developed a truly common language. Some of the breathtaking advances in the integration of engineering and biological systems to create new therapies for the treatment of diseases are described in the paper by Mark Saltzman, professor of chemical and biomedical engineering at Yale University.

Conclusion

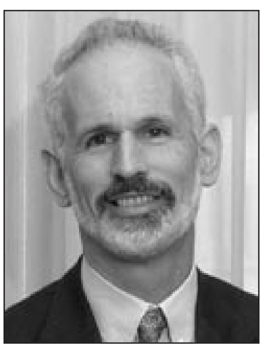
There are abundant reasons for the problems in health care delivery. There are also abundant opportunities for working toward solving these problems. Engineers may not be able to solve all of them, but the benefits of working toward solutions can be tremendous, and the challenges they present are enormously intellectually stimulating. Someday, the engineering profession may look back with pride on its contributions to solving this significant social problem.

W. Dale Compton

Proctor P. Reid

Systemic changes require cooperation between those who deliver care and administrators committed to the public disclosure of outcomes.

Adapting Process-Improvement Techniques in an Academic Medical Center



Paul F. Levy

Paul F. Levy is president and CEO, Beth Israel Deaconess Medical Center in Boston, Massachusetts.

This article is based on a presentation at the NAE Annual Meeting Technical Symposium on October 1, 2007.

Academic medical centers, the crown jewels of the medical system, have a tripartite mission. First, of course, as hospitals, they are intimately involved in clinical care. At Beth Israel Deaconess Medical Center (BIDMC), for example, we take care of about 40,000 inpatients, about 50,000 emergency room patients, and about half a million ambulatory patients a year. BIDMC provides the full range of medical services, from primary care through advanced imaging and diagnostics to liver transplants, bone marrow transplants, and other tertiary and quaternary services.

Research and education, the other two parts of the academic medical center's mission, supplement and reinforce advances in and delivery of clinical care. At BIDMC, research accounts for more than $200 million of our $1.2 billion dollar budget, and clinical care and research are integrated. Say, for example, a specialist in gastroenterology who is treating a patient with irritable bowel syndrome notices something about the patient's condition that prompts her to hypothesize something about the cause of the disease. Based on that observation, she might construct a series of laboratory experiments, perhaps using mice as models, and, over time, she might learn things from these and other experiments that can be applied in the clinical setting. Over the years, this shuttling back and forth between "the laboratory bench and the bedside" informs both clinical care and research.

The third part of the mission is education, teaching the next generation of doctors, from undergraduate medical students (in our case from Harvard Medical School) to residents and fellows from around the world engaged in graduate medical education and advanced training. Nurses, dietitians, laboratory technicians, and many other health care workers are also part of the educational program.

Academic doctors teach not only because they love to teach, but also because teaching keeps them up to date on the latest advances in medicine. Let's say a bright young medical student is following the treatment of a patient by a doctor who says, "This is the way we always care for someone with this problem." If the student asks why, the answer cannot be because it's been done that way for 20 years. Students expect, and demand, more complete, in-depth answers. This kind of give and take with students requires that doctors remain sharp and current in their fields.

Patients, whether in Boston, Seattle, Chicago, or any other city or region with a major academic medical center, are the beneficiaries of this marvelous agglomeration of clinical care, research, and teaching. They are seen by very bright people who are totally committed to taking care of them, using the most up-to-date diagnostics and therapies. Even patients who live in communities that do not have academic medical centers benefit, because advances in research and clinical care diffuse throughout the world, and there are doctors everywhere who have been trained in one of these centers.

Cottage-Industry Care

Notwithstanding the marvelous features of academic medicine, the actual delivery of care and practice of medicine in academic hospitals is still a cottage industry that basically involves a one-to-one relationship between the patient and the provider of the moment. A good deal of what goes on in academic medicine in the clinic is private.

The question is not how care providers make decisions. The issue is how the environment in which they work can be studied and reconfigured to eliminate systemic problems that lead to harmful outcomes and how doctors can be brought into that process. The truth is that even these very well intentioned, bright, experienced, often superb subspecialists, who justifiably inspire confidence, work in a cottage industry that has not had the benefit of the system-improvement practices that are common in other industries. They haven't been educated to take into account how—or how much—the hospital or facility in which they work affects their performance and patient care.

As the Institute of Medicine has documented, a very large number of people are killed or harmed in hospitals in this country (IOM, 2000). In fact, health care does not meet the quality standards we expect from any other industry. Indeed, it does not meet the quality standards (e.g., Six Sigma) of the industries from which healthcare goods and services are purchased. This is true even though everyone involved in the delivery of care is well intentioned and thoughtful. Using theories and practices of process improvement to ensure that quality standards are met is simply not part of their training. And frankly, the administrators of academic hospitals have not been thinking in a systems way either.

Rising Costs

According to insurance companies in Massachusetts, their annual increase in medical costs is 10 to 12 percent, as it has been for several years and is expected to be for years to come (e.g., Krasner, 2006). A key driver for the increase is demographics. Baby boomers, now in their 50s and 60s, the age of hospitalization, are being seen in hospitals for the first time (except for women who had their babies in hospitals). At the same time, thanks to medical advances, like stents, which were invented and proven in academic medical centers, baby boomers' parents, who in previous generations would have already died, are still alive. A person who might have died of a heart attack 15 or 20 years ago may now live long enough to get cancer and might remain under long-term treatment for this disease, now often a chronic condition, once again because of advances developed at academic medical centers. Thus insurance companies are coping with a growing number of people entering the tertiary care system with more expensive and difficult diagnoses and treatments.

The cost increase of 10 to 12 percent a year compares to a 3 percent annual growth in GNP. This means that, as Congress, state legislators, and taxpayers (who pay for Medicare and Medicaid), as well as employers and employees (who pay for insurance in the private sector), experience a 3 percent increase in available income, the cost of health care goes up three or four times faster.

I believe that academic medical centers, which have been at the forefront of so many medical advances, should also take the lead in addressing the cost issue. As anyone who has experience with process improvement in other industries knows, quality improvement and cost improvement go hand in hand. If you improve production processes or service processes, the delivery of those processes or services becomes generally more efficient. So how do we transfer process improvements to health care?

I am not talking about global changes in the way we organize and provide health care all along the continuum. I am talking just about changes in a given hospital, particularly in an academic medical center.

Accountability and Change

Everyone should understand that hospitals are dangerous places where mortality and morbidity occur, and academic medical centers have a responsibility to hold themselves accountable for quality and safety. I believe the best way of doing that is by publishing our data. My hypothesis is that holding ourselves accountable to the public will make our well intentioned doctors and nurses work even harder and "smarter" to improve processes and make hospital stays safer and less expensive.

I noticed that some people on our staff were doing creative and interesting things related to improving quality and safety, and I decided to test the idea that publishing our clinical data would be good for our organization. I thought the transparency of clinical results would produce a kind of creative tension that, in itself, would help drive process improvement. So, a few months ago I started a blog (*www.runningahospital.blogspot.com*) about what is going on in our hospital.

Here is an example about ventilator-associated pneumonia (VAP), a problem relevant to anyone who has been or will be in an intensive care unit (ICU) or who will have a loved one in an ICU. A patient on a ventilator who contracts pneumonia has a 30 percent chance of dying, a pretty high rate of mortality. The good thing is that we know how to prevent many of these cases by taking five well documented steps, including elevating the bed to 30 degrees, plus washing out the patient's mouth every four hours to decrease the chances that bacteria growing there will enter the lungs and cause pneumonia.

Keep in mind that an ICU, even though it is staffed by one nurse for every patient, is a very demanding and busy place and that the staff has a lot to do. To successfully prevent VAP, the five steps plus oral hygiene must, therefore, be part of the culture, part of the routine, required workflow.

This blog posting shows the results of changes in our ICU protocol (Figures 1 and 2). No partial credit was

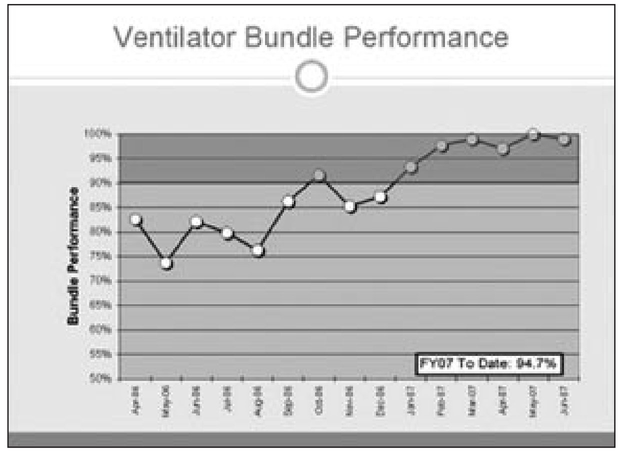


FIGURE 1 Graph showing improvement in performance of five-step VAP bundle.

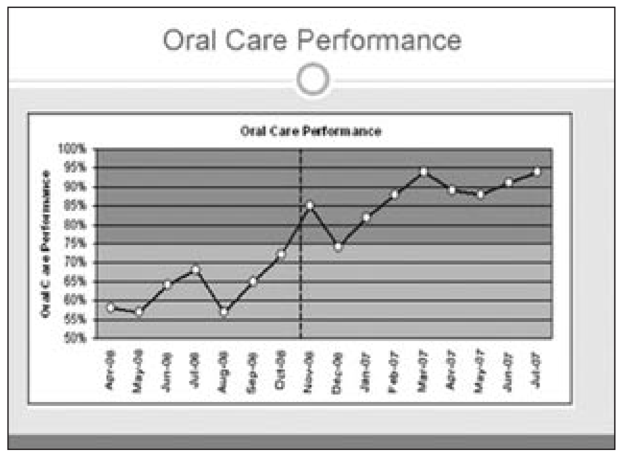


FIGURE 2 Graph showing improvement in ICU oral care.

given—unless all five steps in the "bundle" and the oral hygiene were done, the score was zero. The graph shows that in the months since the ICUs began working on reducing cases of VAP, performance of the five-step bundle, and the oral care, have risen to 100 percent.

Note that the change was not a response to an order from CMS (the Medicare agency), which keeps track of infections and other events and posts results a few years after the fact. Neither the insurance companies nor patients nor even the hospital administrator insisted that these things be done. In fact, it was academic physicians, who read journals and other publications from around the world, who instigated the changes. After several of them had read the recent literature about preventing VAP, they decided they should change the way ICUs cared for patients.

But—and here's the key—they then had to organize the 200 people who work in ICUs. Respiratory therapists, nurses, and doctors all had to be trained to change the "industrial" process, with no increase in staff and with basically no increase in resources. The doctors went to work and made it happen.

Many of the changes were not very complex. It became apparent, for example, that people do not have a good sense of angles. A nurse or doctor might think the head of the bed has been raised to a 30-degree angle when it has only been raised to 20 degrees. To address this problem, protractors were put on the beds—the big ones used by construction companies that are easy to see.

I watched the results of the changes and started posting them before they reached the 90 percent rate. At that point, the head of this group sent an e-mail to his colleagues that read something like this: "As you may have heard, Mr. Levy has a blog on which he is now posting our success rates with ventilator-associated pneumonia prevention. Perhaps we should take this as an additional impetus to do even better, because people out there are watching." This message seemed to support my hypothesis that public disclosure of clinical results could motivate efforts to improve processes.

Estimates of the results of our changes in ICU care are that 300 cases of VAP were prevented last year, and 90 lives were saved. At a cost of $40,000 per case, we believe we avoided about $12 million in health care expenses. This is a clear example of how quality improvement and cost savings can go hand in hand.

Motivations for Change

People in an academic setting are motivated by a combination of factors—competition, data, intellectual curiosity, and deep concern for the welfare of patients. They are decidedly not motivated by demands from on high, particularly from an administrator, who is not necessarily an MD or even an engineer. However, when the administrator or CEO of a hospital posts good results, they feel proud of their efforts and motivated to move on to the next topic and the next opportunity for clinical improvement. To the extent that results have not yet reached the hoped-for target, publication acts as an incentive to do better.

Systemic change occurs as a result of an unusual type of cooperation between the technical experts who deliver care and an administration dedicated to transparency of outcomes. Creative tension creates a climate in which the only way to relieve it is to actually reach the goal, no matter how audacious the target. The only alternative would be to lower the target, an unacceptable result for personal, professional, and institutional reasons.

I would be remiss, however, if I did not point out a symptom of the problems in academic medical centers. When I began posting clinical results on my blog, I received many less than positive reactions from other academic medical centers in Boston. Many were disdainful and convinced that publication of results was "not good for academic medicine."

I hope to break down that attitude and persuade people of the value of public disclosure. From the traffic on my blog (more than 10,000 viewings per week, including visits from medical centers all around the world), it now appears that people are watching. I believe that social and political forces will combine to make public disclosure the norm in the future.

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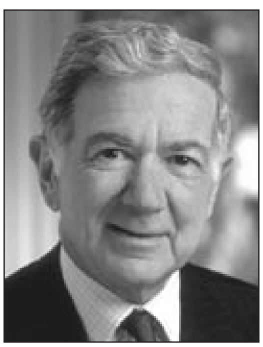
Innovative, "disruptive" changes in the way health care is organized, paid for, and delivered may lead to a transformation of the overall health care system.

Disruptive Innovation in Health Care: Challenges for Engineering

Jerome H. Grossman



Jerome H. Grossman is director of the Harvard/Kennedy School Health Care Delivery Program, John F. Kennedy School of Government, and a member of the Institute of Medicine.

This article is based on his presentation on October 1, 2007, at the NAE Annual Meeting Technical Symposium.

Seven years after the publication of two seminal reports by the Institute of Medicine, *To Err Is Human* (IOM, 2000) and *Crossing the Quality Chasm* (IOM, 2001), which documented uneven quality, dangers, and inconsistencies in health care delivery, a majority of the nation's health care providers are still struggling with those same challenges. Simultaneously, a backlash against the managed-care systems of the 1980s and 1990s has led to very rapid increases in health care expenditures and consequent rapid increases in the number of uninsured and underinsured people, both of which continue unabated. Today, there is a growing consensus that the twentieth-century model of health care is no longer sustainable.

After nearly a decade of subcritical attempts in the public and private sectors to improve the quality of health care and bring costs under control, a buyers' revolt, led by businesses and insurers, combined with advances in medical and information and communication technologies (ICT), has begun to open the closed market for health care services to new business models, as well as to new models of care delivery.

Innovative, "disruptive" models of care delivery are opening the way to a new division of labor among health care providers and changes in the structure and location of care delivery. Eventually, they could catalyze a wholesale transformation of the overall health care system by accelerating the development and application of ICT tools and techniques that would make possible the design, analysis, and governance of new processes and systems throughout the health care system. Engineering will play a major part in supporting this disruptive dynamic and realizing its promise.

Understanding the Logjam

More than 98,000 Americans die and more than one million patients are injured each year as a result of broken health care processes and system failures (IOM, 2000; Starfield, 2000). In addition, the gulf between the rapidly advancing medical knowledge base and the application of that knowledge to patient care continues to widen. In fact, barely 50 percent of patients in the United States receive known "best practice" treatment for their illnesses (Mangione-Smith et al., 2007; McGlynn et al., 2003). According to one survey, 75 percent of patients consider the health care system to be fragmented and fractured, a "nightmare" to navigate, and plagued by duplications of effort, poor communication, conflicting advice, and tenuous links to the evolving medical evidence base (Picker Institute, 2000).

Poor quality is not only dangerous but also costly. David Lawrence, retired chairman and chief executive officer of the Kaiser Foundation Health Plan (2005), estimates that 30 to 40 cents of every dollar spent on health care, more than a half-trillion dollars per year, is spent on costs associated with "overuse, underuse, misuse, duplication, system failures, unnecessary repetition, poor communication, and inefficiency."

Since the late 1990s, annual health care costs have risen by double digits—roughly three times the rate of inflation—claiming an increasingly large share of every American's income, inflicting economic hardships on many, and limiting access to care. By 2006, the nation's uninsured population had risen to nearly 47 million, about 16 percent of people under the age of 65 (DeNavas-Walt et al., 2007), and it has continued to increase since then.

The immediate causes of this "perfect storm" of quality and cost crises in health care are well understood. U.S. health care is a highly complex enterprise with a "cottage-industry" structure (i.e., many small-scale, *interdependent* service providers that act *independently* creating "silos" of function and expertise). This siloed system is sorely mismatched to the nation's overriding health challenge, namely, providing coordinated, integrated, continuous care to more than 125 million Americans who suffer from chronic disease. Seventy-five percent of U.S. health care dollars is spent on patients with one or more chronic conditions (Partnership for Solutions, 2002).

This fragmented care system has been sustained by an outdated fee-for-service reimbursement model and regulatory framework that has rewarded health care providers as well as drug, device, and equipment manufacturers for providing high-priced services based on new medical technologies and procedures. While this framework has supported rapid advances in medical science and the development of increasingly precise diagnostic tools and therapeutic interventions, it has been indifferent to, if not discouraging to, innovation directed at harnessing advances in medical knowledge and precision diagnostics to improve the quality and efficiency of health care.

More than 98,000 Americans die every year as a result of broken health care processes.

Largely because of its cottage-industry structure and dysfunctional reimbursement and regulatory framework, the health care sector has woefully underinvested in ICT—the nervous system of all information-intensive industries—to support core clinical and administrative/business operations. Health care is also underinvested in mathematical/conceptual tools and techniques for designing, analyzing, and controlling a myriad of complex processes and systems. Without these tools and technologies, most health care providers lack the capacity to translate the rapidly expanding stream of diagnostic and therapeutic advances in medical science into high quality, affordable health care for all.

To be sure, there are isolated pockets of progress. Large integrated salaried group practices with managerial hierarchies, such as Mayo Clinic, Kaiser Permanente, Intermountain Healthcare, Veterans Administration (VA), and the Military Health System, are committed to the cost-effective use of precision diagnostics and therapeutics and the consistent practice of evidence-based medicine. These groups have also invested in ICT to support quality care and have even begun to use systems engineering tools and techniques to improve clinical operations.

However, the vast majority of groups and institutions in the health care delivery system have made little progress. The hodgepodge of individual providers, small group practices, clinics, academic medical centers, community hospitals, and others continues to lag far behind in the efficient use of precision diagnostics and therapies, the practice of evidence-based medicine, and the use of ICT systems and tools. For example, it is estimated that only 25 percent of physicians currently use some form of electronic health record and that less than 10 percent of doctors use a "fully operational" system.[1] In the meantime, costs continue to rise, and the quality battle is, at best, at a standstill.

The struggle to improve the quality of care is, at best, at a standstill.

Breaking the Logjam

Private-sector purchasers, especially large self-insured organizations, convinced that the current system is broken and unlikely to be transformed by government action, have begun to purchase health care services for their employees directly (i.e., not through insurers) from existing or new high-value service providers, especially for wellness and preventive care, primary care, and chronic disease management. Many large employers offer fully integrated health care services for their employees from existing large multispecialty salaried group practice providers, such as Kaiser Permanente, Intermountain Healthcare, and others. At the same time, many start-up companies, backed by venture capital, are offering high-quality, low-cost wellness care, primary care, and chronic-care services that can be delivered via the World Wide Web or low-cost intermediaries.

Pressure on regulators to increase transparency in health-care markets and lower entry barriers to new types of service providers is beginning to have an impact, especially at the state level. The primary force behind these changes is "disruptive innovation," a combination of technological advances and new business models that has the potential to transform the structure, organization, and performance of the health-care system as a whole.

Disruptive Innovation

Clay Christensen, professor of business administration at Harvard, introduced the theory of disruptive innovation in his book, *The Innovator's Dilemma*, in 1997. He postulated that consumers will seek out those who can do the jobs they want done and evaluate them by three simple measures: level of transparency, convenience of delivery, and cost that represents value. In the industries Christensen studied, consumers brought about wholesale transformations of the prevailing business models by purchasing new products and services that were much more affordable and accessible than those that had been traditionally offered.

Christensen argues that two conditions are necessary for disruptive innovation to increase to scale: (1) technological enablers (i.e., technologies that provide routine solutions to problems that previously required trial and experimentation); and (2) a disruptive business model that can profitably deliver these routine solutions to customers in affordable and convenient ways.

The personal computer is an instructive example of a disruptive innovation. Prior to the 1970s, only a small number of engineers worldwide had the expertise to design mainframes or minicomputers, which were, therefore, expensive to make and market; in fact, they required gross profit margins of 45 to 60 percent just to cover overhead costs. In addition, users also needed expertise to operate them. The personal computer disrupted this model by making computing affordable and accessible to hundreds of millions of people. The technological enabler of this disruption was the microprocessor, which radically simplified computer design and assembly (Christensen, 1997).

Technological Enablers for Disruptive Innovation in Health Care[2]

Precision Diagnostics and Therapies

Technological enablers of disruptive innovation in health care are: (1) advances in medical knowledge and

[1] The 2006 report of the Robert Wood Johnson Foundation, *Health Information Technology in the United States: The Information Base for Progress*, provides a definition of a fully operational electronic health record: "An electronic approach to collecting, storing and manipulating patient data must be able to *accomplish* at least four tasks: collection of patient health information and data, results management, order entry management, and decision support."

[2] A book on disruptive innovation in health care, by C. Christensen, J. Grossman, and J. Hwang, will be published by McGraw-Hill in late 2008.

more precise medical diagnostics and therapies (including drugs, devices, equipment, and procedures); and (2) advances in ICT, including Web 2.0 applications, broadband communications, and wireless integrated microsystems (WIMS).

Over the past half century, advances in medical knowledge and diagnostic technologies have greatly increased the accuracy of diagnoses and treatments of disease. If precision diagnosis is not available, treatment is determined by "intuitive medicine" (i.e., therapeutic problems solved by highly trained, expensive professionals through intuitive experimentation and pattern recognition). Intuitive medicine gives way to evidence-based medicine when a patient's treatment is guided by data showing which therapeutic interventions are, on average, most effective.

If precision diagnosis is available, treatment becomes "precision medicine"—targeted therapies, including drugs, devices, procedures, and so on, that can be developed and routinized to address the causes rather than the symptoms of an illness. Precision medical care can be delivered by less highly trained, less expensive care providers. So called "minute clinics," for example, staffed by nurse practitioners using rules-based care, offer a limited range of services in shopping malls and drugstores (Scott, 2006). In another case, at Intermountain Healthcare, four specialist physicians supervise the care of nearly 20,000 diabetics, mostly by family physicians, helped by nurse practitioners, specially trained technicians, and volunteers.[3]

Diagnostic technologies have already changed the treatment of most infectious diseases from intuitive to precision medicine. In recent years, the emergence of molecular diagnostics and imaging diagnostics has made medical diagnosis and treatment even more precise. Advances in genomics and proteomics promise even greater precision, as well as personalization, of clinical diagnoses and treatments.

Advances in Information/Communications Technologies

The second technological enabler, advances in ICT, not only supports precision medicine by enabling the development of increasingly precise techniques and devices and the capture and integration of clinical data for research purposes. They also facilitate the codification, continuous updating, and diffusion of precision therapies or best-practice care protocols based on advancing medical knowledge..

ICT can make feasible the integration of a patient's health care data with a continuously advancing medical evidence base to provide real-time medical decision support to professional care providers, as well as to patients and their families. ICT also enables the collection, integration, and analysis of data on the performance of the overall system and supports the use of many advanced systems design, analysis, and governance tools and methods to improve system performance.

Since 1960, efforts have been made to encourage the use of electronic records, but implementation has been limited mostly to integrated multispecialty group practices. One of the most promising disruptive information technologies, the personal health record (PHR), has advanced efforts to put electronic medical records in place throughout the health care system. Omid Moghadam, director of PHR programs at Intel, describes a PHR as a record "owned and controlled by the patient that incorporates data the patient enters, but also includes authenticated information. . . . from all of the places the patient is involved with—insurance company, hospital, doctors' offices, labs, and so forth" (Harvard Medical School, 2006).

The personal health record is one of the most promising disruptive information technologies.

Some companies have already adopted PHRs for their employees, and some insurers are using them to try to retain customers. Even Microsoft and Google are competing for PHR business. The hope is that by bringing together an individual's medical information from all relevant sources, that individual will be in a better position to manage and control his or her medical care.[4] Widespread use of PHRs could create an

[3] Personal communication, Brent James, MD, vice president for medical research at Intermountain Healthcare.

[4] A good analogy is Intuit's Quicken software, which brings together financial information from many sources so an individual can manage and control his or her own assets. See *http://quicken.intuit.com.*

informed consumer base that can begin to buy health services directly, rather than through third parties. PHRs are diffusing very rapidly from academic environments to academic-corporate-consortium partnerships, and recently to the commercial world (e.g., Microsoft HealthVault).[5]

WIMS is another emerging disruptive ICT. These combinations of sensors based on microelectromechanical systems, microelectronics, and wireless interfaces may provide remote, real-time monitoring, diagnosis, and therapeutic intervention in health care (NAE, 2005).

As the information infrastructure to support advancing precision diagnosis and therapy improves, more kinds of precision, routinized diagnostics and therapies can be moved to locations that are convenient for patients (e.g., from outpatient facilities to in-office or even in-home care) staffed by less highly trained, less expensive health care providers—again providing better value.

Precision medicine has been grafted onto the existing organizational framework.

Disruptive Business Models for Health Care

At present, the sustaining business model in health care is the 60-year-old Medicare "fee-for-service" model, which is controlled by special interests with political control over the regulatory and reimbursement system. Most private insurers mimic Medicare, and each state imposes further regulations. This is an inflationary, distorted, "third-party" model.

The two prevailing institutional modes of care delivery in the United States, general hospitals and physician practices, developed more than a century ago when the practice of medicine was focused predominantly on the diagnosis and solution of unstructured problems by highly trained clinicians. As some areas of medicine, especially some aspects of primary and chronic care, moved toward more precise, routinized diagnostics and therapies, the value of care became increasingly determined by the precision, consistency, and efficiency of care delivery.

Rather than change the overall system, precision medicine was grafted onto the existing organizational framework. However, because of their high overhead costs, general hospitals and physician practices have not been able to translate precision medical services to higher value (i.e., low-cost, high-quality, accessible care) for patients. Meanwhile, the development of new business models capable of harnessing the potential of precision medicine to yield value have been stymied by the entrenched fee-for-service model and regulatory framework that protect the intuitive-medicine model of care from disruptive competitors.

Nevertheless, new forces in health-care markets have begun to open the way to disruptive business models in both purchasing and the delivery of care. Large corporations and consortia of organizations are reconfiguring their conceptions of employee health care benefits. One emerging model is "direct-value purchasing" by self-insured enterprises (e.g., large employers, multi-employer union trusts [such as voluntary employee benefit associations]) from entrepreneurial, venture-backed health-service delivery companies. In this model, employers contract directly with providers to deliver high-value health care that matches the needs of employees and their families. The most likely companies to be self-insured have 1,000 or more employees, and estimates are that they now represent more than 100 million employees/consumers. Self-insured companies pay insurance companies an administrative fee to process claims but bear the full cost of medical care.

In response to these disruptive models, new care-delivery models are emerging, such as Carena, a venture-backed enterprise that provides primary care.[6] Microsoft has contracted directly with Carena to make home visits by family practitioners to Microsoft employees and arrange for follow-up (e.g., prescriptions, tests, specialists), as needed. Microsoft has found that, even at a very high hourly rate, employee satisfaction and increased productivity more than cover the costs of the service. In addition, costs for Microsoft families are comparably low. Carena's latest contract is with the state of Kentucky, another self-insured entity, in partnership with Humana.

Other examples of "disruptive care" are delivered

[5] For additional information on Microsoft HealthVault record, see *http://www.healthvault.com.*

[6] For additional information on Carena, see the company's website at: *http://www.carenamd.com.*

by Renaissance Health, a private contractor hired by a union to deliver primary care, including simple blood tests and x-rays, and over-the-counter and generic prescription drugs for $30/month for janitors in the Houston area who are uninsured. Boeing has also contracted with Renaissance Health to care for chronically ill patients. These cases are handled by small care-teams located in the general clinics used by Boeing.[7]

If present trends continue, disruptive business models and advances in precision care and diagnostics are likely to spread to encompass a significant segment of the market, especially for providing primary care and chronic care. As high-quality, reliable, safe, health care services delivered effectively by less highly trained staff are documented by careful, authoritative research, the spread of disruptive service enterprises should accelerate, pulled along by the diffusion of disruptive business models by self-insured private, and eventually, public (state-level) organizations determined to ensure high-value health care.

Implications for Engineering

The dynamics of disruptive innovation in health care present general as well as specific challenges for engineers. On a general level, disruptive innovation will require combining the technologies, tools, and techniques of systems engineering with a deep understanding of business processes and organization in the health care and services industries. As health care markets open up to new business models, engineers can pursue fruitful research on tools, techniques, and engineered technologies to support the design, analysis, and governance of new delivery modes and networks.

On a more specific level, engineers can develop, adapt, and help implement the technological enablers of continuing disruptive innovations in health care. These will include WIMS to support the remote delivery of high-value care (e.g., monitoring, diagnosis, and therapy); the development of decision support tools for professional providers, health care purchasers, and equally important, patients and their families; the application of bioengineering and systems engineering to accelerate the spread of personalized, precision medicine; and the application of systems engineering tools and techniques for managing and improving the performance of complex, interdependent processes and subsystems, guiding investment in ICT infrastructure, and managing policy, reimbursement, and regulatory systems to support the transformed health care system.

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Management of complex adaptive systems requires leadership rather than power, incentives and inhibitions rather than command and control.

Health Care as a Complex Adaptive System: Implications for Design and Management

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For several years, the National Academies has been engaged in a systemic study of the quality and cost of health care in the United States (IOM, 2000, 2001; National Academy of Engineering and Institute of Medicine, 2005). Clearly, substantial improvements in the delivery of health care are needed and, many have argued, achievable, via value-based competition (e.g., Porter and Teisberg, 2006). Of course, it should be kept in mind that our health care system did not get the way it is overnight (Stevens et al., 2006).

Many studies by the National Academies and others have concluded that a major problem with the health care system is that it is not really a system. In this article, I elaborate on the differences between traditional systems and complex adaptive systems (like health care) and the implications of those differences for system design and management.

Complex Adaptive Systems

Many people think of systems in terms of exemplars, ranging from vehicles (e.g., airplanes) to process plants (e.g., utilities) to infrastructure (e.g., airports) to enterprises (e.g., Wal-Mart). In addition, they often think of improving a system by decomposing the overall system performance and management into component elements (e.g., propulsion, suspension, electronics) and subsequently recomposing it by integrating the designed solution for each element into an overall system design.

This approach of hierarchical decomposition (Rouse, 2003) has worked well for designing automobiles, highways, laptops, cell phones, and retail systems that enable us to buy products from anywhere in the world at attractive prices. The success of traditional systems depends on being able to decompose and recompose the elements of the system and, most important, on someone or some entity having the authority and resources to design the system.

Hierarchical decomposition does not work for complex adaptive systems.

Not all system design and management problems can be addressed through hierarchical decomposition. For example, decomposition may result in the loss of important information about interactions among the phenomena of interest. Another fundamental problem for very complex systems like health care is that no one is "in charge," no one has the authority or resources to design the system. Complex adaptive systems tend to have these design and management limitations.

Complex adaptive systems can be defined in terms of the following characteristics (Rouse, 2000):

- They are *nonlinear and dynamic* and do not inherently reach fixed-equilibrium points. As a result, system behaviors may appear to be random or chaotic.
- They are composed of *independent agents* whose behavior is based on physical, psychological, or social rules rather than the demands of system dynamics.
- Because agents' needs or desires, reflected in their rules, are not homogeneous, their *goals and behaviors are likely to conflict*. In response to these conflicts or competitions, agents tend to adapt to each other's behaviors.
- Agents are *intelligent*. As they experiment and gain experience, agents learn and change their behaviors accordingly. Thus overall system behavior inherently changes over time.
- Adaptation and learning tend to result in *self-organization*. Behavior patterns emerge rather than being designed into the system. The nature of emergent behaviors may range from valuable innovations to unfortunate accidents.
- There is *no single point(s) of control*. System behaviors are often unpredictable and uncontrollable, and no one is "in charge." Consequently, the behaviors of complex adaptive systems can usually be more easily influenced than controlled.

Before elaborating on these characteristics in the context of health care, it is useful to reflect on an overall implication for systems with these characteristics. One cannot command or force such systems to comply with behavioral and performance dictates using any conventional means. Agents in complex adaptive systems are sufficiently intelligent to game the system, find "workarounds," and creatively identify ways to serve their own interests.

The Health Care Game

Consider the large number of players, or "agents," involved in the health care game (Table 1). It is reasonable to assume that each type of agent attempts to both serve its own interests and provide quality products and services to its customers. However, there are conflicting interests among stakeholders, just as there are different definitions of quality. Thus, even assuming that all agents are well intentioned, the value provided by the health care system is much lower than it might be, in the sense that health outcomes may be compromised and/or the costs of delivering these outcomes may be excessive.

Working with the American Cancer Society, we studied the value chain associated with disease detection (Rouse, 2000). Many people naively believe that new detection technology is the key to successful detection. However, unless we address consumer awareness, consumer education, physician education, and consumer advocacy, to name a few of the other components of the value chain, patients may not experience the benefits of new detection technologies. In general, enormous investments in medical research will not substantially improve health care outcomes unless they are introduced with an understanding of the overall system.

In this context, it is useful to look more closely at the two cells in Table 1 that include physicians. One aspect of the overall health care value chain is the process of education and certification that provides trained, licensed physicians. Physician education and training are currently being reexamined to identify

TABLE 1 Stakeholders and Interests in Health Care

Stakeholder	Risk Management	Prevention	Detection	Treatment
Public	e.g., buy insurance	e.g., stop smoking	e.g., get screened	
Delivery System			Clinicians[a]	Clinicians and providers[b]
Government	Medicare, Medicaid, Congress	NIH, Government CDC, DoD, et al.	NIH, Government CDC, DoD, et al.	NIH, Government CDC, DoD, et al.
Non-Profits		American Cancer Society, American Heart Association, et al.	American Cancer Society, American Heart Association, et al.	American Cancer Society, American Heart Association, et al.
Academia	Business schools	Basic science disciplines	Technology and medical schools	Medical schools
Business	Employers, insurance companies, HMOs		Guidant, Medtronic, et al.	Lilly, Merck, Pfizer, et al.

[a]The category of clinicians includes physicians, nurses, and other health care professionals.
[b]The category of providers includes hospitals, clinics, nursing homes, and many other types of testing and treatment facilities.

future physician competencies and determine the best way to provide them. Some of the many stakeholders in this process are listed below:

- Accreditation Council for Continuing Medical Education
- Accreditation Council for Graduate Medical Education
- American Academy of Family Physicians
- American Board of Medical Specialties
- American Medical Association
- American Osteopathic Association (AOA)
- AOA Council on Postdoctoral Training
- Council of Medical Specialty Societies
- Federation of State Medical Boards
- Joint Commission on Accreditation of Healthcare Organizations
- Liaison Committee on Medical Education

This list is representative, but not exhaustive. In addition, many functions of these organizations are state specific, so there might be 50 instances of these academies, boards, committees, and councils.

Even from this brief description, it is apparent that the system of health care delivery involves what we might call networks of networks or systems of systems that involve an enormous number of independent stakeholders and interests, layered by organization, specialty, state, and so on. If this system is approached in the traditional way, decomposing the elements of the system, designing how each element should function, and recomposing the overall system would be overwhelming. Thus we must address health care in a different way and from a different point of view—as a complex adaptive system.

Modeling Complexity

The first consideration in designing an effective health care system is complexity. Figure 1 provides a high-level view of the overall health care delivery network based on recent studies of service value networks (Basole and Rouse, 2008). Note that each node in the network includes many companies and other types of enterprises.

Assessing the complexity of networks involves defining the state of the network, that is, the identity of the nodes participating in any given consumer (patient) transaction. We then use information theory to calculate the number of binary questions that have to be asked to determine the state of the network. Given estimates of the conditional probabilities of a node being involved in a transaction, complexity can be calculated and expressed in terms of binary digits (bits).

Figure 1 summarizes an assessment of the complexity of five markets. Note that the complexity of health care is assessed to be 27 bits. This means that determining which nodes (i.e., enterprises) are involved in any particular health care transaction would require on the

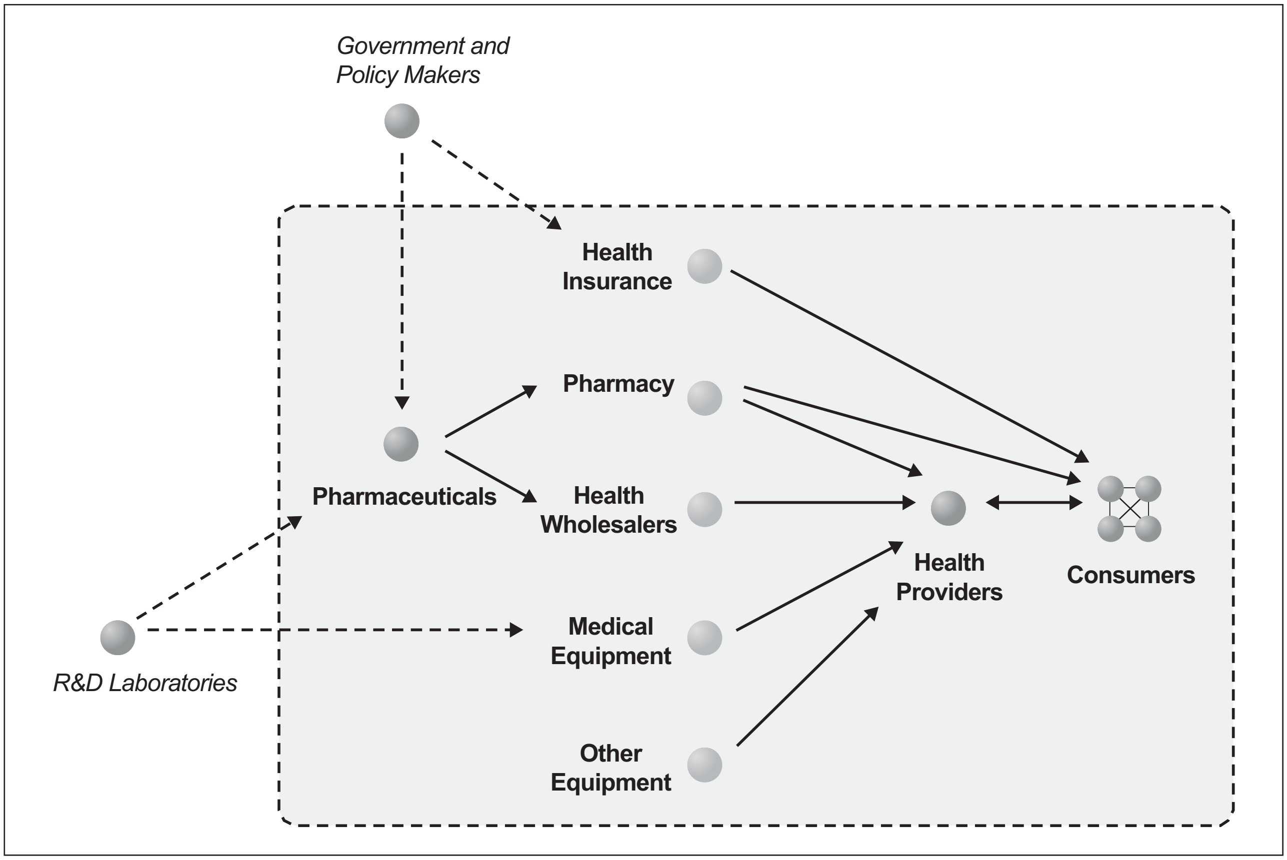

FIGURE 1 A summary of the complexity of five markets in the health care delivery network.

order of 1 billion binary questions. Thus it would be an enormous task to determine the state of the overall health care system.

Notice the ratios of consumer complexity to total complexity in Figure 2. Even though the retail market is the most complex market, the consumer only has to address a small portion of this complexity. The retail industry has been quite successful in managing the complexity of bringing a rich variety of products and services to market without consumers having to be concerned about how this cornucopia arrives on store shelves—or online outlets.

The telecom industry has the worst ratio, as anyone who has tried to call for vendor technical support for a laptop can attest. As a consumer, you need to know much more than you want to know about the hardware and software inside your laptop. A substantial portion of innovations being pursued in this market are aimed at significantly reducing the complexity experienced by consumers. We expect that those who are most successful at reducing consumer complexity will be the winners in this rapidly changing market.

The idea of consumer-directed health care, however, is going in the opposite direction in that it increases complexity for consumers, and possibly for clinicians. Using other markets as benchmarks, we would expect this push to fail, or at least to have limited success. Thus the goal should be to increase the complexity of health care where it can be managed in order to reduce complexity for patients, their families, physicians, nurses, and other clinicians.

The case for decreasing complexity for clinicians is supported in the analyses by Ball and Bierstock (2007), who argue that enabling technologies should support both clinicians' workflow and "thought flow." As long as systems increase clinicians' workload while providing them few if any benefits, the adoption of technology will continue to be difficult.

Design Implications

Our studies of the complexities of markets have led to two propositions for which we have found considerable supporting evidence. Thus we now feel they can be articulated as design principles.

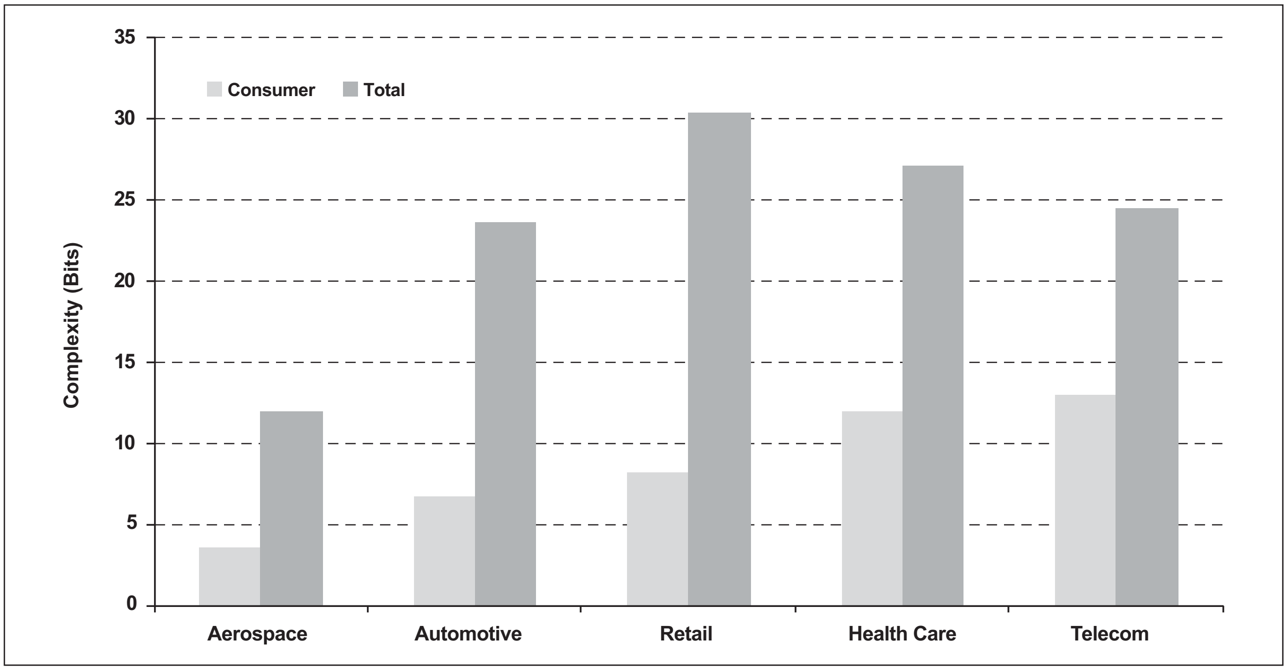

FIGURE 2 Comparative levels of complexity for five markets.

Design Principles

First, the nature and extent of business-to-consumer service value determines business-to-business service value, as well as the value of products and other value enablers. In the context of health care, the value provided to consumers and the payment received for this value determine the financial potential for all of the other players in the network. For example, if consumers do not value and will not pay for a particular test or treatment, none of the participants in this network will be rewarded, no matter how far upstream they are from patients and physicians. This is complicated, of course, when third parties pay for products and services.

The second principle involves the ratio of business-to-consumer complexity to total-market complexity. This ratio tends to decrease as markets mature. The most successful players in a market are those who contribute most to this decrease. To accomplish this, they usually have to increase business-to-business complexity, which often increases total-market complexity. However, this is done in ways that decrease the ratio of consumer complexity to total complexity. This is the strategy that health care should pursue.

As much as possible, complex systems should be designed and not just emerge. Design should begin with the recognition that the health care enterprise—as a system—includes all stakeholder organizations, whether they are customers, partners, collaborators, channels, competitors, or regulators. Starting with this model of the enterprise, the overarching strategy should focus on increasing complexity where it can be managed best and decreasing complexity for end users.

Designing Agile Complex Systems

Most mature enterprises can manage design, development, manufacturing, and sustainment of products and services. Few enterprises can manage economies, markets, competitors, and end users. Put simply, because one cannot control the state of health, education, or preferences of those who seek health care, one cannot assume that they will be able and willing to manage the complexity of the system. Consequently, the design should be focused on managing complexity by providing ways of monitoring and influencing system state, performance, and stakeholders, as elaborated below.

This strategy for managing complexity can be facilitated by also designing an agile enterprise that can readily make decisions to redeploy resources to address opportunities and problems (Rouse, 2006). Achieving agility requires trading off optimization to create the leanest possible enterprise while maintaining flexible resources that can respond to contingencies. The lowest cost health care system would be quite fragile if these contingencies have characteristics outside of the design assumptions for which the system has been optimized. Recent research indicates that the best way to address this trade-off is to use the construct of system architectures (Rouse, 2007a).

Management Implications

Complex adaptive systems can be designed, but only to a certain degree. For instance, as outlined above, one can design an enterprise-wide information system for such systems (Zammuto et al., 2007). However, these systems cannot be designed in the same sense that a vehicle or industrial process can be designed. This is because complex adaptive systems have strong tendencies to learn, adapt, and self-organize.

Consequently, the task of managing complex adaptive systems becomes a challenge because, in effect, the system keeps redesigning itself. In fact, the construct of "management" has to be viewed differently for complex adaptive systems than for other types of systems. Consider the management philosophy. Traditional systems are managed to minimize cost. Health care must be managed to maximize value.

Value Philosophy

Recent attempts at health care reform have tended, in effect, to pursue the lowest cost acceptable health care for our population. In contrast, we should be pursuing the highest value health care. Value focuses on organizational outputs (or outcomes), rather than inputs. Thus we should emphasize the health states (outputs) of patients rather than the revenues (inputs) of providers.

Value relates to the benefits of outcomes, rather than the outcomes themselves. From this perspective, we should be very interested in productivity improvements attributable to wellness, rather than simply the absence of sickness. In an increasingly knowledge-based economy, the intellectual assets embodied in people are central to global competitiveness and economic growth. A recent report from the Milken Institute shows that the costs of lost productivity are often four to five times greater than the costs of health care (DeVol et al., 2007).

Finally, value implies relevant, usable, and useful outcomes, which require that stakeholders understand and appreciate the management philosophy of the system and its implications. In a complex adaptive system, a lack of understanding and/or appreciation tends to result in "dysfunctional" behaviors by one or more stakeholder groups, although these behaviors may be well intended and even reasonable according to the stakeholders' understanding of the ends being sought and the means appropriate to achieving them.

Organizational Behaviors

The best way to approach the management of complex adaptive systems is with organizational behaviors that differ from the usual behaviors, such as adopting a human-centered perspective that addresses the abilities, limitations, and inclinations of all stakeholders (Table 2) (Rouse, 2007b).

Given that no one is in charge of a complex adaptive system, the management approach should emphasize leadership rather than traditional management techniques—influence rather than power. Because none, or very few, of the stakeholder groups in the health care system are employees, command and control has to be replaced with incentives and inhibitions. No one can require that stakeholders comply with organizational dictates. They must have incentives to behave appropriately.

Not only are most stakeholders in health care independent agents, they are also beyond direct observation. Thus one cannot manage their activities but can only assess the value of their outcomes. In a traditional system, one might attempt to optimize efficiency. However, the learning and adaptive characteristics of a complex adaptive system should be leveraged to

TABLE 2 Comparison of Organizational Behaviors

	Traditional System	Complex Adaptive System
Roles	Management	Leadership
Methods	Command and control	Incentives and inhibitions
Measurement	Activities	Outcomes
Focus	Efficiency	Agility
Relationships	Contractual	Personal commitments
Network	Hierarchy	Heterarchy
Design	Organizational design	Self-organization

encourage agility rather than throttled by optimization focused on out-of-date requirements.

Of course, there are contractual commitments in complex systems, but because of the nature of these systems, stakeholders can easily change allegiances, at least at the end of their current contracts. Personal commitments, which can greatly diminish the risks of such behaviors, imply close relationships rather than arm's-length relationships among stakeholder groups and transparent organizational policies, practices, and outcomes.

Work is done by heterarchies, whereas permissions are granted and resources provided by hierarchies. To the extent that the heterarchy has to stop and ask the hierarchy for permission or resources, the efficiency and effectiveness of the system is undermined. Decision-making authority and resources should be delegated to the heterarchy with, of course, the right incentives and inhibitions.

Finally, as noted throughout this article, because complex adaptive systems self-organize, no one can impose an organizational design. Even if a design were imposed, it would inevitably be morphed by stakeholders as they learn and adapt to changing conditions. In that case, the organization that management would think it was running would not really exist. To the extent that everyone agrees to pretend that it still exists, or ever existed, value will be undermined.

Information Systems

Based on the organizational behaviors for complex adaptive systems described above, information to oversee the system should include the following elements:

- Measurements and projections of system state in terms of current and projected value flows, as well as current and projected problems.
- Measurements and projections of system performance in terms of current and projected value, costs, and metrics (e.g., value divided by cost), as well as current and projected options for contingencies.
- Observations of system stakeholders in terms of the involvement and performance of each stakeholder group.
- Capabilities for measurement, modeling, and display of system state, including agile "What If?" experimentation and adaptation.

The question arises about who would be looking at and using the information for the whole health care system. If we were discussing the banking system, the answer would be the Federal Reserve Bank. The Fed does not tell banks what to do, but it sets the prime interest rate and determines each bank's reserve requirements. Banks and investors then decide how they want to adapt to any changes.

The health care system has no overseer,[1] although some have argued that there should be one, considering the importance of the health of the country's human capital to competitiveness and economic growth. The question is which variables an overseer might adjust. Perhaps it would adjust reimbursement rates in relation to the value of health outcomes. Admittedly, outcomes can be difficult to characterize and calibrate, and determining attribution of causes of outcomes can be difficult because multiple actors are involved and outcomes only emerge over time. Nevertheless, at the very least, we should be able to characterize and assess bad outcomes (IOM, 2000).

Because complex adaptive systems self-organize, no one can impose an organizational design.

More controversially, an oversight organization might adjust tax rates so that (risk-adjusted) high-value providers would pay lower taxes, perhaps reflecting the economic benefits of high-value health care. I know this idea is controversial because I have presented it to various groups of thought leaders in health care. Beyond the philosophical objection to using the tax system to improve the public good, the most frequent criticism is that providers cannot fully affect health outcomes because patient behaviors are also essential to success. However, this is also true of markets of all kinds. The enterprises that succeed are the ones that convince and incentivize consumer behaviors that co-create

[1] Some have argued that the Centers for Medicare and Medicaid Services (CMS), an element of the U.S. Department of Health and Human Services, plays a dominant role in setting reimbursement levels for patients enrolled in these programs via the Medicare Payment Advisory Commission. However, CMS does not oversee the whole health care system or address the overall health outcomes and economic impacts discussed in this article.

high-value outcomes. Success for the health care model depends on providers seeing themselves as ensuring high-value outcomes, rather than being reimbursed for the costs of their services.

Conclusions

The models and analyses discussed in this article can be summarized in just two words—information and incentives. Substantial improvement in the system of health care in the United States will require that stakeholders have easy access to information on the state and performance of the whole system, or any subsystem, as well as information on best practices at all levels. This information would be used to assess current and emerging situations in this complex adaptive system, which would lead to adjustments of incentives and inhibitions to motivate stakeholders to change their behaviors to continually increase value.

In general, incentives are essential to complex adaptive systems. Outcomes, as well as activities, must be incentivized. Payments to providers should reflect the (risk-adjusted) value of the outcomes achieved regardless of the cost incurred to achieve them. Poorly informed and/or out-of-date practices should be disincentivized. High-performing providers should reap substantial rewards, and poorly performing providers will go out of business. In this way, the average performance level will continually rise.

Wellness, which contributes to productivity, should also be incentivized. Building on the recent report of the Milken Institute (DeVol et al., 2007), an economic model could be developed of the relationship between wellness and productivity to provide a basis for determining how much should be invested in public awareness and education. The model would also be a basis for designing tax incentives for employers who offer wellness programs and whose employees participate in them.

These are "big" ideas that need much refinement, analysis, and debate, and we must keep in mind the inertial power of the status quo. A few years ago, *The Economist* (2004) published a long survey article on health care financing, which admonished would-be reformers to remember that every health care dollar saved is somebody's income. Aspinall and Hamermesh (2007) reinforced that idea in a recent assessment of the promise of personalized health care.

Thus we clearly need incentives for key stakeholders to change. One incentive might be a crisis. For example, when the percentage of GDP devoted to health care approaches 100 percent, many things would certainly change, and health care might be rationed at that point. However, by acting long before we reach such a crisis point, we can engineer much better solutions to providing high-value health care.

Systems engineering for health care can operate on multiple time scales. Several of the ambitious ideas outlined here will take several years, or more, to be fully realized. However, in the process of pursuing these ideas, we will gain in understanding, which will inevitably result in our identifying much low-hanging fruit, that is, short-term opportunities that can be pursued much faster than the overarching vision. These short-term pursuits will undoubtedly improve the health care system, even as we work on the long-term vision to transform the overall system.

We need to analyze and design the systemic nature of health care delivery and not continue to let it evolve and see whether one idea or another works. Complex adaptive systems require sophisticated and sometimes subtle analyses and designs, which will no doubt require experts in a wide range of disciplines beyond engineering. However, a strong competency for analysis and design of complex adaptive systems will serve us well.

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As biology becomes an information science, health care will learn from nature how to accelerate change.

The Convergence of Information, Biology, and Business: Creating an Adaptive Health Care System

Christopher Meyer is chief executive of Monitor Networks. This article is based on his presentation at the NAE Annual Meeting Technical Symposium on October 1, 2007.

Christopher Meyer

The world of health care lies between the realms of medical science, which continues to deliver new treatments and information at an accelerating rate, and of policy, which is conservative by design to protect patients' safety. Other organizations and businesses have been adapting to changing environments much more quickly than health care, but as biology and information sciences converge, the health care system could use similar techniques to improve the quality of care.

Adaptive Enterprises

Since the days of Henry Ford, traditional businesses have prized stability, efficiency, and predictability. A traditional businessperson looking at the two graphs in Figure 1 might prefer the one on the left because of its stability and narrow range of variation. However, these graphs depict the heart rates of two individuals. The person on the right is healthy; the person on the left died eight days later. One might think a healthy heart would beat at a stable, predictable rate and that a diseased heart would have an erratic and changeable heartbeat. In fact, a healthy heart takes inputs from the body about the concentration of oxygen and sugar in the bloodstream and other conditions and then adapts—that is, it "makes a decision" about what to do. A heartbeat as constant as a metronome is a sign of disease.

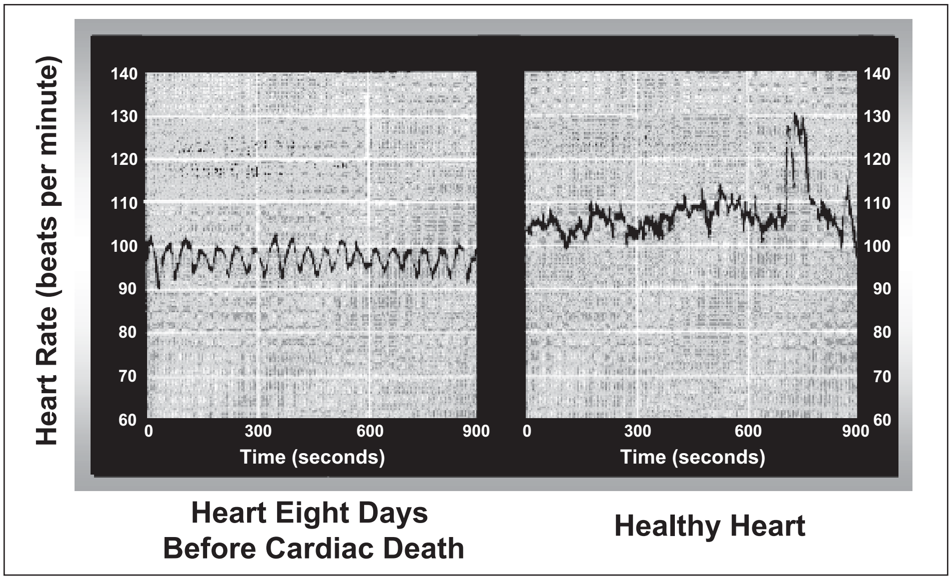

FIGURE 1 Two cardiograms showing (left) an unhealthy heartbeat and (right) a healthy heartbeat.

This analogy holds true for business. In 2006, Ford had to close a plant near Atlanta that had produced the company's line of Ford Taurus and Mercury Sable sedans, essentially identical cars. Although the plant was one of the most productive on the continent, it was not adaptable.

In the same year, Honda constructed a plant that could produce both Civics and Elements, two quite different models. The capital efficiency lost from investing in adaptability was small compared with the robustness gained from being able to follow the market. Asian manufacturers like Honda understand that betting on correctly anticipating the market in an environment of constant change is bound to be expensive in the long run.

But these trade-offs are becoming increasingly old-fashioned, because robustness and efficiency are not necessarily mutually exclusive. Information-intensive approaches, such as mass customization and digital optimization and control, can eliminate the inefficiencies of variation, and real-time feedback loops and learning systems can update the way businesses work as circumstances change. In some industries, however, particularly health care, management approaches have not kept pace.

Learning from Nature

In the words of Stuart Kauffman (1993), a physician and complexity theorist, "Nature's been [adapting] for 3.8 billion years. Maybe we should pay attention to how it does [this]." In the biosphere, adaptation refers to processes by which populations of organisms evolve in response to changing environmental pressures. How does nature do it, and how can managers adopt nature's techniques?

In *It's Alive*, Stan Davis and I created a simplified model of evolution as the outcome of six principles and then translated those principles into business terms (Meyer and Davis, 2003):

- **Self-organization.** Any group of "decision-making units" capable of linking to each other, be they molecules, software routines, or people, is likely to organize autonomously to create something more complex. In nature, 92 chemical elements organized themselves into our planet. In business, farmers have been forming weekly village markets for centuries (Kauffman, 1993).
- **Recombination.** Biology remixes the recipes for species by combining the genetic recipes of parents. This remixing, or recombining, is the source of almost all innovation in nature. In business, the Wright brothers created something completely new by combining the capabilities of the airfoil, the bicycle wheel, and the internal combustion engine.
- **Selective Pressure.** The environment determines the likelihood of passing along genes to the next generation. A specific innovation, whether in the rain forest or the marketplace, may or may not confer an advantage. However, in a rapidly changing environment, a higher rate of innovation improves the odds of a species finding a successful adaptation.
- **Adaptation.** Over time, with cycles of recombination and selection of the fittest, the abilities of a species evolve.
- **Coevolution.** Species share the environment. As Kauffman says, "When the frog evolves a sticky tongue, flies get Teflon feet."
- **Emergence.** From looking at the periodic table, one would not predict that life would emerge from these

diverse elements. However, interactions among self-organization, recombination, selection, adaptation, and coevolution lead to a connected ecology, or, in business, an economy made up of markets. Interdependencies among interactions make it impossible to predict which outcome will emerge. For instance, we cannot predict how a rain forest will change as the climate changes, or how capitalism will evolve as energy becomes scarce.

"General Evolution": Applying Biology to Business

Adaptation is embedded in biological systems, but the general theory can be applied to other kinds of complex systems, including social systems like business. When companies interact with one another they create new economic opportunities and capabilities. Business capabilities are like genes, and we can think of the economy as a set of capabilities turning each other on and off the same way a genetic regulatory network turns gene expression on and off.

For a business to thrive in a volatile, evolving environment, it must apply the lessons learned from biological evolution. Managers must shift from predicting and controlling change to building an organization that senses external change and responds appropriately, like a healthy heart. We refer to this as the shift to "adaptive management."

The six principles of evolution outlined above can be translated into six practical business principles, which we call "memes for managing" (Table 1). In the following sections we describe the business application of two memes: (1) "recombine" and (2) "sense and respond, learn and adapt."

"Recombine" at John Deere

John Deere uses techniques of directed evolution—the intentional recombination and selection techniques used to create thoroughbreds and show dogs—to schedule operations in a highly complex factory in Moline, Illinois. The factory makes seed planters, the large machines farmers tow behind tractors to sow seeds.

Manufacturing planters is challenging because the many kinds of seeds, tractors, soils, and climate generate 1.6 million configurations, most of which are produced in low volumes. Thus Deere could not build a truly automated-transfer assembly-line factory. As

TABLE 1 Memes for Managing

Name	Definition	Business Example	Application to Health Care
Self-organize	Manage your organization from the bottom up. Influence the rules that affect individual choices rather than the overall behavior of the organization.	Southwest Airlines cargo-routing simulator	Hippocratic oath, rule-based HMOs
Recombine	Proliferating connections make recombination—of software code, product attributes, people, and markets—easier. Turn your business into an open system to capture the value and innovation of diversity.	Genetic algorithms to schedule John Deere factory production	Gene shuffling
Sense and respond, learn and adapt	Equip your business to sense changes in real time and to respond immediately, accurately, and appropriately. Then learn from that experience and incorporate the new information into your repertoire of responses.	Honeywell Adaptive Intelligent Recovery Thermostat	Partners HealthCare physician order-entry system
Seed, select, and amplify	Test many diverse options and reinforce the winners. Experiment, don't plan.	Public beta software releases; Sun's Java Fund	Evidence-based medicine
Live at the edge of chaos	The rate of environmental change demands internal instability for survival. Disrupt the static elements in your organization.	Google, Amazon	Dr. Peter Pronovost's checklists to prevent line infections in ICUs
Monetize molecules	The next wave of innovation is in the intersection of molecular science and technology.	Hybridized plants, nanotechnology	Drug discovery

a result, workers wheeled planters through the aisles manually, and, depending on the particular configurations of the planters, they often bumped into each other and impeded each other's progress. Despite the use of standard optimization techniques, such as linear programming, throughput was poor.

Finally, Bill Fulkerson, a Deere engineer, proposed a nonlinear approach—genetic algorithms. Given the set of planters the factory wanted to build the next day, the system created a few random sequences for producing them. The schedules were expressed digitally—each one a string of zeros and ones, just as the instructions for creating an organism are expressed in a string of Gs, Ts, As, and Cs.

Deere engineers then applied the principle of selection to the schedules, evaluating each one with a computer simulator that assigned it a "fitness" score based on its simulated throughput. The winning sequences were then "put out to stud," that is, a genetic algorithm recombined parts of the best schedules to create a new generation of schedules.

Every night, 40,000 new schedules ran simulated races, and the winning plan was used for the real-life production on the factory floor the next day. The genetically engineered schedules were about 15 percent more efficient than the schedules Deere had designed based on traditional linear methods.

The lesson from Deere's recombinant strategy is that nature's approach to adaptation can outperform previous engineering methods. By using genetic algorithms, Deere literally translated the recombination of DNA to recombinant code in another domain.

"Sense and Respond, Learn and Adapt" at Honeywell and BMW

The meme "sense and respond, learn and adapt" (SRLA) has two feedback loops, one short term and one longer term. The thermostat in your home has one of these loops, a real-time sense-and-respond feedback system that senses the temperature in the room and responds by turning on the furnace when it drops below a designated level.

By comparison, the Honeywell Adaptive Intelligent Recovery Thermostat has higher consciousness. It observes the effect of its actions on a room, and if it overshoots the mark one day, perhaps because of the high thermal mass of the radiators, it remembers and turns off the heat earlier the next day. That's the "learn" part of SRLA.

As the seasons change, the effect of the learned behavior also changes, for example because the room loses heat faster in colder weather. Because the thermostat keeps learning, its behavior adapts to these seasonal shifts. It not only senses and responds, but also learns from the results of its actions and adapts to match its performance to the shifting environment.

Recombination and SRLA together can lead to a new phase of economic evolution enabled by the convergence of information and business. BMW recently ran an ad showing a car's wheels screaming and spinning on an icy road. The driver hits a button and talks to the concierge, who quickly finds a solution to the driver's dilemma. The BMW downloads a patch to its traction-control system, and off goes the car with new behavioral rules onboard.

Nature's methods can outperform engineering methods.

However, the new code could have evolved without human intervention. The antilock brake system (ABS), which knows when a wheel is spinning, could have transferred the telemetry to a central information system. Even if the exact configuration of weather condition, climate, load, tire design, and road surface had never been seen before, BMW could have used a genetic algorithm to invent a new software solution by using a simulator to evaluate the problem (as at Deere) and send the "winner" to the traction-control system.

So far we have "sense" (the ABS system), "respond" (telemetry), and "learn" (recombination via a genetic algorithm and the installation of new code in the braking system). What about "adapt"? BMW could take note of the success of the new software and update the ABS not just in one BMW but throughout its fleet. In this way the "species" would evolve, or adapt, in response to the experiences of individual "organisms" to their environment.

Businesses that install and exploit these feedback loops, and have the capacity for innovation to adapt to them, can create the capacity to respond to changing environments, not through studies, surveys, and redesigns, but through a continuous evolutionary process.

Applying Biology to the Business of Health Care

In the words of Jerry Grossman, former head of the New England Medical Center, "Health care has been locked in irons since the end of World War II." While most of the business world has become more adaptable, shortened its product life cycles, increased process innovations, and increased the rates of job and CEO turnover, health care, like the heart of the sick man in Figure 1, has been too stable for too long.

Keep in mind, however, that health care's reluctance to embrace change is based on valid arguments. Experimentation—and innovation always begins with experimentation—can be dangerous. Like an industrial factory floor of the 1930s filled with dangerous technologies such as molten steel and explosive chemicals, hospital environments can be dangerous places, and mistakes can be fatal. Innovation is not a good thing if people die when it leads to an unexpected result. The medical meme for health care management, "First, Do No Harm," is conservative for good reason.

Industry has increased its pace of change in the past two decades by embracing information technologies. Real-time sensing, algorithmic control systems, and simulation, for example, have expanded the performance envelope of all sorts of businesses.

Innovation begins with experimentation, which can be dangerous, especially in health care.

Today, with the convergence of biology and information, health care is poised to follow suit, but the industry is still trying to operate in two places at once—a capital-intensive, dangerous, cost-imperative world and, simultaneously, the area of convergence of medical science and information technology, which is accelerating change and compelling adaptation. Crossing the divide will require a new kind of experimentation.

Medical researchers today can run experiments *in silico*, with computer simulations, rather than *in vivo*, through clinical trials. In this way they can begin to understand how complex biological systems recombine, sense and respond, and learn and adapt as a collective response. Scientists can simulate, for instance, a fully functioning human heart. Researchers at UCLA have studied computer models of a heart to determine how drugs could be targeted more directly to the turbulent breakup of heart waves during sudden cardiac arrest (Xie et al., 2004). The Food and Drug Administration now accepts the results of similar heart simulations as part of filings for drug licenses.

Researchers have also used computer simulations to reduce wait times at a hospital in Canada. Managers were able to model, in the virtual world, the effect of adding a walk-in clinic for people with minor injuries and adding more physicians at peak times. They then put what they had learned from the simulation into practice (Blake and Carter, 1996).

Nature can even be reengineered as biological systems are translated into information and information is translated into biology. As Richard Dawkins (2003) says, "Genetics today is pure information technology. This, precisely, is why an antifreeze gene can be copied from an arctic fish and pasted into a tomato."

The ultimate form of experimentation is the emerging field of "synthetic biology," radical techniques for making the genetic engineering of an organism work as routinely as the design of a new computer chip. One goal of synthetic biology is to design and build engineered biological systems that "manipulate information, construct materials, process chemicals, produce energy, provide food, and help maintain or enhance human health and our environment," according to Drew Endy, a biologist at the Massachusetts Institute of Technology (Endy, 2005).

Unlike genetic engineering, which moves genes one at a time between species to create a new molecular entity, the goal of synthetic biology is to assemble genes from different organisms to create new metabolic pathways, and even new organisms. In the long run, this might involve rewriting genetic code altogether to build organisms that are beyond the capabilities of natural biology.

Experimentation *in silico* simulates existing systems. But synthetic biology is creating a new platform for investigating biological possibilities. Modeling the heart and modeling the hospital emergency room are akin to Sir Isaac Newton watching an apple fall and discovering gravity. Synthetic biology is analogous to Einstein's theory of general relativity, which attempts to explain all of space and time.

The Adaptive Imperative for Health Care

An example of the adaptive imperative in health care is the Partners HealthCare physician order-entry (POE) system, which is already being used by the flagship hospitals in the Partners chain, Brigham and Women's and Massachusetts General in Boston (Davenport and Glaser, 2002). The Partners system uses physicians' experiences and outcomes to continually adapt and change the rules disseminated to physicians in the network.

To order a drug or a procedure or a test, a doctor must put the order into the POE system, which then looks at the patient's information—the other drugs being taken and other important circumstances—and asks the doctor, "Did you know your patient is taking this drug, which is incompatible with what you just asked for?" Or it says, "Do you know that our board of cardiologists thinks that the new drug Avastatin is better than Lipitor?" The system doesn't tell doctors what to do, but it gives them the latest knowledge, which can then change their decisions.

At the back end, the POE system collects information about patient outcomes, enabling the board of cardiologists to review them and revise their recommendations accordingly. Once they make a revision, *every* doctor in the network will see the revised rule the next time he or she logs in—just like the BMWs mentioned above.

When Partners experts determined that a new drug was helpful for heart problems and then made that information automatically available to doctors prescribing treatment, orders for that drug increased from 12 percent to 81 percent. As a result of the POE system, Partners has saved money because doctors are prescribing cheaper and more effective drugs and treatments, and hospital stays are shorter. In addition, adverse drug interactions have been reduced by 17 percent, saving about $10 million annually (Market Wire, 2002).

Conclusion

The health care delivery field has been an isolated ecology, and an ecology that is sheltered for too long becomes vulnerable to predators from the outside. New interloper species are already arriving, in the form of innovative companies like Steve Case's Revolution Health and walk-in clinics at CVS and Wal-Mart stores, to destabilize the health care ecology and disrupt established business models We don't yet know if those species will be invasive, like kudzu, or will be ill-suited to the environment and die out.

Navigating through the increasing turbulence will require adaptive leadership, rather than a command-and-control approach. Ultimately, an adaptive mindset will be necessary for health care executives to meet the increasing demands and for health care as a whole to compete with new species and shape the industry's rapidly evolving transformation. The intensive use of simulation and other less hi-tech information tools—such as checklists—will be essential to ensuring that the evolution proceeds safely (Gawande, 2007).

As John Maynard Keynes wrote in *The General Theory of Employment, Interest and Money* (1936), "The difficulty lies, not in the new ideas, but in escaping from the old ones, which ramify, for those brought up as most of us have been, into every corner of our minds."

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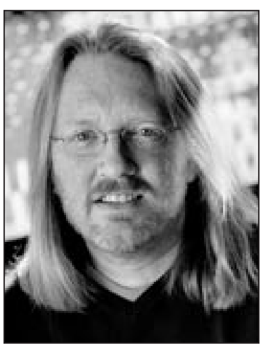
Engineering innovation will continue to improve the quality of life and increase life expectancy.

New Therapies: The Integration of Engineering and Biological Systems



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W. Mark Saltzman

In the twentieth century, overall life expectancy increased by 30 years (Figure 1), and young people today can expect to live longer, healthier, more active lives than their great-grandparents, grandparents, and parents. Dramatic changes in the practice of medicine have affected the life of almost every American. Couples can test for pregnancy at home; new vaccines are available for hepatitis B and chicken pox; inexpensive contact lenses provide clear vision; artificial hips enable recipients to walk and run; magnetic resonance is routinely used for high-resolution imaging of the brain; and many diabetics now use small, reliable pumps that administer insulin continuously.

Much of this progress has resulted from work by engineers, who have been chiefly responsible for the mass production of vaccines, the design of replacement joints, the creation of new techniques for safe imaging inside the human body, and other life-extending and life-improving technologies. In the twenty-first century, engineering innovations will surely continue to improve the quality of life and increase life expectancy. For example, patients may soon be able to live at home while undergoing high-dose chemotherapy.

Some new technologies will create challenges for our health care system, such as questions about how to pay for expensive new treatments, while others will make therapies safer and cheaper. We can reasonably hope that new technologies will contribute to better, more equitable health care in the United States and elsewhere, encouraged, perhaps, by incentives for

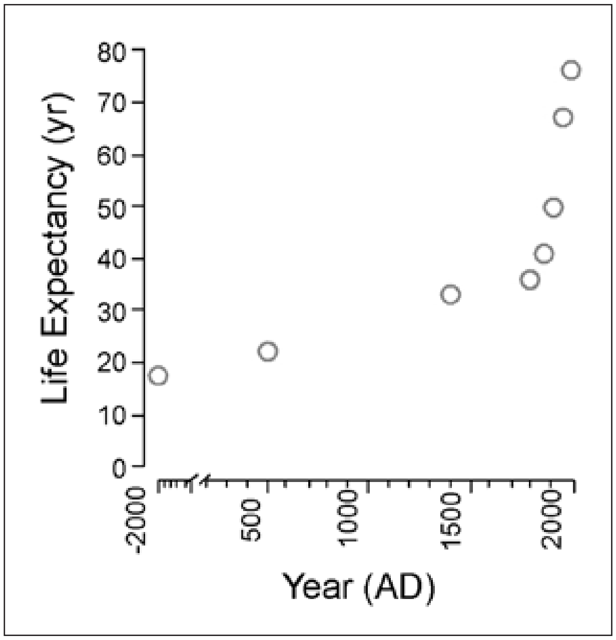

FIGURE 1 Human life expectancy has increased dramatically in the past 200 years.

the development of technologies that make medical care available to large numbers of people. In this brief review, I describe engineering technologies for medicine that are expected to become routine in the next 50 years.

New Materials

The last few decades have been exciting for biomedical engineers, as tremendous advances have been made in biology. The discovery of the structure of DNA in the 1950s was rapidly translated into new kinds of therapies, new treatments for disease, and new ways of diagnosing disease. For example, gene therapy, which was used in humans for the first time several decades ago, has led to drugs designs based on biological principles.

One new opportunity made possible by advances in human biology is the integration of biological features into materials traditionally used in medicine. In the past, most of these materials were developed from synthetic inert materials, such as metals, plastics, ceramics, and composites. New medical materials with integrated biological functions are a major step forward. For example, engineers have developed advanced materials that can provide the long-term release of drugs to a local disease site (Saltzman, 2001, 2004).

Polymers are also now safe and reliable medical tools, many of which can be safely implanted in the body. These materials are referred to as biocompatible because they arouse only weak immune and inflammatory responses. It is not yet possible to predict which polymer structures will be biocompatible, but several classes have been identified. Some of these are hydrophobic and stable, such as poly(ethylene-co-vinyl acetate) and silicon, which are useful in some medical applications because they do not change over the lifetime of the patient. Other polymers are water soluble, such as poly(ethylene glycol). Still others, such as poly(lactide-co-glycolide), degrade slowly with time after exposure to the biological environment. The latter are most useful for delivering drugs because they can be implanted, deliver their drugs, and eventually disappear after the treatment is complete.

Advances in medical materials have also led to new ways of administering drugs. Transdermal patches, polymer devices applied to the skin that slowly deliver drugs into the bloodstream, have been available for several decades. They offer alternative, arguably better, approaches for treating heart disease, preventing unwanted pregnancies, encouraging people to quit smoking, and so on. In addition, new systems for treating cancer, such as the Gliadel® system for brain cancer (described below), are based on principles that have implications for future technologies.

Polymer/Drug Composites

One biomedical engineering technology that is now used routinely involves embedding drug molecules into polymer materials to fashion drug-delivery systems. When a drug/polymer composite is implanted or injected into a patient, it provides a long-term source of the drug inside the body. Materials that release low-molecular-weight drugs can be produced readily; thus materials that release proteins, and even gene therapy vectors, can be designed to work for long periods of time after implantation. The duration and rate of drug release depend on properties that have been engineered into the composite.

Synthetic polymers also offer significant advantages for a variety of other medical applications. For example, polymer-coated metal wires are used in a variety of medical settings, from pacemaker leads to microwires for recording signals in the brain. Many reliable, simple methods, which were developed for coating wires with a thin layer of polymer material, can be used to coat wires with polymer/drug composites (Figure 2). A polymer/drug-coated wire inserted into the brain, for example, can release a drug continuously and locally.

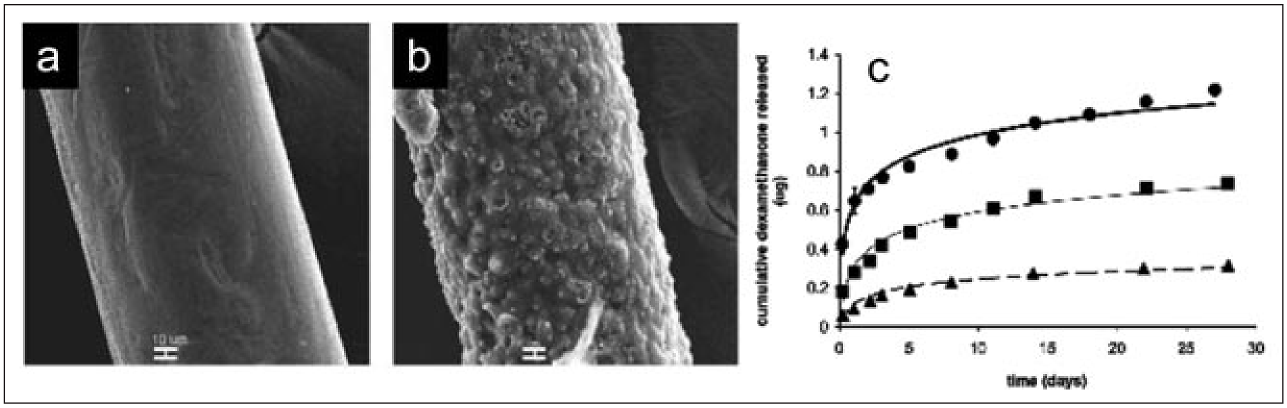

FIGURE 2 Scanning electron microscopy images of (a) an uncoated microelectrode; (b) a dexamethasone-polymer coated microelectrode; (c) the controlled release of dexamethasone from microwires with coatings of 10 (triangle), 30 (square), or 50 percent (circle) dexamethasone coatings. All coatings were produced from dexamethasone in poly(ethylene-co-vinyl acetate). Source: Lo, Laubach, and Saltzman, unpublished data.

Wires can be produced with coatings that release drugs that perform a variety of functions. For example, the local release of steroids could prevent the formation of scar tissue around the surface of a microelectrode, potentially extending its lifetime. This is one example of adding a biological property to a device that is already being used to produce a new device that lasts longer or is less likely to cause medical complications.

The best known product of this sort is the drug-eluting stent, a device placed in an artery to open it mechanically and increase the size of the lumen. Stents are used in patients with arteries that have narrowed to the point that blood flow is not adequate to satisfy the tissue (e.g., a coronary artery on the surface of the heart). Stents provide an alternative to open-heart surgery for many patients, because they can be inserted without surgery using well tolerated intravascular techniques.

A normal metal stent often evokes a tissue response in the blood vessel called restenosis, the regrowth of reactive tissue around the stented area, which can lead to re-narrowing of the vessel. Drug-eluting stents (metal stents coated with drug/polymers, similar to the coating on the wire shown in Figure 2) slowly release an anti-stenosis drug into the region of the vessel where the stent is placed. The drug acts on cells in that area to prevent the reformation of scars, thereby greatly extending the life of the stent.

Drug-eluting stents are not only interesting devices that provide new options for patients with life-threatening disease, they are also harbingers of a change in approach. Whereas previous implanted materials were predominantly made of materials that are known to be inert, new materials are designed to function biologically. In this case, the function is provided by a drug, which is released in a pattern controlled by the device engineer. In other cases, the biological function might be provided by the material itself. For example, the surface chemistry of the material might include elements that interact directly with cells in the tissue, or cells might be implanted with the material (the latter is discussed below).

Local Drug Delivery

Biodegradable polymer/drug composites have also led to new approaches to medical therapy. For example, Gliadel®, a degradable polymer wafer, can be loaded with high concentrations of a highly active, potent chemotherapy drug and placed at a site near a tumor, where it can deliver the drug directly to the tumor cells.

The first clinical application of Gliadel was for brain cancer, which had been difficult to treat with existing techniques. With Gliadel, surgeons resect the tumor and place the polymer/drug wafers into the surgical-resection cavity. The patient leaves the operating room with ongoing high-dose chemotherapy, delivered not throughout the body where it can cause unwanted side effects, but directly to the tumor site where it has maximum effectiveness with low toxicity.

When the technique was first tested in animals with experimentally induced brain cancer, a significant proportion of the test animals were cured when the material was designed properly. Clinical studies then showed that patients who received polymers embedded with drugs had higher survival rates than patients who received placebo polymers that had not been embedded with drugs.

Significantly, there were long-term survivors of this very serious disease—many more long-term survivors than one would expect without therapy (Sawyer et al., 2007). In addition, because Gliadel® is an engineered system that can be produced reliably and in large quantities, and because it augments a treatment already being used, the added cost for this benefit could potentially be low.

Mathematical Models

Mathematical modeling, a valuable tool in the design of new materials, provides information that would be difficult, and expensive, to get any other way. Engineering analysis—the development of mathematical models to describe a phenomenon—requires writing differential equations, which can often be a fairly straightforward process (Fleming and Saltzman, 2002). These models can be critical to understanding how implanted drug-delivery systems work. In the case of Gliadel, the models were able to answer difficult questions, such as where the drug molecules go when released directly into brain tissue, how long they last, and how far they penetrate into the tissue.

Models also provide a mechanism for testing changes in engineered systems. They can suggest ways of engineering drugs—even drugs that are not yet available or have not yet been synthesized—with properties suited for particular kinds of therapy. For example, models that we developed in the early 1990s suggested that certain kinds of drug molecules would be best suited for local delivery in the brain. The ideal molecule was water-soluble, highly diffusible, yet unable to permeate easily through capillary walls (Saltzman and Radomsky, 1991).

One version of that ideal molecule was produced by coupling a synthetic polymer, poly(ethylene glycol), with drug molecules at each end of the linear polymer chain (Figure 3). Models suggested that this design would penetrate much better through brain tissue, thus enabling deeper penetration of the drug into the tissue. Experiments showed that this prediction was correct (Fleming et al., 2004). Subsequently, this drug/polymer conjugate was engineered, based on conventional engineering analysis, to possess properties that would carry it farther throughout the central nervous system.

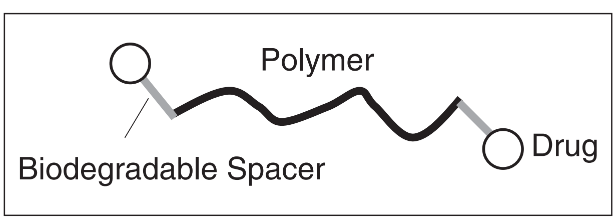

FIGURE 3 Design of conjugates optimized for local delivery. Drug molecules covalently attached to water-soluble polymers will penetrate farther from the implant source than free drugs because they are diffusible but are slowly eliminated from the local site.

As new technologies are more widely used they might reveal opportunities for improvement, as this example illustrates. In this case, the availability of local drug-delivery systems created an opportunity to rethink the way drugs are designed. Drugs created to be administered by the old paradigm, mainly orally, are not always the best candidates for new modes of drug delivery.

Nanotechnology

Nanotechnology will have a dramatic impact on the engineering of materials for new therapies. With nanotechnology, small particles, less than 100 nm in diameter, can be synthesized for drug delivery, imaging, or diagnosis. Fahmy et al. (2005) and Peer et al. (2007) have described some potential advantages of nanoparticles in medical applications.

Nanoparticles provide a new way of thinking about the administration of drugs. With these tiny particles it may be possible to design a vehicle that will carry a drug safely into a cell and only then release it. Current methods of drug administration rely on flooding the body or tissue site with a drug in hopes that an adequate number of molecules reach the intracellular site of action. Drug-loaded nanoparticles promise therapies that are more efficient, more selective, and safer because they will have fewer side effects.

One advantage of nanoparticles as drug carriers is that the delivery system does not have to be implanted, which requires a surgical procedure. These tiny particles can be introduced into the body in many ways, such as injection or inhalation. In addition, some cells internalize nanoscale particles. If these particles are loaded with drugs, such as chemotherapy drugs, they could deliver high doses into the cell interior.

The first major challenge in engineering nanoparticles is to produce them with high drug content, which would enable the administration of a small quantity of particles containing a sufficient quantity of drug molecules for the desired period of release. If this can be achieved, the result would be a totally synthetic, virus-sized particle loaded with active agents. If properly engineered, the drug molecules would be released in a controlled pattern (Figure 4).

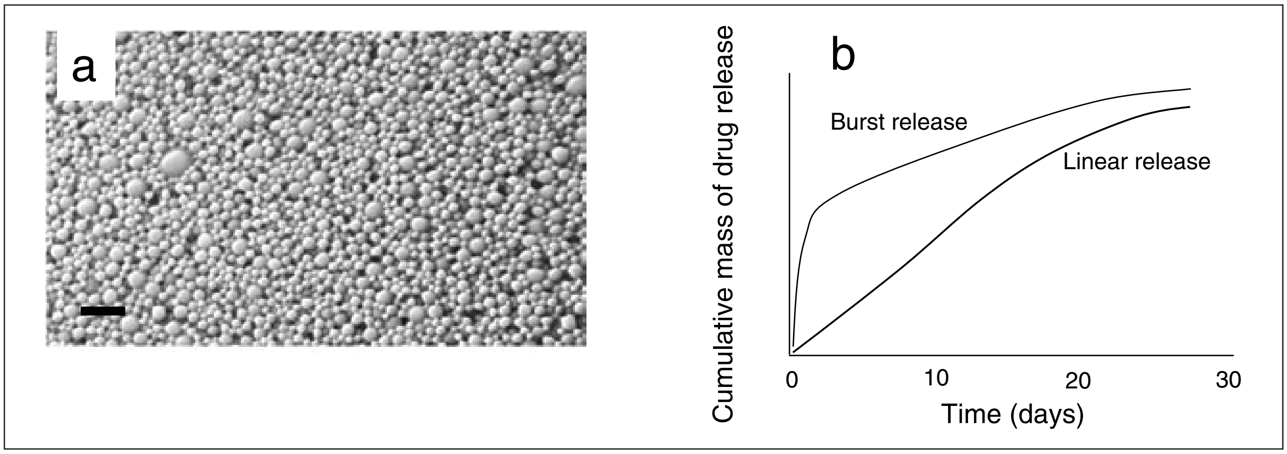

FIGURE 4 Nanoparticles for the controlled release of drugs. (a) A scanning electron micrograph shows nanoparticles formed from poly(lactide-co-glycolide), a biodegradable polymer. Scale bar = 1 micron. (b) Drug molecules are slowly released from the nanoparticles after introduction to a water-rich environment. Although linear release is usually desirable, many nanoparticle formulations release a substantial fraction of their drug load in an initial burst.

A second challenge is to make the nanoparticles smart so they know where to go in the body, which cells to enter, and when to release the drugs. One way to achieve this is to mimic an attribute of viruses by adding ligands, or recognition molecules, to the surface of the particles. In this way, it may be possible to make drug carriers that are much smaller than a cell but capable of delivering large doses of drug directly to the cell's internal machinery. Antibodies, antibody fragments, and mimics are the most common reagents used as recognition elements.

Polymer nanoparticles are a potential new tool of nanotechnology. Others are nanoparticles assembled from lipids (liposomes), polymer micelles (colloidal particles self-assembled from amphiphilic polymers), and dendritic polymers.

Tissue Engineering

All the cells in our bodies are surrounded by a matrix—called the extracellular matrix—that contains elements, often networks of fibers, with typical diameters of 10 to 100 nm. Engineers have developed artificial matrices composed of natural or synthetic polymers that can serve as scaffolds for the transplantation of cells into the body. The purpose of this aspect of biomedical engineering, called tissue engineering, is to develop methods of repairing tissues or organs damaged by disease or trauma. A few pioneering efforts are already being tested in patients, such as engineered skin equivalents to repair wounds and chondrocyte implantation to repair articular cartilage defects. These studies have shown that novel tissue-replacement strategies will work in certain cases.

One of the most difficult problems in tissue engineering has been the reliable production of functional blood vessels to transport nutrients and waste in and out of the newly formed tissue. One promising technique involves using cultured human endothelial cells, usually derived from umbilical veins. In the most promising examples of blood vessel formation, these cells were genetically engineered to express proteins that improve their survival and encourage their transformation into functional blood vessels (Enis et al., 2005; Schechner et al., 2003).

To create new regions of vascularized tissue, the genetically engineered cells are first suspended in a polymer gel, which is then transplanted to a tissue site. Within a few weeks, a robust network of new, functional blood vessels forms the three-dimensional space once occupied by the implanted gel. The cell-loaded polymer gel is a smart material. When implanted into a site in the body that lacks sufficient blood flow, it induces the formation of new blood vessels in that region.

Based on this example, one can envision dozens of new ways to treat disease. The cell-loaded patch could be applied to tissues that have become ischemic to create new pathways for blood flow and the delivery of oxygen. Alternatively, the patch could be loaded with multiple cell types provided in response to the specific needs of the patient. For example, with a patch containing endothelial cells and beta cells—the cells in the pancreas that secrete insulin in response to glucose—a vascularized region of tissue that functions like an endocrine pancreas might be produced after transplantation. Protein-loaded delivery systems might be used to accelerate or direct the process of tissue formation, to facilitate the integration of the tissue, or to suppress unwanted local immune reactions.

These are just a few examples of new kinds of therapy using tissue engineering that might be available in the next 10 years. The development of each new therapy will involve overcoming significant engineering and medical challenges, but progress is certain. One can imagine using engineering principles that are fairly easy to define, perhaps even easy to manufacture, to produce complex transplantable materials built from component parts that are biologically safe. Tissue engineering will change the way health care is delivered to certain patients.

Summary

Engineering and new technologies improved the quality of life and extended life expectancy during the twentieth century. New technology—including safer biomaterials, nanoscale drug-delivery systems, and cell-based therapies like tissue engineering—will build on these advances in the twenty-first century. The impacts of emerging technologies on health care delivery and health care costs are difficult to predict, but they are sure to be profound.

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NAE News and Notes

Class of 2008 Elected

In February, NAE elected 65 new members and 9 new foreign associates, bringing the number of U.S. members to 2,227 and the number of foreign associates to 194. Election to NAE, one of the highest professional distinctions accorded to an engineer, honors those who have made outstanding contributions to "engineering research, practice, or education, including . . . significant contributions to the engineering literature" and to "new and developing fields of technology, . . . major advancements in traditional fields of engineering, or . . . innovative approaches to engineering education." A list of newly elected members and foreign associates follows, with primary affiliations at the time of election and brief descriptions of principal accomplishments.

New Members

Bernard Amadei, professor of civil engineering, University of Colorado, Boulder. For the creation of Engineers Without Borders, leadership in sustainable development education, and research on geomechanics.

Robert C. Armstrong, Chevron Professor of Chemical Engineering, Massachusetts Institute of Technology, Cambridge. For conducting outstanding research on non-Newtonian fluid mechanics, coauthoring landmark textbooks, and providing leadership in chemical engineering education.

Arvind, Charles W. and Jennifer C. Johnson Professor, Department of Computer Science and Engineering, Massachusetts Institute of Technology, Cambridge. For contributions to data flow and multi-thread computing and the development of tools for the high-level synthesis of hardware.

Dennis N. Assanis, Jon R. and Beverly S. Holt Professor of Engineering, University of Michigan, Ann Arbor. For scientific contributions to improving fuel economy and reducing emissions of internal combustion engines, and for promoting automotive engineering education.

Wanda M. Austin, president and chief executive officer, Aerospace Corporation, Los Angeles, California. For leadership in the engineering and integration of national space intelligence systems.

Ray Henry Baughman, Robert A. Welch Professor of Chemistry and director of the Alan G. MacDiarmid NanoTech Institute, University of Texas at Dallas. For pioneering novel applications of conjugated polymers and related nanomaterials.

Pallab K. Bhattacharya, Charles M. Vest Distinguished University Professor of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor. For contributions to quantum-dot optoelectronic devices and integrated optoelectronics.

Paul N. Blumberg, independent consultant, Southfield, Michigan. For the synthesis of automotive-system models that has led to more effective control of emissions and improvements in fuel economy.

Gerald G. Brown, distinguished professor of operations research, U.S. Naval Postgraduate School, Monterey, California. For contributions to large-scale optimization theory and its military and industrial applications.

Howard J. Bruschi, executive consultant, Westinghouse Electric Company, Pittsburgh, Pennsylvania. For leadership in the design, development, and licensing of the passively safe Westinghouse reactors, the AP600 and AP1000.

Gary S. Calabrese, former vice president and chief technology officer, Rohm and Haas Company, North Andover, Massachusetts. For the development of advanced electronic materials and processes for semiconductor device manufacture.

Mau-Chung Frank Chang, professor, Electrical Engineering Department, University of California, Los Angeles. For the development and commercialization of GaAs power amplifiers and integrated circuits.

Stephen Z.D. Cheng, dean, College of Polymer Science and Polymer Engineering, University of Akron, Akron, Ohio. For the development of materials for liquid crystal displays and the elucidation of structure-property relationships in polymeric materials.

Peter A. Cundall, principal and senior consultant, Itasca Consulting Group Inc., Minneapolis, Minnesota. For advancing the understanding of rock-deformation and failure processes and the development of innovative computational procedures in rock mechanics.

Robert H. Dodds Jr., professor and department head, M.T.

Geoffrey Yeh Chair of Civil Engineering, Department of Civil and Environmental Engineering, University of Illinois, Urbana. For contributions in nonlinear fracture mechanics and applications to practice in nuclear power and space systems.

Cynthia Dwork, senior researcher, Microsoft Research, Mountain View, California. For fundamental contributions to distributed algorithms and the security of cryptosystems.

David A. Dzombak, Walter J. Blenko Sr. Professor of Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania. For the development of models used in evaluating chemical behavior in water quality engineering and environmental remediation.

Anthony E. Fiorato, chairman, CTLGroup, Skokie, Illinois. For research on improved concrete materials and construction, development of tests and standards, and technical leadership.

Thomas J. Fogarty, president, Fogarty Engineering, Portola Valley, California. For invention of the balloon catheter and devices that have revolutionized vascular surgery, and for creating companies to commercialize these inventions.

James D. Foley, professor, College of Computing, and Stephen Fleming Chair in Telecommunications, Georgia Institute of Technology, Atlanta. For contributions to the establishment of the fields of computer graphics and human-computer interaction.

Lee-Lueng Fu, senior project scientist, Jet Propulsion Laboratory, Pasadena, California. For contributions to the development of satellite altimetry and applications in oceanography, geodesy, and climatology.

Gary Stephen Grest, Distinguished Member of the Technical Staff, Sandia National Laboratories, Albuquerque, New Mexico. For development of large-scale simulations for improved understanding of metals, polymers, and particulate matter.

Barbara J. Grosz, interim dean, Radcliffe Institute for Advanced Study, and Higgins Professor of Natural Sciences, School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts. For pioneering research in natural language communication between humans and computers and its application to human-computer interaction.

Donald J. Haderle, president, Haderle Consulting LLC, Los Gatos, California. For contributions to the management of high-performance relational databases and leadership in founding the relational database-management industry.

J. Michael Harrison, Adams Distinguished Professor of Management, Stanford University, Stanford, California. For fundamental contributions to stochastic networks and financial engineering.

John L. Hudson, Wills Johnson Professor, Department of Chemical Engineering, University of Virginia, Charlottesville. For advances in the understanding and engineering of complex dynamic chemical-reaction systems.

Michael W. Hunkapiller, general partner, Alloy Ventures Inc., Palo Alto, California. For the invention and commercialization of DNA and protein sequencers and DNA synthesizers that have revolutionized comparative genetics and the mapping of the human genome.

Enrique Iglesia, Chancellor Professor, Department of Chemical Engineering, University of California, Berkeley. For outstanding contributions to the understanding of catalyst structure-function relationships, the development of novel catalysts, and leadership in the field of catalysis.

Jon M. Kleinberg, professor of computer science, Cornell University, Ithaca, New York. For contributions to the understanding of the structure and behavior of the World Wide Web and other complex networks.

Anthony David Kurtz, chairman and chief scientist, Kulite Semiconductor Products, Leonia, New Jersey. For the conception, development, and commercialization of the silicon semiconductor pressure transducer.

Burn-Jeng Lin, senior director, Nanopatterning Technology, Taiwan Semiconductor Manufacturing Company Ltd., Taiwan, Republic of China. For technical innovations and leadership in the development of lithography for semiconductor manufacturing.

Thomas Anthony Lipo, director, Wisconsin Power Electronics Research Center, University of Wisconsin, Madison. For contributions to the design and development of variable-speed drives and motor controls.

Alexis C. Livanos, president, Northrop Grumman Space Technology, Redondo Beach, California. For contributions to the development and insertion of advanced semiconductor technology for commercial and government space systems.

Michael J. Lockett, corporate fellow, Praxair Inc., Tonawanda, New York. For contributions to the theory and practice of distillation.

David G. Luenberger, professor, Department of Management Science and Engineering, Stanford University, Stanford, California.

For contributions to control theory, optimization algorithms, and economic dynamics.

Stephen Malkin, Distinguished Professor, Department of Mechanical and Industrial Engineering, University of Massachusetts, Amherst. For pioneering research in and the implementation of grinding-system simulation and optimization.

W. Allen Marr Jr., president and chief executive officer, Geocomp Corporation, Boxborough, Massachusetts. For innovative applications of numerical methods, risk analysis, advanced laboratory techniques, and field instrumentation to geotechnical engineering and construction.

John C. Martin, president and chief executive officer, Gilead Sciences Inc., Foster City, California. For the invention, development, and commercialization of anti-viral medicines, especially treatments for HIV/AIDS.

James A. Miller, Distinguished Member of the Technical Staff, Sandia National Laboratories, Livermore, California. For research on the theory and modeling of combustion chemistry that has led to universally applied codes for combustion modeling.

David L. Mills, professor, Electrical and Computer Engineering and Computer and Information Sciences, University of Delaware, Newark. For contributions to Internet timekeeping and the development of the Network Time Protocol.

Shree K. Nayar, T.C. Chang Professor of Computer Science, Columbia University, New York, New York. For the development of computational cameras and physics-based models for computer vision and computer graphics.

Chrysostomos L. (Max) Nikias, provost and senior vice president for academic affairs, University of Southern California, Los Angeles. For contributions to the development and diverse applications of adaptive signal processing, and for leadership in engineering education.

Malcolm R. O'Neill, independent consultant, Vienna, Virginia. For exceptional leadership and innovative management of national missile-defense programs and other high-profile military-technology capabilities.

Prabhakar Raghavan, senior vice president and head, Yahoo! Research, Santa Clara, California. For significant contributions to algorithms and the structure of the World Wide Web.

Yahya Rahmat-Samii, Northrop Grumman Professor, Department of Electrical Engineering, University of California, Los Angeles. For contributions to the design and measurement of reflector and handheld-device antennas.

Marc Raibert, president, Boston Dynamics Inc., Waltham, Massachusetts. For biomechanically motivated analysis, synthesis, control, and application of multilegged robots.

Bhakta B. Rath, head of Materials Science and Component Technology Directorate and associate director of research, Naval Research Laboratory, Washington, D.C. For leadership in advancing materials research and technology to support national security.

Rebecca Rae Richards-Kortum, Stanley C. Moore Professor and chair, Department of Bioengineering, Rice University, Houston. For research on the diagnosis and treatment of cancer in women, and for leadership in bioengineering education and global health initiatives.

Stephen M. Robinson, professor of industrial engineering and computer sciences, University of Wisconsin, Madison. For fundamental contributions to the theory of nonlinear optimization and to military planning.

Vladimir Rokhlin, professor of computer science and mathematics, Yale University, New Haven, Connecticut. For the development of fast multipole algorithms and their application to electromagnetic and acoustic scattering.

Thomas P. Russell, professor, Polymer Science and Engineering Department, University of Massachusetts, Amherst. For contributions to the processing of thin-block copolymer films to achieve well-organized nanostructures.

Robert F. Sawyer, Class of 1935 Professor of Energy Emeritus, Department of Mechanical Engineering, University of California, Berkeley. For pioneering work in reducing energy consumption and improving the environment, and for contributions to our understanding of air pollution.

James A. Sethian, vice chair for undergraduate affairs and professor, Department of Mathematics, University of California, Berkeley. For the development of efficient methods of tracking moving interfaces.

Paul H. Siegel, director, Center for Magnetic Recording Research, and CMRR Endowed Chair, Department of Electrical and Computer Engineering, University of California, San Diego, La Jolla. For the invention and development of advanced coding techniques for digital recording systems.

R. Paul Singh, professor, Biological and Agricultural Engineering Department, University of California, Davis. For innovation and leadership in food engineering research and education.

Kumares C. Sinha, Olson Distinguished Professor of Civil Engineering, Purdue University, West Lafayette, Indiana. For contributions to the advancement of highway infrastructure engineering and management and to the education of transportation professionals worldwide.

Richard L. Sites, software engineer, Google Inc., Mountain View, California. For leadership in using rigorous cost and benefit analyses in processor designs, and leadership in the development of binary translation technology.

Frans Spaepen, John C. and Helen F. Franklin Professor of Applied Physics, School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts. For contributions to the understanding of structures of melts, amorphous metals, and semiconductors.

Zhigang Suo, Allen E. and Marilyn M. Puckett Professor of Mechanics and Materials, School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts. For fundamental and applied contributions to the thermomechanical performance of electronic material systems, actuator materials, and composites.

David A. Tirrell, Ross McCollum-William H. Corcoran Professor and chair, Division of Chemistry and Chemical Engineering, California Institute of Technology, Pasadena. For pioneering contributions to bioengineered materials and the synthesis of novel artificial proteins.

David R. Walt, Robinson Professor of Chemistry, Tufts University, Medford, Massachusetts. For the development of revolutionary sensors that can simultaneously image and perform biochemical analyses.

Andrew M. Weiner, Scifres Distinguished Professor of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana. For contributions to the development of femtosecond optical-pulse shaping technology.

William W-G. Yeh, Distinguished Professor and chair, Department of Civil and Environmental Engineering, University of California, Los Angeles. For the development of methodologies for optimizing the management of water resources, and for inverse methods of estimating subsurface parameters.

Roe-Hoan Yoon, Nicholas T. Camicia Professor, Department of Mining and Minerals Engineering, Virginia Polytechnic Institute and State University, Blacksburg. For advancing the surface chemistry of mineral systems and developing new mineral processing technology and flotation kinetic models.

Yannis C. Yortsos, dean, Viterbi School of Engineering, University of Southern California, Los Angeles. For fundamental advances in fluid flow, transport, and reactions in porous media applied to the recovery of subsurface resources.

New Foreign Associates

Isamu Akasaki, professor, Meijo University, Nagoya, Japan. For contributions to the development of nitride-based semiconductor materials and optoelectronic devices.

Ann P. Dowling, professor and head of the division, Department of Engineering, University of Cambridge, Cambridge, United Kingdom. For advances in acoustics and unsteady flow, and for leadership in collaborative research between industry and universities.

Thomas W. Healy, professorial fellow, Department of Chemical and Biomolecular Engineering, University of Melbourne, Victoria, Australia. For contributions to mineral-water interfacial phenomena, their application to mineral processing, and leadership in industry-government-academic cooperation.

Akihisa Inoue, president, Tohoku University, Sendai, Japan. For outstanding achievements and international leadership in the design of advanced bulk metallic glasses and other metastable materials.

Alexander I. Leontiev, professor, Department of Thermogasdynamics and Gas Turbine Engines, Moscow State Technical University, Moscow, Russia. For contributions to the fundamental understanding of convective heat transfer, and for furthering international scientific cooperation.

Arthur John Robin Gorell Milner, Emeritus Professor, University of Cambridge, Cambridge, United Kingdom. For fundamental contributions to computer science, including the development of LCF, ML, CCS, and the pi-calculus.

Ekkehard Ramm, professor, Institute for Structural Mechanics, University of Stuttgart, Stuttgart, Germany. For contributions to the finite element analysis of plates and shells and leadership in computational mechanics.

Rutger Anthony van Santen, professor, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, Eindhoven, Netherlands. For pioneering work on the fundamentals of reaction mechanisms in heterogeneous catalysis.

Tadashi Watanabe, project leader, RIKEN, Tokyo, Japan. For contributions to the design and development of vector architectures for supercomputers.

NAE Newsmakers

Zdenek P. Bazant, McCormick Institute Professor and W.P. Murphy Professor of Civil Engineering and Materials Science at Northwestern University, has been elected a **foreign member** of the **Accademia Nazionale dei Lincei** (Italian National Academy) in Rome; the academy, of which Galileo was a member, was founded by the pope in 1603. Dr. Bazant is a member of four other national academies—National Academy of Sciences, National Academy of Engineering, Austrian Academy of Sciences, and Czech Engineering Academy.

John Junkins, George J. Eppright Distinguished Professor of Aerospace Engineering, Texas A&M University, was honored by the UCLA Henry Samueli School of Engineering and Applied Science. Dr. Junkins received the **2007 Alumni Achievement in Academia Award** in recognition of his outstanding contributions to engineering research and education.

Subhash Singhal, Battelle Fellow and director, Fuel Cells, Pacific Northwest National Laboratory, received the **2007 Fuel Cell Seminar and Exposition Award** during the plenary session of the seminar held in San Antonio, Texas. Dr. Singhal was honored for outstanding leadership and innovation in the promotion and overall advancement of fuel cell technology.

Wm. A. Wulf, University Professor and AT&T Professor of Engineering and Applied Sciences, Department of Computer Science, University of Virginia, and former NAE president, is the **first foreign corresponding member** of the **Venezuela Academy of Engineering**.

2007 Japan-America Frontiers of Engineering Symposium

Speaker Jennifer Elisseeff from Johns Hopkins University describes the engineering of human arteries.

The seventh Japan-America Frontiers of Engineering (JAFOE) Symposium was held on November 5, 6, and 7, 2007, at HP Labs in Palo Alto, California. Approximately 60 engineers, 30 from each country, attended the meeting, along with representatives of the Japan Science and Technology Corporation and the Engineering Academy of Japan (partners in the JAFOE program) and the National Science Foundation.

The five topics addressed at the 2007 meeting were: human-computer interaction, battery technologies, rocketry/aerospace, next-generation data centers, and materials for medicine. Japanese and American speakers described their cutting-edge research in these areas, such as voice-based, continuous control of electromechanical devices; recent advances in electrode materials in lithium-ion batteries; simulation of advanced rockets; recent advances in the environmental control of data centers; and the engineering of human arteries from "off-the-shelf" biomaterials.

In the dinner speech on the first evening, Dr. Stan Williams, HP Senior Fellow and founding director of the HP Quantum Science Research Group, described a new architecture for computing called "memristance." On the following afternoon, all of the participants had an opportunity to describe their technical work or research during a lively poster session, and on the second day, everyone was treated to tours of four HP labs: a data center and other labs dealing with nanoprint lithography; digital commercial printing; and Pluribus, a technology that combines multiple, inexpensive projectors to create a scalable "superprojector."

Glenn H. Fredrickson, Mitsubishi Professor of Materials and Chemical Engineering and director of the Mitsubishi Chemical Center for Advanced Materials at the University of California, Santa Barbara, and Kohei Itoh, professor in the Department of Applied Physics and Physico-Informatics at Keio University, cochaired the organizing committee and the symposium. Dr. Fredrickson, who completed his second term as U.S. cochair for JAFOE, will be succeeded by **Dr. Arup Chakraborty**, Robert T. Haslam Professor of Chemical Engineering at the Massachusetts Institute of Technology, who will co-chair the 2008 JAFOE Symposium on November 17, 18, and 19 in Tsukuba, Japan. The topics for that meeting will be advances in automation for biotechnology in health, natural language processing, alternative energy, and sensors.

Funding for the 2007 JAFOE Symposium was provided by the Japan Science and Technology Agency, National Science Foundation, Armstrong Endowment for Young Engineers, and National Academy of Engineering Fund.

NAE has hosted JAFOE meetings since 2000. Like the U.S.FOE meetings, German-American meetings (GAFOE), and India-U.S. meetings (Indo-U.S. FOE), JAFOE meetings bring together outstanding engineers (ages 35 to 45) from industry, academe, and government to share their experiences and describe exciting new developments, techniques, and approaches at the forefront of many areas of engineering. The meeting also facilitates contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series or to nominate an outstanding engineer to participate in a future FOE meeting, contact Janet Hunziker in the NAE Program Office at (202) 334-1571 or by e-mail at *jhunziker@nae.edu*.

Call for 2008–2009 Award Nominations

Traditionally, NAE has awarded five prizes (Founders Award, Arthur M. Bueche Award, Charles Stark Draper Prize, Fritz J. and Dolores H. Russ Prize, and Bernard M. Gordon Prize) for outstanding achievements in engineering. We invite you to help continue that tradition by nominating outstanding individuals for the 2008–2009 awards.

NAE Awards

The **Founders Award** is presented to an NAE member or foreign associate whose professional, educational, or personal achievements and accomplishments exemplify the ideals and principles of NAE. The recipient of the **Arthur M. Bueche Award** is an engineer who has been actively involved in determining U.S. science and technology policy, promoting U.S. technological development, and improving relations among industry, government, and academia. The Founders and Bueche awards are presented each fall at the NAE Annual Meeting. Recipients receive gold medallions, hand-lettered certificates, and $2,500 cash prizes.

The **Charles Stark Draper Prize** is awarded annually for innovation and reduction to practice of an advancement in engineering or technology that contributes to the welfare and freedom of humanity. The biennial **Fritz J. and Dolores H. Russ Prize** is awarded in recognition of an engineering achievement that has contributed to the advancement of the human condition. Currently focused on bioengineering, the Russ Prize encourages collaborations between engineers and the medical and biological disciplines. The **Bernard M. Gordon Prize for Innovation in Engineering and Technology Education** is given annually to honor educators whose programs have contributed to the quality of the engineering workforce. The focus is on innovations in curricular design, teaching methods, and technology-enabled learning. The Gordon Prize is shared equally between the recipient(s) and the institution. The Draper, Russ, and Gordon prizes, which include $500,000 cash awards, gold medallions, and hand-lettered certificates, are presented during National Engineers Week at the NAE Annual Awards Dinner. Nominators of the winning recipients are also invited to attend.

To Submit a Nomination

Nominations for the 2008 Founders and Bueche awards and the 2009 Draper and Gordon prizes will be accepted through April 4, 2008. A list of previous recipients can be found on our web site (*www.nae.edu/awards*). Members and foreign associates have received nomination materials by mail. Nonmembers may obtain materials from the NAE Awards Office by calling (202) 334-1628 or sending an e-mail to *awards@nae.edu*. Nomination materials can also be downloaded from our web site (*www.nae.edu/awards*).

Nominations should be mailed to NAE Awards, National Academy of Engineering, 500 Fifth Street, N.W. (#1048), Washington, DC 20001, or faxed to (202) 334-2290.

Mirzayan Science and Technology Policy Fellows

Jessica Buono

Ana Ferreras

Shelby Perkins

Rafi Soulé

Michael Tomlinson

Greta Zornes

We are happy to introduce six new Mirzayan Science and Technology Policy Fellows who joined NAE in January.

Jessica Buono is currently pursuing a master's in public health in epidemiology at George Washington University. She received a B.S. in behavioral neuroscience from Lehigh University, where her research was focused on specialized properties of neurons in the brain and their functional relationships in both biology and psychology. Jessica plans to pursue a career in health research at the National Institutes of Health.

Since moving to Washington, D.C., Jessica has conducted research on issues in health policy ranging from traumatic brain injury to diabetes. As a Mirzayan fellow she hopes to learn more about the policy behind the science in her studies. She is working with the Committee on Women in Science, Engineering, and Medicine of the Policy and Global Affairs Division on projects involving women in science and interdisciplinary health careers. In addition, she is conducting research in the NAE Program Office for a study on using systems engineering tools and techniques to improve the quality of military health care, particularly for patients with traumatic brain injuries. Her goals are to learn to write efficiently about policy as it relates to health and scientific research and to communicate effectively about science to raise the level of public understanding.

Ana M. Ferreras is currently completing her Ph.D. in industrial engineering (IE) at the University of Central Florida (UCF). For her doctoral research, she is developing a company-success index model to assess and predict organizational performance based on critical factors, such as profit, productivity, efficiency, quality, employee morale, safety, and ergonomics. She holds an M.S. in engineering management from the Florida Institute of Technology and a B.S. in electrical engineering from UCF. Along with her doctoral research, Ana has assisted in the reengineering of the undergraduate IE curriculum at UCF, taught courses on quality engineering, and written proposals for the development of educational programs consistent with the skills identified in the *Engineer of 2020* reports. While at NAE, Ana is working at CASEE on using the World Wide Web as a platform for delivering and assessing innovative content for engineering faculty and students.

Ana holds a Six-Sigma Black Belt and enjoys certifying other students working to improve processes and systems for community nonprofit organizations and government agencies. Her career goal is to improve the quality of engineering education in academic institutions to help the United States maintain its leadership role. In her free time, she enjoys making pottery, attending theater performances, designing clothes, traveling, dancing, snorkeling, and reading.

Shelby Perkins completed her J.D. and master's degree in environmental law at Vermont Law School. After becoming a member of the New Mexico Bar, she practiced nuclear waste law as an attorney for the U.S. Department of Energy (DOE), where her work was focused mostly on the preparation of the natural-systems portions of DOE's Yucca Mountain construction permit application to the Nuclear Regulatory Commission. In addition, she worked on environmental, regulatory, and budgetary issues concerning the U.S. nuclear weapons complex.

In 2006, Shelby traveled to Antarctica, where she was inspired to expand her study of environmental policy to include human impacts on the environment. She plans to continue to diversify her career experience in handling policy issues related to science and technology.

During her Mirzayan Fellowship, Shelby is working with Rachelle Hollander, director of the Center on Engineering, Ethics, and Society. Shelby works with an advisory group to develop studies of ethical and societal issues associated with emerging technologies and collective professional responsibility.

Rafi Soulé, a graduate student at George Washington University, expects to complete her M.S. in systems engineering/project management in May 2008. Her graduate research involves the development of policies for fighting the spread of the Ebola virus in central Africa. She has also worked on using systems engineering tools for the requirements of the U.S. "VIP Gunfire Protection System," particularly for the deployment and testing of the shield system

Rafi also has a B.S. in finance from the State University of New York in Plattsburgh and an A.S. in business administration and management from Clinton Community College. Throughout her studies, Rafi has been interested in the intersection between microbusiness and macroeconomic factors in international markets and systems development and integration. She has been a member of Phi Theta Kappa, an international honors society, since 2003.

Rafi's career goal is to work on governmental risk-management systems and international systems-management projects. At CASEE, she is looking into the impediments and enablers of student transfers from community colleges to baccalaureate engineering programs at liberal arts colleges. She enjoys playing Scrabble and tennis, reading, traveling, and debating current issues.

Michael Tomlinson earned his Ph.D. in chemical and biomolecular engineering from North Carolina State University in 2005. His postgraduate research was focused on modifying surfaces with end-tethered macromolecules, also known as polymer brushes. Specifically, he developed combinatorial methods for quick verification of previous brush theory and investigation of the morphological characteristics of multiblock brush surfaces.

During his postgraduate years, Michael served on the leadership committee for the Self Knowledge Symposium, a nonprofit student organization that promotes "authentic living." After graduation, he joined the PolyFilm Network (an EU-funded Marie Curie Research Training Network); based at the University of Sheffield in England, he conducted research on pH-responsive polyelectrolyte brushes, specifically using neutron reflectometry to study interfaces between reversibly adhesive polyelectrolyte surfaces. During his three years in Europe, he met people from around the world and spent his leisure time hiking through historical and natural sites. His passions include teaching, learning, and traveling.

Michael's project at CASEE is to review the literature on linkages between asserted and actual faculty instructional behavior. This work is related to two projects supported by the National Science Foundation—the development of an assessment of student and faculty engagement in engineering education and the development of metrics of instructional scholarship.

Greta Zornes recently completed her Ph.D. in environmental health sciences at Tulane University in New Orleans. Her doctoral research was on the status and potential of water reuse in Hyderabad and Delhi, India. She received her M.S. in environmental engineering from Manhattan College in 2000, where her research was on biofilm formation in drinking water systems. Her undergraduate studies in environmental science at the University of Oklahoma included a year at the University of Dundee, Scotland.

Greta has completed internships with the World Health Organization in India and with the Socio-Economic Union in Russia; she is currently employed as an engineering consultant with CH2M HILL. Her goal is to work on international water/wastewater/water reuse issues, particularly policies and programs that affect water and wastewater management. Greta is active in Engineers Without Borders and is currently involved in a project in the community of Amayo, Nicaragua.

During her Mirzayan fellowship, Greta is working with the Diversity in the Engineering Workforce Program supporting the *EngineerGirl!* and "Engineer Your Life" web sites.

A Message from NAE Vice President Maxine L. Savitz

Maxine L. Savitz

Private philanthropy enables the National Academies to bring together experts to address multidimensional questions that underlie our country's most urgent concerns. One example is the privately funded 2005 report *Rising Above the Gathering Storm*, which influenced the America COMPETES Act. Donations by members, and support from foundations and corporations, make it possible for us to produce critical studies like this in the absence of government funding.

As questions regarding our nation's energy future mount, NAE has assumed the leadership role for America's Energy Future: Technology Opportunities, Risks, and Tradeoffs, an academies-wide project to explore the role of energy in long-term U.S. economic vitality, national security, and environmental quality. The purpose of the project is to provide a sound, factual basis to inform policy decisions that will affect us locally and nationally and impact the global community. On March 13 and 14, the academies sponsored the National Academies Summit on America's Energy Future. The summit was attended by leading thinkers from the private sector, universities, and government agencies with different points of view on energy issues.

The engagement of NAE's corporate partners, which include Dow Chemical Company, GE Energy, General Motors, and Intel, has been critical to launching the America's Energy Future project. The NAE Development Committee was instrumental in securing funding from these partners, each of which has committed $300,000 to the project. We are very fortunate to have also received support from several foundations and government agencies.

In addition to our leadership in the America's Energy Future project, NAE continues to seek and receive funding for other initiatives. To honor past NAE president Wm. A. Wulf, members, friends, foundations, and corporations have contributed $6.3 million to the Wulf Initiative. The purpose of the initiative is to help ensure that current academy leaders have the resources they need to lead the academy into the future.

On behalf of the NAE Council, I wish to thank all of our members and the organizations, corporations, foundations, government sponsors, and friends of NAE who have provided generous support for NAE programs. Their donations enable us to address proactively issues that are critical to the technological welfare of our nation.

Maxine L. Savitz
NAE Vice President

National Academy of Engineering

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America's Energy Future: Technology Opportunities, Risks, and Trade-offs

NAE took the lead in initiating and funding a major new inter-academy study on America's energy future, a critical factor in the vitality of the U.S. economy, national security, environmental quality, and quality of life. The rising global demand for energy from continued population and economic growth, especially in developing countries; the vulnerabilities of energy supplies to political instabilities and terrorism; limited energy resources, especially oil; growing global concerns about emissions of greenhouse gases from the burning of fossil fuels, which currently supply most of the world's energy; questions about the adequacy of investments in the infrastructure and technologies necessary to develop alternate energy sources; and concerns about the large-scale deployment of some alternate energy sources, such as nuclear power, have combined to create a sense of urgency about America's energy future and the government policies that affect it.

Although a number of studies have been published in recent years exploring technology options for energy, their conclusions often conflict, reflecting disagreements about the potential of these technologies, particularly biomass energy, renewable electric power-generating technologies, nuclear power, and advanced coal technologies. The nation sorely needs an up-to-date, credible analysis of technology options, costs, and impacts as a basis for making sensible decisions about our energy future that take into account competing national priorities and interests, such as (1) reducing dependence on imported oil; (2) ensuring that abundant, affordable energy is available; and (3) reducing emissions of carbon dioxide.

After discussions with leaders and experts from across the spectrum, including very senior representatives of industry, academia, and government and members and staff of all of the academies partners, the National Academies initiated the America's Energy Future (AEF) project to inform the national debate. The study will provide authoritative estimates of current and potential contributions of existing and new energy technologies to meet both supply and demand, as well as associated impacts and projected costs. The study will anchor a portfolio of follow-on studies at the academies and elsewhere related to energy research and development, strategic energy technologies, policy analysis, and related subjects.

As part of the project, the academies hosted the National Academies Summit on America's Energy Future on March 13 and 14 to stimulate discussion among experts with different points of view. Leaders in energy policy from government, research institutions, and the private sector addressed three major themes—energy security, energy and the economy, and energy and the environment. Their presentations included overviews of recent major studies by the National Petroleum Council, Council on Foreign Relations, National Commission on Energy Policy, the Interacademy Council, and others.

The 25 members of the AEF study committee are experts on all aspects of the issues and represent all of the major interested parties. Three independent panels have been organized to investigate and publish separate reports on three classes of technologies—energy efficiency, alternative transportation fuels, and renewable electric power generating technologies—about which there are considerable uncertainties and disagreements. The final report is expected to be published by the end of 2008.

"News and Terrorism: Communicating in a Crisis" Workshops

NAE began a new series of "News and Terrorism: Communicating in a Crisis" interactive workshops in January 2008. On January 17, the first event of the new series was held in Charlotte, North Carolina, and additional workshops are being planned around the country throughout the year. The NAE Program Office produces these workshops in collaboration with the Radio and Television News Directors Foundation and the U.S. Department of Homeland Security.

At each workshop, local reporters, government officials, and engineers and scientists participate in a terrorism or disaster scenario exercise focused specifically on their region. Because large organizations will be significant sources of information for their employees, the current series of workshops also includes representatives of the private sector. As scenarios unfold, panelists from each community enact their particular roles, bringing to light concerns and responsibilities. After the scenarios, workshop attendees break into small groups where they analyze the handling of events and discuss how they can improve their preparation for terrorist events or disasters.

For more details or information on future workshops, please e-mail Randy Atkins at <*atkins@nae.edu*>. As part of the project, the National Academies has produced fact sheets on biological, chemical, nuclear, and radiological attacks. Fact sheets are available in PDF format at <*http://www.nae.edu/factsheets*>.

China/U.S. Air Pollution Study

A joint study by NAE and the Policy on Global Affairs Division of the National Research Council (NRC) is the latest phase of an ongoing project with the Chinese Academies of Science and Engineering. As the number of economic, scientific, and technical issues common to China and the United States increases, exchanges of information are becoming increasingly important to both countries. A case in point is China's current efforts to secure energy concessions from countries around the world to ensure its supply of transportation fuel for a burgeoning vehicle fleet. In addition, China's energy decisions will have regional and global implications.

China's most secure form of energy is indigenous coal, which provides much of the power for its electricity, urban heating, and cooking. However, air pollution from burning coal has had severe detrimental effects on public health and the nation's biota and water resources. Economists have determined that air pollution has also slowed the growth of China's GDP. In recent energy and air-quality policies, China acknowledges the effects of pollution from coal, but leaves the implementation of these policies largely to local leaders.

In 2007, a committee of Chinese and U.S. experts, led by Dr. John Watson, a researcher on air quality at the University of Nevada Desert Research Institute, completed a consensus study on the energy and air pollution challenges facing both countries. The report details the situation in four cities—Los Angeles, Pittsburgh, Dalian, and Huainan. A prepublication version released in September 2007 received widespread press coverage in China and the United States. The final report was released in January 2008 (the Chinese translation is expected in February 2008).

In November, delegates from the U.S. committee traveled to China to attend joint workshops and discuss the findings and recommendations. Mayors, environmental managers, and researchers representing both national and local interests participated in discussions in Beijing, Huainan, and Tianjin. During the meetings, the U.S. and Chinese academies agreed, in principle, to conduct a follow-on study on wind, solar, and biomass energy.

Building on an ongoing NRC project, America's Energy Future, the proposed follow-on study would provide an assessment of resource potential in China, explore near-term market opportunities for inter-country technology transfer, and recommend priorities for future collaborations on cost reductions, efficiency improvement, grid connectivity, and energy storage.

Proctor Reid, director of the NAE Program Office, and Derek Vollmer, senior program associate, Policy and Government Affairs Division, participated in the November workshops.

Launch of the *Engineer Your Life* Web Site

On February 20, NAE hosted the official launch of *Engineer Your Life* (*http://www.engineeryourlife.org*), a web site that encourages high school girls with the necessary academic background to enroll in undergraduate engineering programs. The web site is part of a nationwide effort to inform high school girls, and the adults in their lives, about the professional and personal aspects of engineering.

Engineer Your Life provides a forum where high school girls can "meet" young women engineers and learn about their careers. Twelve women tell inspiring stories about working in communities to solve real problems and explain why they chose to pursue engineering careers. The site also provides descriptions of 11 fields of engineering, a wide range of engineering projects, information about starting salaries and resources, and videos of young engineers describing their careers. A third section provides information about how to prepare for a college engineering program, including which classes to take in high school; descriptions of the personal experiences of engineering students; and information about choosing an engineering program. In addition, the site provides resources and training on advising students about engineering careers for parents, counselors, teachers, and other educators

Engineer Your Life™ is a production of WGBH Educational Foundation and NAE in partnership with the Extraordinary Women Engineers Coalition. The Engineer Your Life web site is part of NAE's ongoing commitment to diversifying the engineering workforce. The new site complements material on other NAE web sites, such as *EngineerGirl!* (*http://www.engineergirl.org*), a site designed specifically for girls in middle school.

Major funding for the *Engineer Your Life* project is provided by the National Science Foundation and Northrop Grumman Foundation. Additional funding is provided by Stephen D. Bechtel Jr. and the United Engineering Foundation.

Grand Challenges for Engineering in the 21st Century

In 2006, the National Science Foundation asked NAE to convene an international group of leading thinkers for the purpose of developing a list of grand challenges for engineering in the 21st century. Information about the 18-member blue-ribbon committee, chaired by former U.S. Secretary of Defense William J. Perry, can be found at *www.engineeringchallenges.org*. Early last year, the committee invited NAE members, engineering societies, and the worldwide public to contribute ideas. So far, people in more than 40 countries have responded.

The goal of the Grand Challenges Project is not to make predictions but to identify what we need to do to help people everywhere and to keep our planet healthy. The overall goal is to increase public awareness and stimulate discussion about global challenges and how they can be addressed through engineering. These discussions might ultimately inspire policy makers to recognize the importance of engineering in addressing these major issues.

On February 15, 2008, the committee announced its conclusions at a news conference at the American Association for the Advancement of Science annual meeting and on the Grand Challenges website (*www.engineeringchallenges.org*), where the public can vote on which items should be included in the final list of 14 challenges. The committee has not ranked the challenges, and findings are not meant to be comprehensive or specific about particular approaches.

The committee believes the 14 challenges should be realistically addressable by the end of this century, at the latest, and that overcoming any one of them would dramatically improve life on Earth.

Calendar of Meetings and Events

March 1–31	Annual election of officers and councillors
April 2	NAE Regional Meeting California Institute of Technology, Pasadena, California
April 9	Governing Board Executive Committee Meeting
April 10	NAE Regional Meeting University of Wisconsin, Madison, Wisconsin
April 23	NAE Regional Meeting Arizona State University, Tempe, Arizona
April 24–27	German-American Frontiers of Engineering Symposium Beckman Center, Irvine, California
May 1	NAE Regional Meeting IBM, Yorktown Heights, New York
May 5–6	NAE Convocation of Professional Engineering Societies
May 6–7	NRC Governing Board Meeting
May 8–9	NAE Council Meeting Annapolis, Maryland
June 12	NRC Governing Board Meeting
June 20	NAE/NAEF Audit Committee Meeting

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

In Memoriam

STEVEN F. CLIFFORD, 64, Senior Research Scientist Emeritus, University of Colorado, died on September 18, 2007. Dr. Clifford was elected to NAE in 1997 "for contributions to the understanding of electromagnetic and acoustic propagation in random media, leading to the development of new sensing techniques."

C. ALLIN CORNELL, 69, Professor Emeritus, Department of Civil and Environmental Engineering, Stanford University, died on December 14, 2007. Dr. Cornell was elected to NAE in 1981 "for the development of practical methods for application of probability to structural and earthquake engineering."

GENE H. GOLUB, 75, Fletcher Jones Professor of Computer Science, Computer Science Department, Stanford University, died on November 16, 2007. Dr. Golub was elected to NAE in 1990 "for contributions in developing and analyzing robust and stable numerical algorithms used in solving complex engineering problems."

SERGE GRATCH, 86, Professor Emeritus, Kettering University, died on December 4, 2007. Dr. Gratch was elected to NAE in 1983 "for contributions to the thermodynamic properties of gases, development of successful automotive exhaust control systems, and utilization of alternative fuels."

DONALD R. HERRIOTT, 79, retired head, Lithographic Systems Department, AT&T Bell Laboratories, died on November 8, 2007. Mr. Herriott was elected to NAE in 1982 "for the invention of the helium-neon laser, and inventions and development of lithographic systems for integrated circuit fabrication."

DAVID N. KENNEDY, 71, consulting engineer, died on December 23, 2007. Mr. Kennedy was elected to NAE in 1998 "for planning and management of water resources."

HERBERT J.C. KOUTS, 88, retired board member, Defense Nuclear Facilities Safety Board, died January 7, 2008. Dr. Kouts was elected to NAE in 1978 "for contributions in nuclear engineering, especially physical principles and safety of nuclear power reactors and nuclear materials safeguards."

JOHN H. MCELROY, 76, Dean of Engineering Emeritus, University of Texas at Arlington, died on September 14, 2007. Dr. McElroy was elected to NAE in 1998 "for the development and applications of laser technology to space-based geodesy, atmospheric science, and communications."

DANIEL A. OKUN, 90, Kenan Professor of Environmental Engineering Emeritus, University of North Carolina, died on December 10, 2007. Dr. Okun was elected to NAE in 1973 "for innovative contributions to sanitary engineering and to teaching and research."

COURTLAND D. PERKINS, 95, past president, National Academy of Engineering, died on January 6, 2008. Dr. Perkins was elected to NAE in 1969 "for leadership in the fields of airplane stability and control and airplane dynamics."

CHARLES ELI REED, 94, retired senior vice president, General Electric Company, died on November 16, 2007. Dr. Reed was elected to NAE in 1969 "for his engineering accomplishments in blending scientific, technological, and commercial elements to the production of man-made diamonds, new silicones, commercialization of oxidative technology in the form of lexan polycarbonates and the plant design and process developments accompanying these new materials."

DAVID SLEPIAN, 84, retired head, Mathematical Studies Department, Bell Laboratories, Lucent Technologies, died on November 29, 2007. Dr. Slepian was elected to NAE in 1976 "for contributions to the elucidation of fundamental limits that apply to the processes of communications, signal detection, and data extraction."

J. EDWARD SNYDER JR., 83, retired oceanographer, U.S. Navy, died on November 4, 2007. Rear Adm. Snyder was elected to NAE in 1979 "for contributions to the Polaris missile reentry systems and to the National Oceanographic Program."

PETER STAUDHAMMER, 73, retired vice president, Science and Technology, TRW Inc., died on January 14, 2008. Dr. Staudhammer was elected to NAE in 1996 "for engineering achievements in space systems, plasma and microwave processes, remote sensing, instrumentation, and their application to commercial systems."

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055. For more information or to place an order, contact NAP online at <*http://www.nap.edu*> or by phone at (888) 624-8373. *(Note: Prices quoted are subject to change without notice. Online orders receive a 20 percent discount. Please add $4.50 for shipping and handling for the first book and $0.95 for each additional book. Add applicable sales tax or GST if you live in CA, DC, FL, MD, MO, TX, or Canada.)*

Frontiers of Engineering: Reports on Leading-Edge Engineering from the 2007 Symposium. U.S. Frontiers of Engineering (USFOE) symposia bring together 100 outstanding engineers (ages 30 to 45) to exchange information about leading-edge technologies in a range of engineering fields. The 2007 symposium covered the engineering of trustworthy computer systems, control of protein conformations, biotechnology for fuels and chemicals, the modulation and simulation of human behavior, and safe water technologies. Papers in this volume describe leading-edge research on disparate tools in software security, decoding of the "mechanome," corn-based materials, modeling of human cultural behavior, water treatment by UV irradiation, and many other topics. A speech by dinner speaker Dr. Henrique (Rico) Malvar, managing director of Microsoft Research, is also included. Appendixes provide information about contributors, the symposium program, summaries of break-out sessions, and a list of participants. This is the thirteenth volume in the USFOE series.

NAE member **Julia M. Phillips**, director, Physical, Chemical, and Nano Sciences Center, Sandia National Laboratories, chaired the symposium organizing committee. Paper, $46.00.

Energy Futures and Urban Air Pollution: Challenges for China and the United States. This bilateral report summarizes current trends in combating air pollution in urban areas, profiles two U.S. and two Chinese cities, and recommends measures to help both countries improve urban air quality. The study committee, formed by the National Research Council and National Academy of Engineering in cooperation with the Chinese Academy of Sciences and Chinese Academy of Engineering, concludes that China can learn specific lessons from the successes and failures of U.S. efforts. The overarching conclusion, however, is that both countries must improve energy efficiency in power generation, transportation, and other economic sectors.

NAE member **Glen T. Daigger**, senior vice president and chief technology officer, CH2M Hill Inc., was a member of the study committee. Paper, $76.25.

Water Implications of Biofuels Production in the United States. Rapidly increasing production of corn-based ethanol in the United States and prospects for the next generation of biofuels have raised concerns about the impact on water resources. This report, based in part on a colloquium held in 2007, concludes that water quality could be considerably compromised as the result of soil erosion and increases in the use of fertilizers and pesticides. Water supplies could also be overstressed by requirements for growing biofuel crops and supplying water to ethanol-processing plants, especially in areas where water supplies are already stressed. "Cellulosic ethanol" is expected to have less impact on water quality but cannot yet be produced on a commercial scale. The study committee concludes that a policy bridge may be necessary to encourage the development of new technologies, the use of best agricultural practices, and the development of crops for fuel production that require less water and fertilizer.

NAE members on the committee were **Jerald L. Schnoor** (chair), Allen S. Henry Chair Professor, Department of Civil and Environmental Engineering, University of Iowa, and **Edward A. Hiler**, Ellison Chair in International Floriculture, retired, Texas A&M University. Paper, $18.00.

Condensed-Matter and Materials Physics: The Science of the World around Us. The development of the transistor, integrated circuit, liquid-crystal display, and even the DVD player can be traced back to fundamental research in the field of condensed-matter and materials physics (CMMP). Although the United States has been a leader in CMMP, that status is now in jeopardy. This report, part of the Physics 2010 decadal survey project, assesses the present status of the United States; suggests directions for the 21st century; identifies scientific challenges for American researchers in the areas of energy demand, the physics of life, information technology, nanotechnology, complex phenomena, and behavior far from equilibrium; and recommends allocation priorities for federal funds.

NAE members **Mildred S. Dresselhaus**, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology, and **William J. Spencer**, Chairman Emeritus, SEMATECH, were cochairs of the study committee. Paper, $52.00.

New Directions for Understanding Systemic Risk. The vulnerabilities of the financial system to systemic events have long been critical issues for central bankers and researchers. Recent world events and the growing complexity of the financial system suggest that older models of countering systemic shock might not be able to address future disturbances. To assess these concerns, the Federal Reserve Bank of New York and the National Research Council cosponsored a conference to bring together engineers, scientists, economists, and experts in financial markets to discuss systemic risk in a variety of fields. The conference discussions addressed: tools used in ecology and engineering to study systemic collapses; trends in research on systemic risk in the economy, payment systems, and the market of interbank funds; and the effects of systemic risk on trade.

NAE member **Elisabeth Paté-Cornell**, Burt and Deedee McMurty Professor, and chair, Management Science and Engineering, Stanford University, was a member of the conference oversight committee. Paper, $31.00.

Plasma Science: Advancing Knowledge in the National Interest. The U.S. Department of Energy, National Science Foundation, and National Aeronautics and Space Administration asked for an assessment (as part of Physics 2010, a decadal survey) and outlook for plasma science and engineering for the next several years. The study reviews progress in plasma research, identifies the most promising and important scientific opportunities, evaluates prospects for new applications of plasmas, and offers guidance for realizing these opportunities. The study committee adopted a "demand-side" perspective to emphasize how plasma research can contribute to meeting national goals, such as the development of fusion energy, improving economic competitiveness, and reinforcing stewardship of the nuclear weapons stockpile. The report covers low-temperature plasma science and engineering, plasma physics at high energy density, plasma science of magnetic fusion, space and astrophysical science, and basic plasma science.

NAE members **James D. Callen**, Donald W. Kerst Professor Emeritus of Engineering Physics and Physics, University of Wisconsin, Madison, and **Erich P. Ippen**, Elihu Thomson Professor of Electrical Engineering and professor of physics, Massachusetts Institute of Technology, were members of the study committee. Paper, $38.00.

Approaches for Evaluating the NRC Resident Research Associateship Program at NIST. The National Research Council Resident Research Associateship Program at the National Institute of Standards and Technology (NIST) provides two-year appointments for outstanding scientists and engineers. This report includes descriptions of program applicants and awardees and offers suggestions for an in-depth assessment of career outcomes. Preliminary investigation indicates that outreach efforts have attracted more qualified applicants than NIST can accommodate, the pool of applicants is becoming increasingly diverse, and many Research Associates go on to permanent positions at NIST. The assessing committee suggests that the agency conduct a thorough evaluation of the program, including outreach to potential applicants, individuals who decline awards, the program's impact on the careers of awardees, and the benefits of the program to NIST and the larger scientific and engineering community.

NAE member **Isaac C. Sanchez**, William J. Murray Endowed Chair in Engineering, Department of Chemical Engineering, University of Texas, Austin, chaired the study committee. Paper, $39.50.

Technical Input on the National Institutes of Health's Draft Supplementary Risk Assessments and Site Suitability Analyses for the National Emerging Infectious Diseases Laboratory, Boston University: A Letter Report. The state of Massachusetts requested that the National Research Council (NRC) evaluate a draft supplemental risk assessment prepared by the National Institutes of Health (see *http://www.nems.nih.gov/aspects/nat_resources/programs/nepa2.cfm*) for a proposed biocontainment laboratory at Boston University. The risk assessment is intended to provide a scientific basis for an environmental impact report requested by the state. The NRC committee concludes that the draft assessment does not adequately develop worst-case scenarios or provide comparisons with alternative sites in case of the release and spread of a pathogen. A more acceptable analysis would include agents that are readily transmissible and would demonstrate that the models used take into account biological complexities, reflect what is known about outbreaks of disease, and take into account population density.

NAE member **John F. Ahearne**, director, Ethics Program, Sigma Xi Center, Sigma Xi, The Scientific Research Society, chaired the study committee. Free PDF.

Human-System Integration in the System Development Process: A New Look. This report focuses on how human capabilities can be integrated into system design using an incremental model of systems engineering that continually assesses risks, including risks associated with human participation, at each phase of development. Chapters focus on methods of describing human capacities and limitations; needs, tasks, and work environments; and methods of characterizing and evaluating designs. As systems become more complex and the focus shifts from the design and operation of individual systems to systems of systems, new methods and approaches will be necessary.

NAE member **Barry W. Boehm**, TRW Professor of Software Engineering, University of Southern California, was a member of the study committee. Hardcover, $59.00

Countering the Threat of Improvised Explosive Devices: Basic Research Opportunities, Abbreviated Version. Attacks in London, Madrid, Bali, Oklahoma City, and elsewhere have demonstrated that improvised explosive devices (IEDs) are weapons of choice for terrorists. Scientists and engineers have developed technologies to counter individual IED attacks, but events in Iraq and elsewhere have shown that IEDs remain effective weapons of asymmetric warfare. The Office of Naval Research asked the National Research Council to examine the current state of knowledge and practice in the prevention, detection, and mitigation of the effects of IEDs and to recommend areas for research for mitigating their effectiveness. The recommendations in this study include identifying the most important and most vulnerable elements in the chain of events leading up to an IED attack, determining how resources can be controlled to prevent the construction of IEDs, using new analytical methods and data modeling to predict the behavior of insurgents/terrorists, improving the understanding of social divisions in societies, improving surveillance capabilities, and improving IED detection.

NAE member **John L. Anderson**, provost and university vice president, Case Western Reserve University, chaired the study committee. NAE members **Edward H. Kaplan**, William N. & Marie A. Beach Professor of Management Sciences, professor of public health, and professor of engineering, Yale School of Management, and **Alexander MacLachlan**, retired senior vice president, research and development, E.I. du Pont de Nemours & Co., were members of the study committee. Paper, $15.00.

Proceedings of a Workshop on Statistics on Networks. Knowing how complex networks in biological, physical, and social systems operate is critical to a general understanding of network behavior. Each of these disciplines has developed its own statistical theories for inferring network data. To improve overall understanding, the National Research Council sponsored a workshop to bring together researchers who deal with network data in these various contexts. This report—which is available only on CD—includes the texts of 18 workshop presentations focused on five major areas of research: network models, dynamic networks, data and measurement of networks, robustness and fragility of networks, and visualization and scalability of networks.

NAE members on the study committee were **Thomas M. Cover**, Kwoh-Ting Li Professor of Engineering and professor of electrical engineering and statistics, Stanford University, and **Michael Lesk**, professor, Rutgers, The State University of New Jersey. CD, $90.50.

Prospective Evaluation of Applied Energy Research and Development at DOE (Phase Two). Since the passage of the Government Performance and Results Act and other mandates, federal agencies have been required to measure their performance. At the request of Congress, the National Research Council has undertaken a series of studies to provide quantitative evaluations of the effectiveness of research and development (R&D) on applied energy at the U.S. Department of Energy. This third report in the series provides the results of an assessment (based on a benefits-evaluation methodology developed in the second study) to evaluate six R&D programs: carbon sequestration, integrated gasification combined-cycle technology, natural gas exploration and production, distributed energy resources, light-duty vehicle technology, and chemical industrial technologies. The report also includes explanations of improvements in the methodology, such as the addition of indicators of environmental and security benefits, and refinements of the evaluation process based on case studies. Finally, an appendix to the report provides a detailed analysis of each of the six programs.

NAE members on the study committee were **Maxine L. Savitz** (chair), retired general manager, Technology/Partnerships, Honeywell Inc., and **Wesley L. Harris**, department head and Charles Stark Draper Professor, of Aeronautics and Astronautics, Massachusetts Institute of Technology. Paper, $50.50.

Core Competencies for Federal Facilities Asset Management through 2020: Transformational Strategies. In the face of shrinking budgets, an aging workforce, and rising costs, the U.S. government must find new ways to manage federal facilities and infrastructure. This fourth study by the Federal Facilities Council of the National Research Council focuses on the people and skills necessary to managing federal facilities in the next decade and beyond. The report includes a description of the current environment for facilities management, an analysis of the forces affecting federal facilities asset management, an assessment of the core competencies necessary, a comprehensive strategy for workforce development, and recommendations for implementing that strategy.

NAE members on the study committee were **David J. Nash** (chair), president, BE&K Government Group, and **Richard L. Tucker**, Joe C. Walter Jr. Chair in Engineering Emeritus, University of Texas. Paper, $29.00.

The Role of Theory in Advancing 21st Century Biology: Catalyzing Transformative Research. Theoretical and conceptual frameworks inform every step of biological research, including which experiments are undertaken, which techniques and technologies are developed, and how data are interpreted. At the request of the National Science Foundation, this report by a committee of experts examines the question of whether more emphasis on theory would advance biological research. The committee concludes that, although theory is already inextricably involved, explicitly stating that theory has equal status with other aspects of biological research could catalyze transformative research that might lead to creative, dynamic, and innovative advances in our understanding of life.

NAE member **Leroy E. Hood**, president, Institute for Systems Biology, was a member of the study committee. Paper, $45.00.

Identification of Research Needs Relating to Potential Biological or Adverse Health Effects of Wireless Communication Devices. In recent years the use of wireless communication devices has increased dramatically, and a great deal of research has been done on possible biological or human health effects resulting from their use. The U.S. Food and Drug Administration asked the National Research Council to organize a workshop to identify research needs and gaps in knowledge in the areas of dosimetry and exposure, epidemiology, human laboratory studies, mechanisms, and animal and cell biology. The workshop did not include the evaluation of health effects or provide recommendations for how identified research needs should be met. Research needs identified at the workshop include: (1) characterization of exposures in juveniles, children, fetuses, and pregnant women to wireless devices and radio frequency base station antennas; and (2) evaluation of the effect of devices based on newer technologies (e.g., texting, web surfing).

NAE member **Frank S. Barnes**, Distinguished Professor, Department of Electrical and Computer Engineering, University of Colorado at Boulder, chaired the study committee. Paper, $21.00.

Manpower and Personnel Needs for a Transformed Naval Force. Advances in science and technology will be critical to efforts by the U.S. Department of Defense (DOD) to transform the armed services to meet future military challenges. Changes resulting from new technologies have already highlighted the need for changes in personnel policies. To assist the Navy in defining these changes, the National Research Council was asked to review the military manpower and personnel policies and studies currently underway at DOD and to develop a strategy for the Navy's future manpower and personnel needs. This report provides an introduction to current personnel policies and concerns; an assessment of demographic, technological, and other aspects of future personnel needs and availability; summaries and assessments of previous studies; a discussion of the need for research on implementing changes in personnel policy; and an analysis of obstacles to and strategies for transforming the naval force.

NAE members **Barry M. Horowitz**, professor of systems engineering, University of Virginia, and **John B. Mooney Jr.**, J. Brad Mooney Associates Ltd. and U.S. Navy retired, were members of the study committee. Paper, $39.50.

Research Priorities in Emergency Preparedness and Response for Public Health Systems: A Letter Report. The passage of the Pandemic and All Hazards Preparedness Act (PAHPA) (Public Law 109 417, 2006, 101 et seq.) created an immediate need to define research priorities for the Centers for Public Health Preparedness (CPHP) at schools of public health. The Institute of Medicine (IOM) formed an ad hoc committee, conducted a fast-track study, and issued this report, which defines near-term research priorities for emergency preparedness and response in public health systems. These priorities will be used by the Coordinating Office for Terrorism Preparedness and Emergency Response to develop a research agenda and announcements of funding for research projects. The study committee's priorities are based on information presented at a public meeting and workshop, as well as the expert judgments of committee members. The research areas recommended are divided into four areas representing specific aspects of systems of public health preparedness: (1) making training more effective and useful; (2) improving timely emergency communications; (3) creating and maintaining sustainable response systems; and (4) generating criteria and metrics for determining effectiveness.

NAE member **Richard C. Larson**, Mitsui Professor, Department of Civil and Environmental Engineering, Engineering Systems Division, Massachusetts Institute of Technology, was a member of the study committee. Free PDF.

Minerals, Critical Minerals, and the U.S. Economy. Minerals are part of virtually every product we use; common examples include copper in electrical wiring and titanium in airplane frames and paint pigments. Information Age products also contain minerals, such as tantalum in cell phones and indium in liquid-crystal displays. For some critical minerals, such as the platinum group metals used to make catalytic converters in cars, there are no substitutes. Thus restrictions on the supply of a critical mineral could significantly affect certain sectors of the economy, as well as consumers. Mineral supplies can be threatened by sudden increases in demand, increased difficulty in extracting the mineral, or the exhaustion of natural ores. The most vulnerable minerals are those that are extracted from a limited number of mines or by a few mining companies or are found in only a few places. Baseline information on minerals is currently collected at the federal level, but no methodology has been developed to identify potentially critical minerals. This report develops such a methodology and suggests that efforts to collect and analyze data to support it be increased.

NAE members on the study committee were **Thomas E. Graedel**, Professor of Industrial Ecology, Yale University; **Terence P. McNulty**, president, T.P. McNulty and Associates Inc.; and **Brij M. Moudgil**, Distinguished Professor and director, Particle Engineering Research Center, University of Florida. Paper, $42.00.

Pre-Milestone A and Early-Phase Systems Engineering: A Retrospective Review and Benefits for Future Air Force Acquisition. The ability of the U.S. military to field new weapons systems quickly and to contain costs has declined significantly. There are many reasons for this, including increased complexity of the weapons systems, funding instability, increased bureaucracy, and more diverse user requirements. However, many people are now convinced that better systems engineering could help shorten development times. To investigate this idea, the U.S. Air Force asked the National Research Council to examine the effectiveness of using systems engineering to address the causes of program failure, especially during pre-milestone A and early phases of an acquisition program. This report provides an assessment of the relationship between systems engineering and program outcome; an assessment of the systems engineering workforce; and an analysis of systems engineering functions and guidelines, including a definition of minimum systems engineering processes necessary during project development.

NAE member **Paul G. Kaminski**, chairman and CEO, Technovation

Inc., chaired the study committee. Other NAE members on the committee were **Natalie W. Crawford**, senior fellow, RAND Corporation; **Robert A. Fuhrman**, retired vice chairman, president, and chief operating officer, Lockheed Corporation; and **Wesley L. Harris**, department head and Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology. Paper, $36.00.

Mississippi River Water Quality and the Clean Water Act: Progress, Challenges, and Opportunities. Regulatory and nonregulatory measures authorized under the Clean Water Act have reduced a good deal of pollution in the Mississippi River from "point sources," such as industrial facilities and water-treatment plants. However, pollution caused by urban and agricultural runoff and other "non-point sources" have proven to be more difficult to control. This report concludes that the Environmental Protection Agency (EPA) must provide stronger leadership to ensure that the 10 states along the river coordinate their efforts in monitoring and assessing water quality in the Mississippi. Specifically, EPA should establish a data-sharing system and work with states to establish and enforce water-quality standards. In addition, states must be more proactive and must participate in cooperative water-quality programs.

NAE member **Jerald L. Schnoor**, Allen S. Henry Chair Professor, Department of Civil and Environmental Engineering, University of Iowa, was a member of the study committee. Paper, $56.00.

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