Winter 2006

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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BRIDGE

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LINKING ENGINEERING AND SOCIETY

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Editor's Note

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Papers from the 12th U.S. Frontiers of Engineering Symposium

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

The twelfth USFOE Symposium, held on September 21–23, 2006, at the Ford Research and Innovation Center in Dearborn, Michigan, encompassed four themes: the rise of intelligent software systems and machines; the nano/bio interface; engineering personal mobility for the twenty-first century; and supply chain management applications with economic and public impact.

The session on the rise of intelligent software systems and machines was chaired by M. Brian Blake and David Fogel. The first speaker, Lloyd Watts, argued that current knowledge of auditory brain function and available computing power are sufficient for us to begin to build a realistic real-time model of human hearing. Completion of the model is not expected for more than 10 years, but shorter term applications, such as noise suppression in cell phones, are closer at hand. Risto Miikkulainen, whose paper appears on p. 5, outlined the creation of intelligent agents in games through biologically inspired computational techniques. He explained how these could lead to the construction of entirely new genres of video games that are more engaging and entertaining than current games. Robert Axtell's presentation focused on aspects of co-evolution of computer and social sciences. Alan Schultz concluded the session with a discussion of how computational cognitive models could be used to improve human-robot interaction. Building such models, he said, requires that we reconsider how humans interact with each other as peers and translate the details of those interactions into algorithms that govern robot responses and behavior.

The session on the nano/bio interface was chaired by Tejal Desai and Hiroshi Matsui. Speakers addressed the potential impact of nanotechnology on biology and medicine, as well as the impact of biological systems on nanotechnology. Timothy Deming described recent progress in the laboratory synthesis of biological materials with properties not found in conventional synthetic-organic materials. Using these same strategies, he said, researchers have made progress in designing and fabricating entirely new materials with applications in biotechnology. Morley Stone, whose paper appears on p.14, described the incorporation of capabilities found in biological systems into robots to give them new functionality, for example, the ability to climb walls. Rebekah Drezek outlined emerging technologies for quantitative optical imaging for medical diagnoses, focusing on the diagnosis and monitoring of cancer. The presentation by Marcel Bruchez, whose paper appears on p. 19, was focused on commercialization and future developments in bionanotechnology. He described recent innovations in materials chemistry and electronics coupled with chemical specificity derived from biological processes in the development of new magnetic and fluorescent probes.

Apoorv Agarwal and William Schneider chaired the session on personal mobility for the twenty-first century. Andreas Schäfer, whose paper appears on p. 24, began the session with a discussion of long-term trends in global passenger mobility. Surprisingly, he argued, only a few variables are needed to explain past levels of aggregate, world-regional travel demand and mode choice and to make internally consistent projections for the future. Matthew Barth described the competing demand for unlimited personal mobility with the reality of congestion arising from inadequate transportation infrastructure. He described some recent proposals for constructive ways of surmounting the impasse. Susan Zielinski's paper, beginning on p. 33, presents a vision for the next generation of sustainable urban transportation called New Mobility. Andreas Schell described an international collaboration, involving automobile companies based on several continents, to advance the state of hybrid-vehicle technology.

The subject of the final session was supply-chain management applications with economic and public impact. Jennifer Ryan and Julie Swann chaired the session. Brenda Dietrich discussed a mathematical and computational approach to optimizing the mix of products produced from a finite supply of initial materials. The method has been used successfully by a number of major companies, including IBM. Mark Wang outlined the U.S. Army's efforts to analyze and improve management of its supply chain. This complex problem has been addressed in sections. Wang described the dramatic improvements that resulted from the first analyses a few years ago. Larry Snyder and Zuo-Jun Max Shen, whose paper begins on p. 39, consider how management of supply chains can address the added complexity of supply disruptions. He focused on the differing strategies for disruptions in supply and demand. In the final presentation, Michael Johnson described the impact of engineering-based methods on planning for affordable housing and sustainable community development.

The technical talks were followed by extended Q&A sessions with enthusiastic participation by the audience. The program this year also featured 90-minute get-acquainted sessions. Attendees were divided into groups of 10 to 15 individuals; each person then presented a transparency (prepared in advance) representing his/her work and a two-minute introduction and explanation. The balance of time was devoted to discussions of research interests and activities. These get-acquainted sessions turned out to be highly interactive and very educational.

The dinner speaker, a traditional highlight of FOE programs, was **W. Dale Compton**, Lillian M. Gilbreth Distinguished Professor of Industrial Engineering, Emeritus, School of Industrial Engineering, Purdue University. He discussed the importance of engineering and engineering education to American competitiveness. The interplay of engineering, economic well-being, and society was also highlighted in a number of session talks, as well as in small group discussions throughout the symposium.

It was a pleasure for me to chair this year's symposium and to have the opportunity to learn from and exchange ideas with these impressive future engineering leaders. I know of no other meeting as interdisciplinary, diverse, and stimulating as FOE, and I hope that the six papers included in this issue convey some of the excitement we experienced in Dearborn in September.

Note: Papers for all of the presentations and the dinner speech will be published in the annual U.S. FOE volume in February 2007.

Video games provide an ideal platform for the development and testing of machine-learning techniques.

Creating Intelligent Agents in Games

Risto Miikkulainen is a professor of computer sciences at the University of Texas at Austin.

Risto Miikkulainen

Games have long been a popular area for research in artificial intelligence (AI), and for good reason. Because games are challenging yet easy to formalize, they can be used as platforms for the development of new AI methods and for measuring how well they work. In addition, games can demonstrate that machines are capable of behavior generally thought to require intelligence without putting human lives or property at risk.

Most AI research so far has focused on games that can be described in a compact form using symbolic representations, such as board games and card games. The so-called good old-fashioned artificial intelligence (GOFAI; Haugeland, 1985) techniques work well with symbolic games, and to a large extent, GOFAI techniques were developed for them. GOFAI techniques have led to remarkable successes, such as Chinook, a checkers program that became the world champion in 1994 (Schaeffer, 1997), and Deep Blue, the chess program that defeated the world champion in 1997 and drew significant attention to AI in general (Campbell et al., 2002).

Since the 1990s, the field of gaming has changed tremendously. Inexpensive yet powerful computer hardware has made it possible to simulate complex physical environments, resulting in tremendous growth in the video game industry. From modest sales in the 1960s (Baer, 2005), sales of entertainment software reached $25.4 billion worldwide in 2004 (Crandall and Sidak, 2006). Video games are now a regular part of many people's lives, and the market continues to expand.

Curiously, very little AI research has been involved in this expansion. Many video games do not use AI techniques, and those that do are usually based on relatively standard, labor-intensive scripting and authoring methods. In this and other respects, video games differ markedly from symbolic games. Video games often involve many agents embedded in a simulated physical environment where they interact through sensors and effectors that take on numerical rather than symbolic values. To be effective, agents must integrate noisy input from many sensors, react quickly, and change their behavior during the game. The AI techniques developed for and with symbolic games are not well suited to video games.

In contrast, machine-learning techniques, such as neural networks, evolutionary computing, and reinforcement learning, are very well suited to video games. Machine-learning techniques excel in exactly the kinds of fast, noisy, numerical, statistical, and changing domains that today's video games provide. Therefore, just as symbolic games provided an opportunity for the development and testing of GOFAI techniques in the 1980s and 1990s, video games provide an opportunity for the development and testing of machine-learning techniques and their transfer to industry.

Very little machine learning is used in current commercial video games.

Artificial Intelligence in Video Games

One of the main challenges for AI is creating intelligent agents that can become more proficient in their tasks over time and adapt to new situations as they occur. These abilities are crucial for robots deployed in human environments, as well as for various software agents that live in the Internet or serve as human assistants or collaborators.

Although current technology is still not sufficiently robust to deploy such systems in the real world, they are already feasible in video games. Modern video games provide complex artificial environments that can be controlled and carry less risk to human life than any real-world application (Laird and van Lent, 2000). At the same time, video gaming is an important human activity that occupies millions of people for countless hours. Machine learning can make video games more interesting and reduce their production costs (Fogel et al., 2004) and, in the long run, might also make it possible to train humans realistically in simulated, adaptive environments. Video gaming is, therefore, an important application of AI and an excellent platform for research in intelligent, adaptive agents.

Current video games include a variety of high-realism simulations of human-level control tasks, such as navigation, combat, and team and individual tactics and strategy. Some of these simulations involve traditional AI techniques, such as scripts, rules, and planning (Agre and Chapman, 1987; Maudlin et al., 1984), and a large part of AI development is devoted to path-finding algorithms, such as A*-search and simple behaviors built using finite-state machines. AI is used to control the behavior of the non-player characters (NPCs, i.e., autonomous computer-controlled agents) in the game. The behaviors of NPCs, although sometimes impressive, are often repetitive and inflexible. Indeed, a large part of the gameplay in many games is figuring out what the AI is programmed to do and learning to defeat it.

Machine learning in games began with Samuel's (1959) checkers program, which was based on a method similar to temporal-difference learning (Sutton, 1988). This was followed by various learning methods applied to tic-tac-toe, backgammon, go, Othello, and checkers (see Fürnkranz, 2001, for a survey). Recently, machine-learning techniques have begun to appear in video games as well. For example, Fogel et al. (2004) trained teams of tanks and robots to fight each other using a competitive coevolution system, and Spronck (2005) trained agents in a computer role-playing game using dynamic scripting. Others have trained agents to fight in first- and third-person shooter games (Cole et al., 2004; Hong and Cho, 2004). Machine-learning techniques have also been applied to other video game genres, from Pac-Man (Lucas, 2005) to strategy games (Bryant and Miikkulainen, 2003; Yannakakis et al., 2004).

Nevertheless, very little machine learning is used in current commercial video games. One reason may be that video games have been so successful that a new technology such as machine learning, which would fundamentally change the gaming experience, may be perceived as a risky investment by the industry. In addition, commercial video games are significantly more challenging than the games used in research so

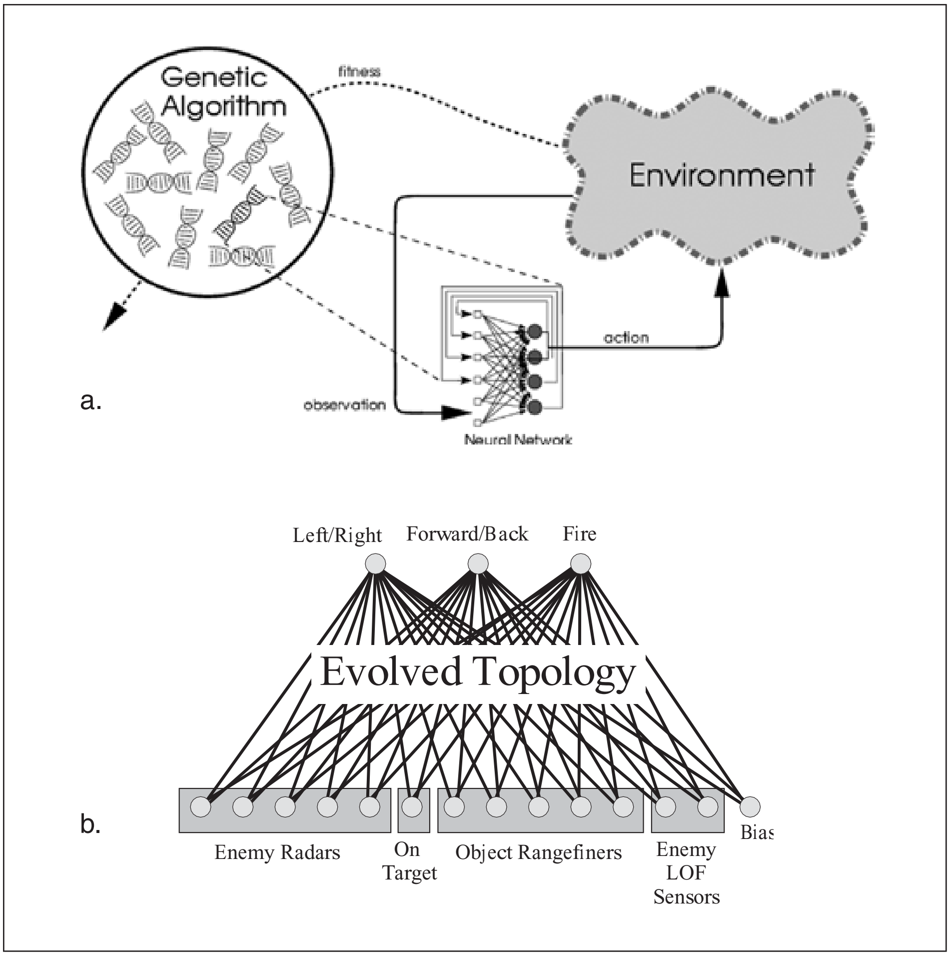


FIGURE 1 1a. Evolving neural networks. Solutions (such as neural networks) are encoded as chromosomes, usually consisting of strings of real numbers, in a population. Each individual is evaluated and assigned a fitness based on how well it performs a given task. Individuals with high fitness reproduce; individuals with low fitness are thrown away. Eventually, nearly all individuals can perform the task. 1b. Each agent in neuroevolution receives sensor readings as input and generates actions as output. In the NERO video game, the network can see enemies, determine whether an enemy is currently in its line of fire, detect objects and walls, and see the direction the enemy is firing. Its outputs specify the direction of movement and whether or not to fire. In this way, the agent is embedded in its environment and must develop sophisticated behaviors to do well. For general neuroevolution software and demos, see *http://nn.cs.utexas.edu*.

far. They not only have large state and action spaces, but they also require diverse behaviors, consistent individual behaviors, fast learning, and memory of past situations (Gomez et al., 2006; Stanley et al., 2005)

Neuroevolution

The rest of this article is focused on a particular machine-learning technique, neuroevolution, or the evolution of neural networks. This technique not only promises to rise to the challenge of creating games that are educational, but also promises to provide a platform for the safe, effective study of how intelligent agents adapt.

Evolutionary computation is a computational machine-learning technique modeled after natural evolution (Figure 1a). A population of candidate solutions are encoded as strings of numbers. Each solution is evaluated in the task and assigned a fitness based on how well it performs. Individuals with high fitness are then reproduced (by crossing over their encodings) and mutated (by randomly changing components of their encodings with a low probability). The offspring of the high-fitness individuals replace the low-fitness individuals in the population, and over time, solutions that can solve the task are discovered.

In neuroevolution, evolutionary computation is used to evolve neural network weights and structures. Neural networks perform statistical pattern transformation and generalization, and evolutionary adaptation allows for learning without explicit targets, even with little reinforcement. Neuroevolution is particularly well suited to video games because (1) it works well in high-dimensional spaces; (2) diverse populations can be maintained; (3) individual networks behave consistently; (4) adaptation takes place in real time; and (5) memory can be implemented through recurrency (Gomez et al., 2006; Stanley et al., 2005).

Several methods have been developed for evolving neural networks (Yao, 1999). One particularly appropriate for video games is called neuroevolution of augmenting topologies (NEAT; Stanley and Miikkulainen, 2002), which was originally developed for learning behavioral strategies. The neural networks control agents that select actions in their output based on sensory inputs (Figure 1b). NEAT is unique in that it begins evolution with a population of small, simple networks and *complexifies* those networks over generations, leading to increasingly sophisticated behaviors.

With neuroevolution, entirely new game genres can be developed.

NEAT is based on three key ideas. First, for neural network structures to increase in complexity over generations, a method must be found for keeping track of which gene is which. Otherwise, it will not be clear in later generations which individuals are compatible or how their genes should be combined to produce offspring. NEAT solves this problem by assigning a unique historical marking to every new piece of network structure that appears through a structural mutation. The historical marking is a number assigned to each gene corresponding to its order of appearance over the course of evolution. The numbers are inherited unchanged during crossover, which allows NEAT to perform crossover without expensive topological analysis. Thus, genomes of different organizations and sizes remain compatible throughout evolution.

Second, NEAT speciates the population, so that individuals compete primarily within their own niches instead of with the population at large. In this way, topological innovations are protected and have time to optimize their structures. NEAT uses the historical markings on genes to determine the species to which different individuals belong.

Third, unlike other systems that evolve network topologies and weights, NEAT begins with a uniform population of simple networks with no hidden nodes. New structure is introduced incrementally as structural mutations occur, and only those structures survive that are found to be useful through fitness evaluations. This way, NEAT searches through a minimal number of weight dimensions and finds the appropriate complexity level for the problem. This process of complexification has important implications for the search for solutions. Although it may not be practical to find a solution in a high-dimensional space by searching that space directly, it may be possible to find it by first searching in lower dimensional spaces and complexifying the best solutions into the high-dimensional space.

As is usual in evolutionary algorithms, the entire population is replaced with each generation in NEAT. However, in a real-time game or simulation, this would seem incongruous because every agent's behavior would change at the same time. In addition, behaviors would remain static during the large gaps between generations. Therefore, in order to apply NEAT to video games, a real-time version of it, called rtNEAT, was created.

In rtNEAT, a single individual is replaced every few game ticks. One of the poorest performing individuals is removed and replaced with a child of parents chosen from among the best performing individuals. This cycle of removal and replacement happens continually throughout the game and is largely invisible to the player. As a result, the algorithm can evolve increasingly complex neural networks fast enough for a user to interact with evolution as it happens in real time. This real-time learning makes it possible to build machine-learning games.

Machine-Learning Games

The most immediate opportunity for neuroevolution in video games is to build a "mod," a new feature or extension, to an existing game. For example, a character that is scripted in the original game can be turned into an adapting agent that gradually learns and improves as the game goes on. Or, an entirely new dimension can be added to the game, such as an intelligent assistant or tool that changes as the player progresses through the game. Such mods can make the game more interesting and fun to play. At the same time, they are easy and safe to implement from a business point of view because they do not change the original structure of the game. From the research point of view, ideas about embedded agents, adaptation, and interaction can be tested with mods in a rich, realistic game environment.

With neuroevolution, however, learning can be taken well beyond game mods. Entirely new game genres can be developed, such as machine-learning games, in which the player explicitly trains game agents to perform various tasks. The fun and challenge of machine-learning games is to figure out how to take agents through successive challenges so that in the end they perform well in their chosen tasks. Games such as Tamagotchi "Virtual Pet" and Black & White "God Game" suggest that interaction with artificial agents can make for viable and entertaining games. In NERO, the third such game, the artificial agents adapt their behavior through sophisticated machine learning.

The NERO Game

The main idea of NERO is to put the player in the role of a trainer or drill instructor who teaches a team of agents by designing a curriculum. The agents are simulated robots that learn through rtNEAT, and the goal is to train them for military combat.

The agents begin the game with no skills but with the ability to learn. To prepare them for combat, the player must design a sequence of training exercises and goals. Ideally, the exercises will be increasingly difficult so that the team begins by learning basic skills and then gradually builds on them (Figure 2). When the player is satisfied that the team is well prepared, the team is deployed in a battle against another team trained by another player, allowing the players to see if their training strategies pay off.

The challenge is to anticipate the kinds of skills that might be necessary for battle and build training exercises to hone those skills. A player sets up training exercises by placing objects on the field and specifying goals through several sliders. The objects include static enemies, enemy turrets, rovers (i.e., turrets that move), flags, and walls. To the player, the sliders serve as an interface for describing ideal behavior. To rtNEAT, they represent coefficients for fitness components. For example, the sliders specify how much to reward or punish agents for approaching enemies, hitting targets, getting hit, following friends, dispersing, etc. Each individual fitness component is normalized to a Z-score (i.e., the number of standard deviations from the mean) so all components can be measured on the same scale. Fitness is computed as the sum of all components multiplied by their slider levels, which can be positive or negative. Thus, the player has a natural interface for setting up a training exercise and specifying desired behavior.

Agents have several types of sensors (Figure 1b). Although NERO programmers frequently experiment with new sensor configurations, the standard sensors include enemy radars, an "on target" sensor, object range finders, and line-of-fire sensors. To ensure consistent evaluations, agents all begin in a designated area of the field called the factory. Each agent is allowed to spend a limited amount of time on the field during which its fitness can be assessed. When time on the field expires, the agent is transported back to the factory, where another evaluation begins.

Training begins by deploying 50 agents on the field. Each agent is controlled by a neural network with random connection weights and no hidden nodes, which is the usual starting configuration for NEAT. As the neural networks are replaced in real-time, behavior improves, and agents eventually learn to perform the task the player has set up. When the player decides performance has reached a satisfactory level, he or she can save the team in a file. Saved teams can be reloaded for further training in different scenarios, or they can be loaded into battle mode.

In battle mode, the player discovers how well the training has worked. Each player assembles a battle team of 20 agents from as many different trained teams as desired, possibly combining agents with different skills.

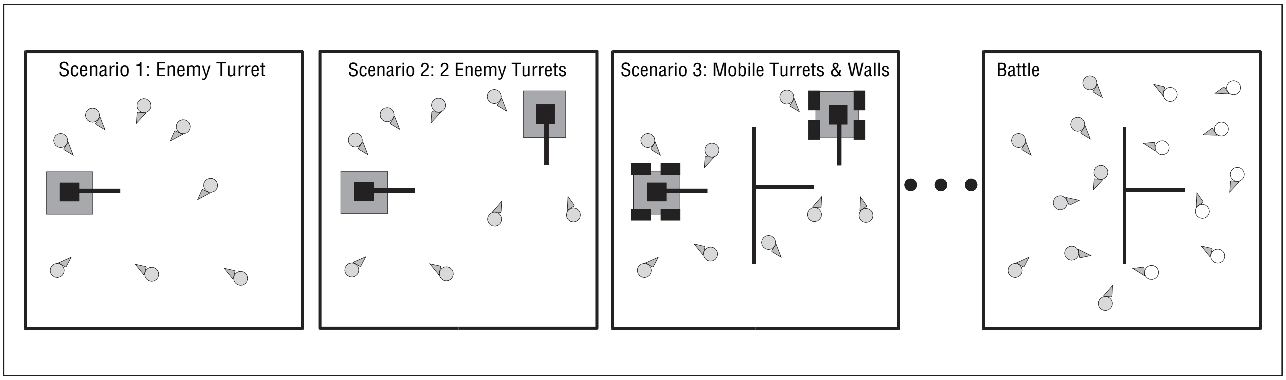
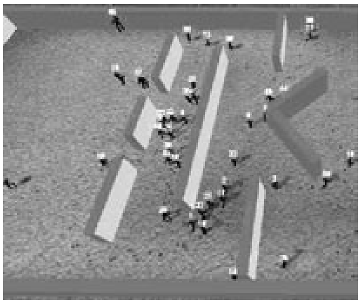


FIGURE 2 A sample training sequence in NERO. The figure depicts a sequence of increasingly difficult training exercises in which agents attempt to attack turrets without getting hit. In the first exercise, there is only a single turret; additional turrets are added by the player as the team improves. Eventually walls are added, and the turrets are given wheels so they can move. Finally, after the team has mastered the hardest exercises, it is deployed in a battle against another team. For animations of various training and battle scenarios, see *http://nerogame.org*.

a.



b.

FIGURE 3 Behaviors evolved in NERO. 3a. This training screenshot shows several agents running away backward while shooting at the enemy, which is being controlled from a first-person perspective by a human trainer with a joystick. This scenario demonstrates how evolution can discover novel and effective behaviors in response to challenges set up by the player. 3b. Incremental training on increasingly complex wall configurations produced agents that could navigate this complex maze to find the enemy. Remarkably, they had not seen this maze during training, suggesting that they had evolved general path-navigation ability. The agents spawn from the left side of the maze and proceed to an enemy at the right. Notice that some agents evolved to take the path through the top, while others evolved to take the bottom path, suggesting that protecting innovation in rtNEAT supports a range of diverse behaviors with different network topologies. Animations of these and other behaviors can be seen at *http://nerogame.org*.

The battle begins with two teams arrayed on opposite sides of the field. When one player presses a "go" button, the neural networks take control of their agents and perform according to their training. Unlike training, however, where being shot does not cause damage to an agent's body, agents in battle are destroyed after being shot several times (currently five). The battle ends when one team is completely eliminated. In some cases, the surviving agents may insist on avoiding each other, in which case the winner is the team with the most agents left standing.

Torque, a game engine licensed from GarageGames (*http://www.garagegames.com/*), drives NERO's simulated physics and graphics. An important property of Torque is that its physics is slightly nondeterministic so that the same game is never played twice. In addition, Torque makes it possible for the player to take control of enemy robots using a joystick, an option that can be useful in training.

Behavior can be evolved very quickly in NERO, fast enough so that the player can be watching and interacting with the system in real time. The most basic battle tactic is to seek the enemy aggressively and fire at it. To train for this tactic, a single static enemy is placed on the training field, and agents are rewarded for approaching the enemy. This training requires that agents learn to run toward a target, which is difficult because they start out in the factory facing in random directions. Starting with random neural networks, it takes on average 99.7 seconds for 90 percent of the agents on the field to learn to approach the enemy successfully (10 runs, *sd* = 44.5s).

Note that NERO differs from most applications of evolutionary algorithms in that the quality of evolution is judged from the player's perspective based on the performance of the entire population, instead of the performance of the population champion. However, even though the entire population must solve the task, it does not converge to the same solution. In seek training, some agents evolve a tendency to run slightly to the left of the target, while others run to the right. The population diverges because the 50 agents interact as they move simultaneously on the field at the same time. If all of the agents chose exactly the same path, they would often crash into each other and slow each other down, so agents naturally take slightly different paths to the goal. In other words, NERO is a massively parallel, coevolving ecology in which the entire population is evaluated together.

Agents can also be trained to avoid the enemy, leading to different battle tactics. In fact, rtNEAT is flexible enough to devolve a population that has converged on seeking behavior into its complete opposite, a population that exhibits avoidance behavior. For avoidance training, players control an enemy robot with a joystick and run it toward the agents on the field. The agents learn to back away to avoid being penalized for being too near the enemy. Interestingly, they prefer to run away from the enemy backward so they can still see and shoot at the enemy (Figure 3a). As an interesting combination of conflicting goals, a turret can be placed on the field and agents asked to approach it without getting hit. As a result, they learn to avoid enemy fire, running to the side opposite the bullets and approaching the turret from behind. This tactic is also effective in battle.

Other interesting behaviors have been evolved to test the limits of rtNEAT, rather than specifically prepare troops for battle. For example, agents were trained to run around walls in order to approach the enemy. As performance improved, players incrementally added more walls until the agents could navigate an entire maze (Figure 3b). This behavior was remarkable because it was successful without any path planning.

The agents developed the general strategy of following any wall that stood between them and the enemy until they found an opening. Interestingly, different species evolved to take different paths through the maze, showing that topology and function are correlated in rtNEAT and confirming the success of real-time speciation. The evolved strategies were also general enough for agents to navigate significantly different mazes without further training. In another example, when agents that had been trained to approach a designated location (marked by a flag) through a hallway were attacked by an enemy controlled by the player, they learned, after two minutes, to take an alternative path through an adjacent hallway to avoid the enemy's fire. Such a response is a powerful demonstration of real-time adaptation. The same kind of adaptation could be used in any interactive game to make it more realistic and interesting.

Teams that were trained differently were sometimes surprisingly evenly matched. For example, a seeking team won six out of ten battles, only a slight advantage, against an avoidant team that ran in a pack to a corner of the field next to an enclosing wall. Sometimes, if an avoidant team made it to the corner and assembled fast enough, the seeking team ran into an ambush and was obliterated. However, slightly more often the seeking team got a few shots in before the avoidant team could gather in the corner. In that case, the seeking team trapped the avoidant team and had more surviving numbers. Overall, neither seeking nor avoiding provided a significant advantage.

Strategies can be refined further by observing behaviors during battle and setting up training exercises to improve them. For example, a seeking team could eventually be made more effective against an avoidant team when it was trained with a turret that had its back against the wall. The team learned to hover near the turret and fire when it turned away and to back off quickly when it turned toward them. In this way, rtNEAT can discover sophisticated tactics that dominate over simpler ones. The challenge for the player is to figure out how to set up the training curriculum so sophisticated tactics will emerge.

NERO was created over a period of about two years by a team of more than 30 student volunteers (Gold, 2005). The game was first released in June 2005 at *http://nerogame.org* and has since been downloaded more than 100,000 times. NERO is under continuing development and is currently focused on providing more interactive play. In general, players agree that the game is engrossing and entertaining. Battles are exciting, and players spend many hours perfecting behaviors and assembling teams with just the right combination of tactics. Remarkably, players who have little technical background often develop accurate intuitions about the underlying mechanics of machine learning. This suggests that NERO and other machine-learning games are viable as a genre and may even attract a future generation of researchers to machine learning.

Games with adapting intelligent agents are likely to be in high demand.

Games like NERO can be used as research platforms for implementing novel machine-learning techniques. For example, one direction for research is to incorporate human knowledge, in terms of rules, into evolution. This knowledge could then be used to seed the population with desired initial behaviors or to give real-time advice to agents during evolution (Cornelius et al., 2006; Yong et al., 2006). Another area for research is to learn behaviors that not only solve a given problem, but solve it in a way that makes sense to a human observer. Although such solutions are difficult to describe formally, a human player may be able to demonstrate them by playing the game himself or herself. An evolutionary learning system can then use these examples to bias learning toward similar behaviors (Bryant, 2006).

Conclusion

Neuroevolution is a promising new technology that is particularly well suited to video game applications. Although neuroevolution methods are still being developed, the technology can already be used to make current games more challenging and interesting and to implement entirely new genres of games. Such games, with adapting intelligent agents, are likely to be in high demand in the future. Neuroevolution may also make it possible to build effective training games, that is, games that adapt as the trainee's performance improves.

At the same time, video games provide interesting, concrete challenges for machine learning. For example, they can provide a platform for the systematic study of methods of control, coordination, decision making, and optimization, within uncertainty, material, and time constraints. These techniques should be widely applicable in other fields, such as robotics, resource optimization, and intelligent assistants. Just as traditional symbolic games catalyzed the development of GOFAI techniques, video gaming may catalyze research in machine learning for decades to come.

Acknowledgments

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Biology can provide tools for controlling and synthesizing materials at the molecular level.

Applications of Biomimetics

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Morley Stone

At first glance, imitating nature via biomimetics seems to be a straightforward proposition. For example, if you are a roboticist, add legs to the platform instead of wheels. Unfortunately, as is often the case, the devil is in the details. After a short synopsis of examples of biomimetic material synthesis, sensing, and robotics, I will attempt to identify some lessons learned, some surprising and unanticipated insights, and some potential pitfalls in biomimetics. (For recent perspectives on combining biology with other disciplines, see Naik and Stone, 2005).

"Just DON'T Add Water"

Often, biologists and engineers speak completely different languages. Perhaps the most graphic example of this is a comparison of the world of electrical engineers and sensor designers with the world of biologists. Manipulation of biological macromolecules (i.e., nucleic acids and/or proteins) involves the use of buffered solutions (usually pH ~ 7), controlled salinity, and regulated temperatures. Incorporating these biological salt solutions into electronics and sensor architectures seems like an oxymoron. However, the conversion of biological materials away from solution to solid-state processing has been a major objective in our laboratory.

The key to overcoming this seemingly insurmountable incompatibility is the use of "bridging" materials systems, such as polymer host materials that capture and maintain biological functionality (Brott et al., 2004). Many polymer systems, such as poly(vinyl alcohol), qualify as hydrogels because they incorporate and maintain an enormous amount of water. While the biological side of this equation can be satisfied via the incorporation of water, polymer systems can be spin-coated, lithographically patterned, made conductive, and undergo a host of other treatments that electrical engineers routinely use. Thus, polymers represent a truly bridging material system in making biological macromolecules mesh with synthetic technology.

Another recent example highlights the potential of biological materials that have been integrated into a common electrical construct, such as a light-emitting diode (LED). To accomplish this, however, there must be a paradigm shift in materials thinking—namely, what would happen if DNA were processed in gram and kilogram quantities, instead of the traditional microgram quantities.

The fishing industry in Japan, which processes tons of seafood yearly, also throws away tons of DNA from fish gametes. Researchers at the Chitose Institute of Science and Technology in Japan, in partnership with our laboratory, have processed this discarded DNA into a surfactant complex and scaled the process up to a multigram scale (Wang et al., 2001). In this form and at this scale, DNA can be spin-coated into traditional electronics architectures. Recently, a DNA electron-blocking layer spin-deposited on the hole-injection side of the electron-hole recombination layer greatly enhanced LED efficiency and performance (Hagen et al., 2006) (Figure 1).

In another approach, we have attempted to use biology indirectly in advanced material synthesis and devices. Similar to the refrain from a commercial for a popular chemical company, biology isn't in the final material, but it makes the final material better. Researchers around the world racing to harness the incredible electronic, thermal, and mechanical properties inherent in single-walled carbon nanotubes (SWNTs) have run into a formidable obstacle. After a typical synthesis run, there is a large variety (both in length and diameter) of carbon nanotubes. This variety contributes to a number of chiralities, which dictate the metallic or semiconducting nature of the SWNT. Much of this size heterogeneity arises from the heterogeneity of the starting metallic nanoparticles used to catalyze the growth of SWNTs.

Ferritins and ferritin-like proteins sequester iron (in the form of iron oxide) in precisely defined cavities ranging from 8 nm to 4 nm for human and bacterial forms, respectively. We recently engineered a bacterial form called DPS to produce uniform, monodisperse iron oxide particles (Kramer et al., 2005). We reasoned that a monodisperse starting pool of nanoparticles would lead to a more monodisperse population of SWNTs. After the bacterial protein was used to produce the iron oxide particles, the biological shell was removed via scintering in a reduced atmosphere and subjected to gas-phase carbon-nanotube growth. The resulting SWNTs adopted the monodisperse character of the starting catalyst particles. Thus, biology was not in the final product but was used to make a technologically promising material better.

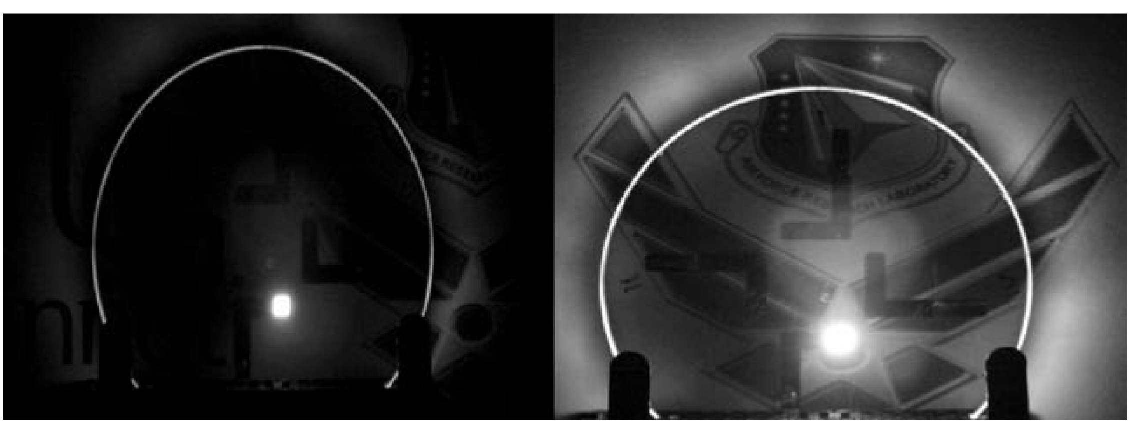

FIGURE 1 Photographs of Alq3 green emitting bio-LED and baseline OLED devices in operation.

Materials Science and Engineering Overlap Biology

From a materials science and engineering perspective, favorable electronic and structural properties usually emerge when the synthesis process can be controlled at finer and finer levels. Hence the frenzy and hype over nanotechnology. As illustrated in the carbon nanotube example, biology can provide tools for controlling and/or synthesizing materials at the molecular level.

An example of this control is unicellular algae, called diatoms, which make exquisite cellular structures out of silica. Thousands of species of diatoms exist in salt and fresh water. Each diatom species makes unique silica structures and patterns—from hinges to intricate arrays of holes and spines. Silica synthesis occurs at ambient temperature and pH and has a complexity greater than anything we can make synthetically using sol-gel techniques.

Kröger and colleagues (1999) provided insight into the silica-deposition process of diatoms, which has led to a complete rethinking of the molecular evolution of this process (Naik et al., 2002) and how it can be used in practical applications, such as enzymatic encapsulation (Luckarift et al., 2004). Based on work by Kröger and others, the field of biomineralization has expanded the range of materials synthesized via a biological route to encompass not only oxides, but also metals and semiconductors (Slocik et al., 2005).

Specific peptides can now be used for the nucleation and growth of inorganic nanomaterials. When one considers that peptides specific for inorganic binding and nucleation can be combined (i.e., genetically fused) with peptides that bind another moiety, endless possibilities begin to emerge. For example, biological macromolecules might be incorporated directly into electronic structures/devices. One can imagine literally growing a field-effect transistor (FET) metal-oxide-metal architecture via a biological route, rather than relying on standard top-down photolithographic processes.

There might also be new approaches in optics and catalysis where there are now significant challenges in assembling and interconnecting the building blocks of a nanoscale device. One might be able, for example, to address or measure responses electronically at the molecular level. The very real scale gap between the size of the molecule and the limits of lithography is shrinking. Bio-based approaches are being pursued to develop bottom-up self-assembly techniques that provide specificity and versatility. Peptides that recognize inorganic surfaces can be used as templates to organize and/or synthesize inorganic materials. By combining different functional peptides, we can create multifunctional polypeptides that can be used to synthesize and assemble hybrid materials. Recently, we demonstrated that by growing bimetallic systems using a bio-based approach, we can enhance catalytic activity of bimetallic materials (Slocik and Naik, 2006).

In nature, the programmed assembly of amino acids in a polypeptide sequence gives rise to protein molecules that exhibit multifunctional properties. Similarly, using protein engineering, inorganic binding peptide segments can be fused to create multifunctional polypeptides to assemble and/or synthesize hybrid materials. By exploiting the interaction between peptides and inorganic materials, a peptide that contains two separate domains (each responsible for binding to a specific metal species) can be used to assemble hybrid materials (Figure 2). Thus, we can control/program synthesis of bimetallic structures. The bimetallic nanoparticles made by using the designer peptides were found to be efficient catalysts in the hydrogenation of 3-buten-1-ol.

This method represents a generalized approach to achieving hybrid structures by programming the amino acid sequence presented by the peptide interface. The peptide interface may be used to conjugate nanoparticle surfaces to polymers, organic molecules, or other biomolecules. However, to fully appreciate the potential of peptides and other biological building blocks as molecular templates, we will need a better understanding of the interaction between biomolecules and inorganic surfaces. Using computational modeling, we should get a much clearer understanding of the mechanism of peptide-inorganic interactions. In the future, one should be able to create hybrid materials using protein engineering by dialing in the sequence domains to direct their synthesis and assembly.

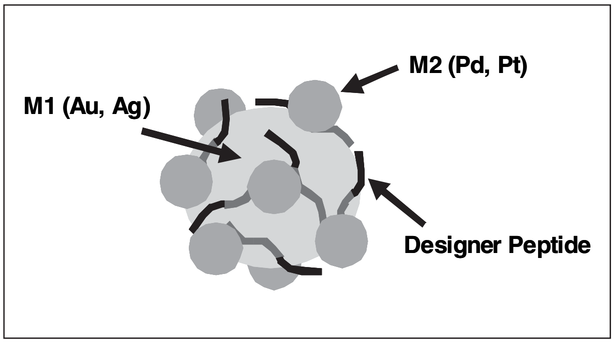

FIGURE 2 Assembly of hybrid materials using designer peptides.

Bio-Inspired Robotics: Applied Biology and Engineering

The combination of biological principles, mechanical engineering, and robotics has opened entirely new areas and possibilities. Starting with the question of why legs matter, the field of biodynotics is exploding to encompass why materials properties matter, why mechanics and architecture matter, and how biological insights can lead to completely new capabilities. For example, entirely new lessons and robotic capabilities have emerged, such as dynamic compliance, molecular adhesion, conformal grasping, and dynamic stability, to name just a few of the concepts that have been implemented into robotic platforms.

The first contributions of biology to robotics were based on the insight that a sprawled posture used opposing forces to achieve self-stabilization (Dickenson et al., 2000; Full and Tu, 1991). Much of this early work was focused on understanding the mechanics involved in legged locomotion. The spring-loaded inverted-pendulum model has been accepted as an accurate model of biological locomotion independent of the number of legs or the biological platform (i.e., horse or human or cockroach).

Recently, the Cutkosky laboratory at Stanford, where pneumatically driven hexapod running robots were developed, has been challenged to build a wall-climbing platform capable of emulating gecko-like behavior (Clark et al., 2001). From a materials science perspective, the challenge has been to produce synthetic, self-cleaning hair arrays with a diameter of 200 nm at a density of 1–2e9 hairs/cm^2.

The field of robotics would also benefit immensely from the development of tunable (dynamic) modulus materials. Today, compliance is usually tuned mechanically, which entails high costs in weight and power and produces less than satisfactory performance. There are numerous biological models of tunable modulus materials (e.g., the sea cucumber), and extrapolating these lessons to robotics could have a huge impact.

Conclusion

In our research, we are framing future investments in an area we call biotronics, a term that encompasses both bioelectronics and biophotonics. As the LED and FET examples described above suggest, this area is ripe for revolutionary breakthroughs. New capabilities, like tunable dielectrics, could revolutionize sensing and electronic readout. We believe that an integrated package of sensing and readout will emerge.

Biology may also enable us to fabricate materials, structures, and devices from the bottom up. Many believe that we will have to turn to biology for commercially viable nanomanufacturing. Catalysis and self-assembly have been mastered by biological systems like enzymes and viruses, respectively. These lessons are being applied to traditional solid-state electronics, and engineers are beginning to realize the possibilities.

To continue advancements in biomimetics, we must include these principles in undergraduate and graduate training programs. Many other countries are also awakening to this realization. Thus, the future technical base of our country will depend on how well the science and engineering departments in our universities encourage this interdisciplinary training.

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Researchers are making the first "blunt-fingered" attempts to extend the capabilities of biological systems.

Commercialization and Future Developments in Bionanotechnology

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Marcel P. Bruchez

Perfection in nanotechnology has long been achieved by biological systems. An enzyme represents a nearly perfect robot, stamping out molecular patterns from unique templates designed to execute individual tasks with nearly perfect efficiency. Evolution has driven these efficient designs to enable life forms to thrive in harsh environments. Evolutionary improvements have developed over a period of at least 3.5 billion years, with impressive results. The fact that we are here at all is a testament to the power and vast potential of nanotechnology.

Recently, we have made the first blunt-fingered attempts to extend the capabilities of biological systems by harnessing innovations in materials chemistry and electronics coupled with biologically defined specificity for both magnetic and fluorescent probes. In these cases, we have succeeded in introducing relatively limited new functionalities to existing biological systems. But we have barely tapped the potential of engineering of these systems, and from here on, our efforts will undoubtedly expand dramatically.

At the present time, we are guided by empirical observations and not by a detailed understanding of the interactions of biological systems with the materials and devices we are preparing. Thus, not only are we blunt-fingered, but we are also nearly blind. Before we can realize substantial commercial rewards and benefits in health and medicine, we will have to

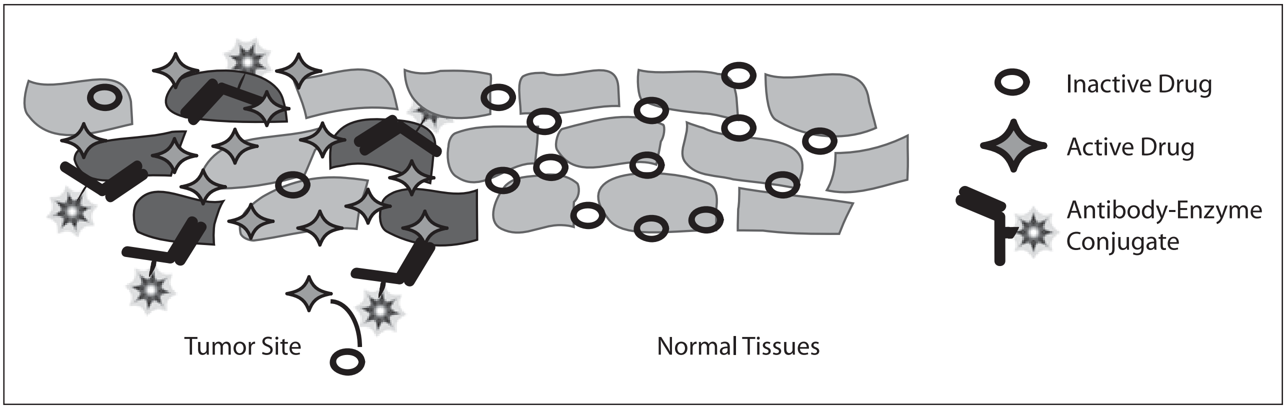

FIGURE 1 Antibody-directed enzyme prodrug therapy (ADEPT) uses antibodies to target particular cells with an enzyme that then converts prodrug molecules to an active drug at the target site.

expand our efforts dramatically to develop new characterization methods and basic specifications and predictors of biological performance.

Definition of Bionanotechnology

At the present time, there is no consensus definition of bionanotechnology. To take advantage of the enthusiasm of funding agencies, a number of old (and important) areas, such as colloid science, molecular biology, and implantable materials surface science, have been relabeled "nanotechnology." In fact, all of these fields, coupled with biological systems, should be included in bionanotechnology. In general, the idea of bionanotechnology is the engineering of interfaces between molecules or materials and biological systems. Looking ahead, the key areas for commercialization will be bringing engineered systems into biological contact and biological function.

The version of bionanotechnology popularized in the media has been largely oversold. The general idea, which was popular 20 years ago as the "magic-bullet" theory of biotechnology and has been adopted as the bionanotechnology target, can be described as the "dump truck" model of technology. In this conception, the technology components consist of a targeting moiety, either biological or nanotechnological, and one or more cargoes, which are envisioned as small machines capable of specific destructive or corrective action.

In reality, designing targeting molecules that are selective for diseased tissues and capable of delivering cargoes larger than a typical antibody has proven extraordinarily difficult, and molecular targeting of nanoscale devices greater than 5 nm outside the vascular space may prove to be prohibitively difficult. However, with no guiding principles for the effective biological direction of non-biological molecules, this is still an open question.

In this paper, I describe three recent examples of commercialized bionanotechnology, beginning with the one that is the best characterized system. The three are antibody-directed enzyme prodrug therapy (ADEPT), superparamagnetic iron oxide particles for enhancing contrast on MRIs, and quantum-dot technology for biological detection. Each of these shows the potential power and some of the challenges of integrating technologies at the molecular level.

Antibody-Directed Enzyme Prodrug Therapy

Perhaps the most salient and relevant example of a bionanotechnology currently being commercialized is the antibody-directed enzyme prodrug therapy (ADEPT) method being investigated by Genencor and Seattle Genetics (Figure 1). In this method, an antibody-enzyme fusion is first prepared and isolated. This molecule can be designed with precise chemical (biological) composition, precise linkage geometry, and complete definition and characterization using standard molecular-biology techniques and biochemical methods. The antibody, linked to the enzyme, can be used to target the particular antibody-enzyme conjugate to the site of interest. In this way, a small antibody fragment is used to target a molecular machine (an enzyme) to a particular site of interest, and the machine is then used to generate a specific molecule at that site. In the clinic, a prodrug (a drug molecule modified to an inactive state that can be converted to an active state in situ) is administered to the patient. After the antibody-enzyme construct reaches its target site, the prodrug is administered and is converted by the enzyme to an active state. The local concentration of the active drug can be driven very high, even though the overall concentration remains very low. Thus, the therapy is both safer and more effective than a high dose of the toxic compound.

ADEPT is a highly characterized, highly effective example of bionanotechnology in action. However, even after 15 years of active research, these targeted prodrug strategies are still in the research or early clinical trial stage and not in general practice. This is a reflection of the complexities of developing biospecific performing technologies, which is likely to be a general problem for the development of nanotechnologies with high clinical impact.

Superparamagnetic Iron Oxide Particles

A second, more recognizable example of bionanotechnology in clinical use is Ferridex and Combidex superparamagnetic particles, marketed by Advanced Magnetics, which are being commercialized for enhancing MRI (magnetic resonance imaging) signals (Figure 2). The particles are modified with dextran (a polymerized sugar molecule) to create a biocompatible coating, which dramatically reduces nonspecific interactions in the body and increases the contrast of the instrument wherever the particles are present. When administered intravenously, they can easily be measured in a standard clinical MRI imaging instrument. These materials are currently approved for imaging cancers of the liver and spleen.

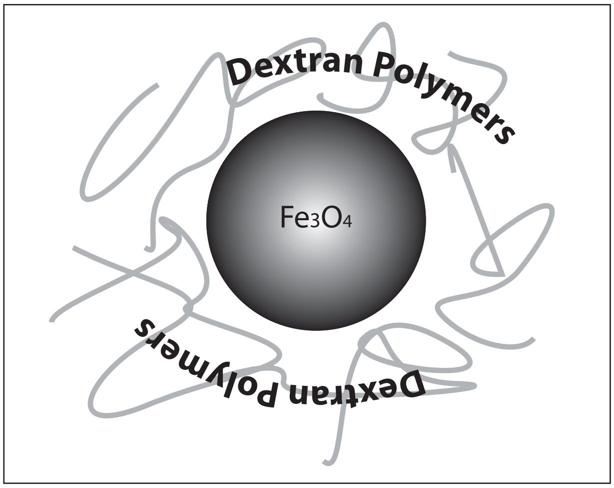

FIGURE 2 Combidex particles, which enhance contrast on MRIs, consist of superparamagnetic iron oxide nanoparticles covered with dextran. Because these particles are excluded from tumor-bearing regions of lymph nodes, they can help identify tumor-bearing nodes noninvasively.

Recently, the Combidex agent was rejected by the Food and Drug Administration (FDA) because of safety concerns and a lack of efficacy data. Questions regarding safety had arisen when at least one patient died in a clinical trial investigating the use of the Combidex agent for sentinel-node detection (finding near-nodes that are most likely to contain cancerous cells), which is critical to the grading, staging, and appropriate treatment of cancers. The FDA did recommend, however, that with further appropriately designed trials, the compound may be approvable for specific indications.

Quantum-Dot Technology

I have been extensively involved in work on the third example—the use of fluorescent quantum dots for biological detection in research and, ultimately, clinical applications (Figure 3). Semiconductor nanocrystals (i.e., quantum dots), specifically designed to have intense monochromatic emission spectra, are coupled to biological targeting molecules, such as antibodies and nucleic acids. The conjugates can then be used to detect the presence of particular analytes in biological samples. Although these particles dramatically increase experimental information and sensitivity, the clinical community has been slow to adopt them because of subtle protocol differences between these materials and the typical fluorescent dyes and enzymatic methods used in detection. Many of the protocol differences are thought to arise from distinct size differences between typical probes and nanotechnology-based probes. Such idiosyncrasies are likely to be ubiquitous in nanotechnology-enabled product commercialization.

The technology for the use of quantum dots in biology was initially published in September 1998 in two simultaneous papers in *Science* (Bruchez et al., 1998; Chan and Nie, 1998). Although these articles generated significant enthusiasm in the scientific community, biologically useful products were not launched until November 2002. In the meantime, Quantum Dot Corporation (QDC) was accused of hoarding the technology, stalling progress, and many other things.

In fact, the reasons for the delay were hardly nefarious—we have no rational framework for "optimizing" these materials. Therefore, although we were working very hard to make products that could be used successfully by the average biologist, every time we made an improvement to any aspect of the system, the entire process had to be revalidated. This empirical approach to product development resulted in a very long development time.

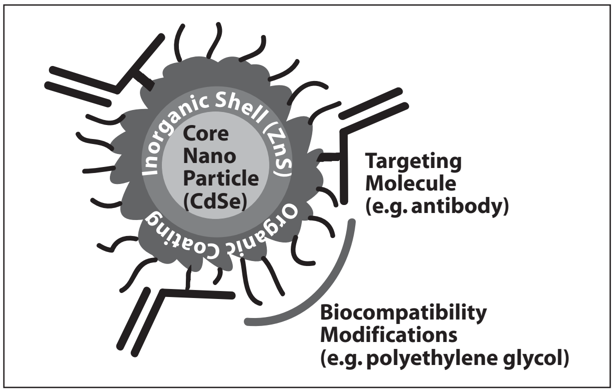

FIGURE 3 Quantum-dot conjugates have bright emission and multicolor capability, allowing researchers to view many targets in a single sample and simplifying detection strategies. The overall structure of these conjugates is designed and optimized for performance in biological applications (e.g., stability, brightness, and specificity).

This delay was in addition to unavoidable delays in process development. A nanoparticle designed for a particular application is a complex multilayer structure, shown schematically in Figure 3. Scale-up of the initial chemistries used to make these nanoparticles (as published in *Science*) was exceptionally dangerous; procedures involved pyrophoric precursors, flammable solvents, and rapid additions and releases of explosive gases. To develop safe, scaleable procedures, our scientists had to develop innovative techniques in all aspects of nanoparticle chemistry. Again, every innovation had to be validated through to the utility of the final material, making the development cycle exceptionally onerous. Just imagine if, to validate a change in one hose of a car, you had to build an entire car with only that change included.

The lack of specifiability of our modules was a key challenge to commercialization. Specification will require detailed basic investigations of the properties and chemistry of nanoparticle materials in biological systems. In addition, we will have to establish analytical tools and quantitative descriptors to detail the distribution of properties present in a population of nanoparticles. This is categorically different from specification for organic molecules and proteins, in which properties can be effectively described by an average. In nanomaterials, performance properties may be dominated by a relatively small population of particles, so averaging cannot always be used.

The Challenge of Characterization

Dramatically different tools are necessary for characterization of the three examples I have described. ADEPT, a fully biological system, can be characterized structurally, chemically, and on the basis of activity to ensure that each component of the system is capable of acting independently and that this behavior is preserved as the system components are brought together. Nevertheless, for reasons related to biological complexity, the use of ADEPT in the clinic has not yet proven beneficial. This problem gives some indication of the challenges ahead for nanotechnology solutions.

The second example, Combidex technology, is a homogeneous-particle technology covered with a natural material, dextran, that minimizes the complexity of the system. In this case, the particle size and shape (which can be characterized by electron microscopy) dictate its magnetic properties. The interaction of dextran on the surface dictates the in vivo behavior of these materials. Although the components can be characterized in great detail, the interaction of the dextran with the surface (e.g., the number of surface iron atoms that are actually covered) may be crucial to the fate of these materials in clinical use, an obstacle that was not predicted.

The interaction of molecules with surfaces in complex environments represents a critical area for analytical development. At the moment, many studies are carried out by x-ray photoelectron spectroscopy (XPS), a vacuum technique that does not show many solution interactions in the normal biological environment. Micro-rheology techniques might be valuable in addressing this issue.

The final example, quantum dots, an entirely engineered material, presents many characterization challenges. First, the particle itself is a complex structure, and the best available tools for characterizing these materials are capital intensive and often inaccessible. Essentially, methods such as energy-dependent XPS require a synchrotron source. Other methods, such as Z-contrast scanning transmission-electron microscopy, require unique instrumentation that is available only in a few laboratories in the world. In addition, these tools are suited either for measuring average properties or measuring single-particle properties, but not both. Bridging the gap to a statistical method that shows single-particle properties in a large population of particles would allow for discrimination of population properties from single-particle properties.

Moving out in the structure, the surface is coated with ligands. Thus, surface interactions will cause the same problems as have arisen for Combidex—routine tools do not give a detailed molecular picture of interactions at the surface. The problem is further complicated as particles are modified for biological applications, for instance by coupling polyethylene glycol molecules to the surface.

The characterization of chemistry on the surface of these particles has not matured to the level of typical organic chemical reactions. In fact, much of the characterization is still inferential (i.e., we analyze what does not react with the particle to determine what does react with it). The tools we have today neither discriminate between adsorbed and reacted materials nor determine whether the chemistry is homogeneous or heterogeneous from particle to particle. These distinctions will be critical for the development of nanoparticle tools with biomedical applications.

Outlook

Where, then, will bionanotechnology take us? As the examples I have described show, advances have progressed from ADEPT, a completely characterized system with a defined molecular structure (still encountering difficulty in clinical acceptance), to a system in which components are well characterized (Combidex), to quantum dots, a system we still cannot fundamentally characterize. Chemists have tools like mass spectrometry and nuclear magnetic resonance spectroscopy to guide them. Engineers have testing and measurement systems for validating systems as small as a few hundred nanometers. In the middle range, however, nanoengineers (or nanochemists) still do not have the fundamental tools to determine how well they have done their jobs or in what direction they should look for improvements.

Devices are synthesized on molar ($\sim 10^{26}$) scales, but the characterization tools designed for molecules do not work effectively for bionanotechnology systems. Clearly, the device characterization methods (typically single "device" characterization on enough devices to ensure a reliable measurement of production-run statistics) are inappropriate, especially when a dose is 10^{13} devices and a minor population component can dominate the bad effects (for instance pore-clogging).

Thus, we have an acute and growing need for specifiability in the design of bionanotechnology tools. To achieve engineerable systems, a concerted effort must be made to conduct a basic scientific investigation of the impact of materials properties on the biological behavior of bionanotechnology systems, combined with a physical scientific investigation of new methods to characterize the detailed physical and population properties of nanometer-scale materials and components. Specifiability will make predictability, falsifiability, and rapid progress in commercial bionanotechnology feasible.

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World travel demand will increase approximately in proportion to the increase in income.

Long-Term Trends in Global Passenger Mobility

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Andreas Schäfer*

Anticipating changes in travel demand on aggregate levels is critical for industries making decisions about meeting the demand for vehicles and fuel and for governments planning infrastructure expansions, predicting transport-sector (greenhouse-gas) emissions, and evaluating mitigation policies. In this paper, I show that only a few variables are necessary to explain past levels and project internally consistent future levels of aggregate, world-regional travel demand and transport modes. I then highlight the enormous challenges that must be met to reduce greenhouse-gas emissions, especially from passenger aircraft, the fastest growing transport mode.

Determinants of Aggregate Travel Demand and Transport Modes

Growth in per capita income and population are the two single most important factors in passenger mobility. During the past 50 years, global average per capita income has increased slightly more than threefold, and world population has more than doubled. This combined growth, by a factor of 7.4, has translated into a nearly proportional increase in passenger mobility. The nearly direct relationship can be explained by so-called travel budgets, roughly constant averages of expenditure shares of money and time.

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* The fundamental ideas underlying the model described in this paper were developed jointly with David G. Victor, Stanford University. See Schäfer and Victor (2000).

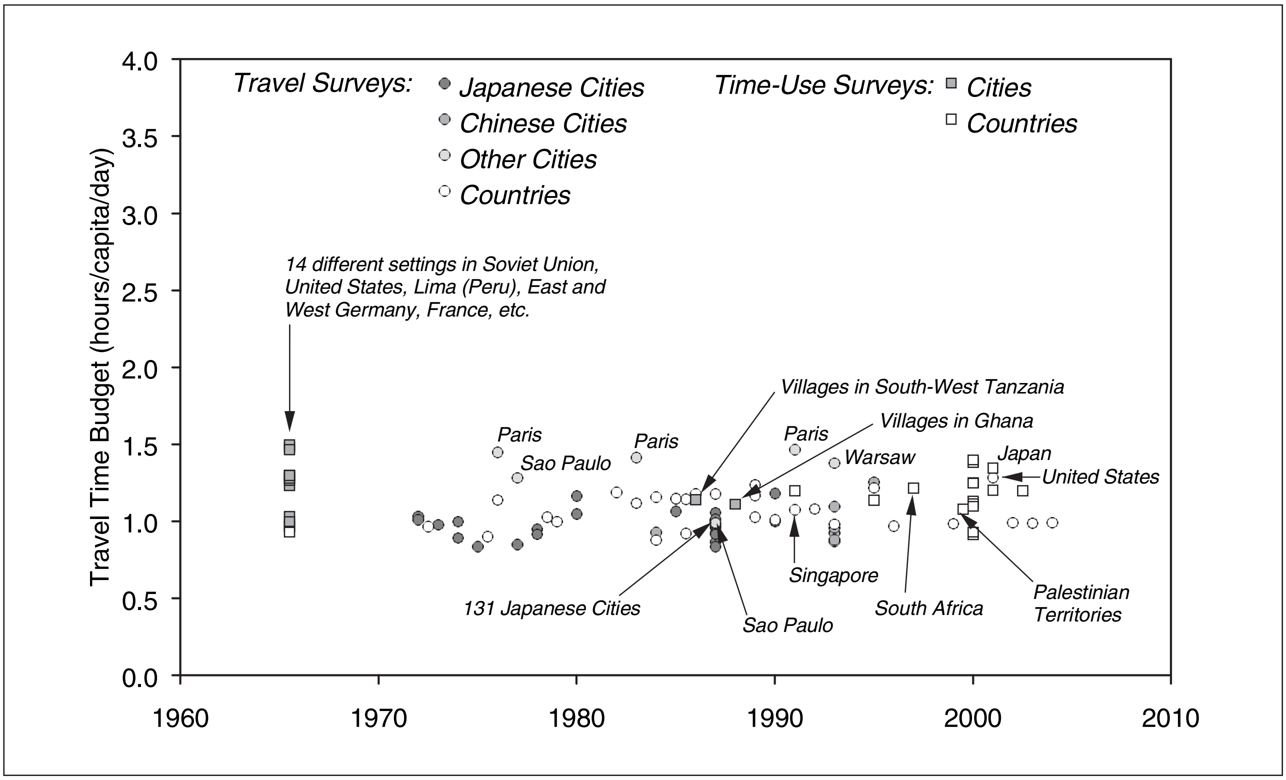

FIGURE 1 Average daily travel time as a function of per capita GDP.

Although the amount of time spent traveling is highly variable on an individual level, large groups of people spend about 5 percent of their daily time traveling. The stability of the aggregate "travel-time budget," first hypothesized in similar form for urban travelers by the late Yacov Zahavi (1981), is illustrated in Figure 1 for a wide range of income levels. On average, residents in African villages, the Palestinian Territories, and the suburbs of Lima spend between 60 and 90 minutes per day traveling, the same as for people living in the automobile-dependent societies of Japan, Western Europe, and the United States.

A similar transition, from variability at disaggregate levels to stability at aggregate levels, can be observed for travel-expenditure shares (i.e., the percentage of income dedicated to travel). Zahavi observed that households that rely exclusively on non-motorized modes of transport and public transportation spend only about 3 to 5 percent of their income on travel; that percentage rises to 10 to 15 percent for people who own at least one motor vehicle. Figure 2 shows that the aggregate "travel-money budget," here defined as total travel expenditures divided by the gross domestic product (GDP), follows a similar pattern, rising from about 5 percent of GDP at motorization rates close to zero cars per 1,000 capita (nearly all U.S. households in 1909 and the least developed countries today) to around 10 percent of GDP at about 300 cars per 1,000 capita (industrialized countries today), an ownership level of about one car per household of three to four people. In addition, travel demand and choice of transport mode depend on average door-to-door speed and travel costs to the consumer. The drastic decrease in the cost of air travel in the past decades has contributed to the rising share of that transport mode.

The Past Five Decades in World Travel Demand

To study the historical development and project the future development of global travel demand, we estimated a unique data set of passenger mobility for 11 world regions, covering passenger-kilometers (km) traveled (PKT) using four major modes of transport (light-duty vehicles, buses, railways, and aircraft) and spanning 51 years (1950 to 2000).[1] The overall relationship between GDP per capita and per person PKT is

[1] This data set is an update of an older data set for 1960 to 1990 by the same author. See Schäfer (1998).

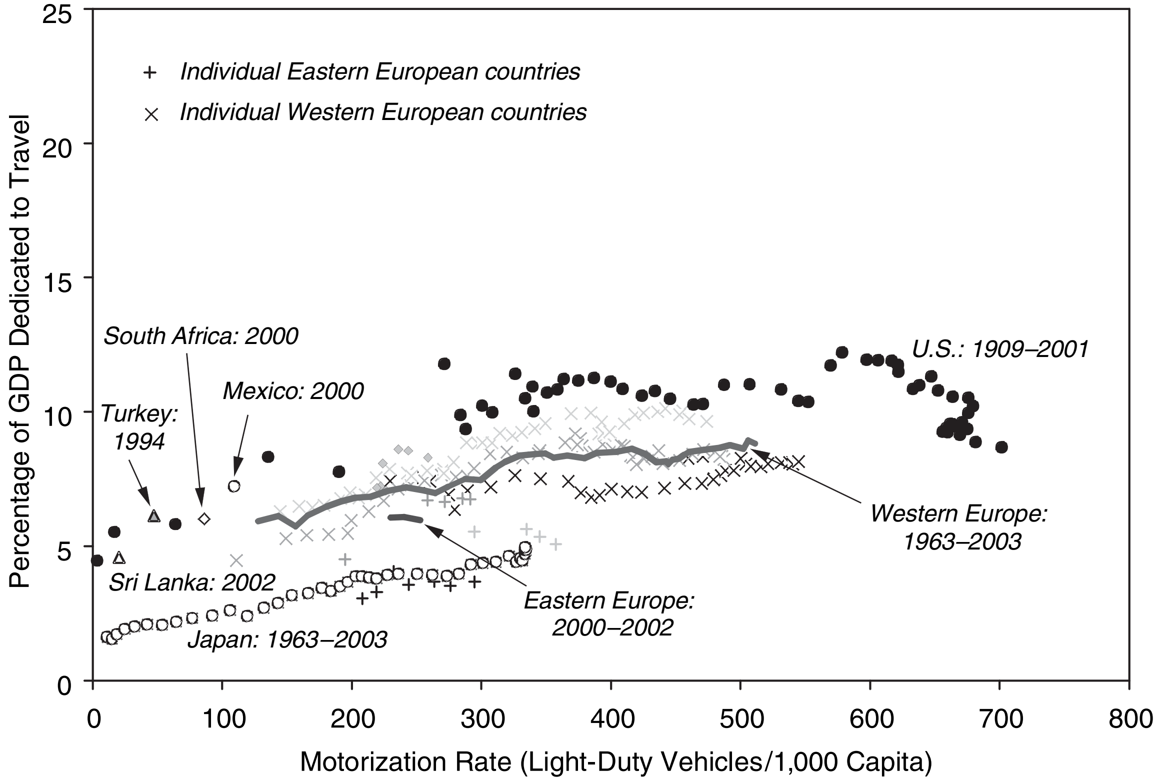

FIGURE 2 Travel expenditures as a fraction of income for annual travel distance.

shown in Figure 3. The saturating travel-money budget, described above, helps explain how rising GDP translates into rising travel demand.

Over the past five decades, Earth's inhabitants have increased their travel demand from an average of 1,400 to 5,500 km, using a combination of automobiles, buses, railways, and aircraft. Since the world population grew nearly 2.5-fold during the same period, world PKT increased by one order of magnitude, from nearly 3.6 to some 33 trillion PKT. The biggest increase in PKT, by a factor of more than 20, occurred in the developing world, where the combined growth in per capita GDP and population was largest.

However, the "mobility gap" between developing and industrialized regions remains substantial. In 2000, residents in North America, the Pacific OECD (Japan, Australia, and New Zealand), and Western Europe traveled 17,000 PKT per capita on average, five times as much as people in the developing world. These differences are even larger on a world-regional scale. Residents of North America, the region with the highest level of mobility, traveled 25,600 km per year, while people in sub-Saharan Africa (not including South Africa) traveled just 1,700 km.

GDP is the most important, but not the only, determinant of per-person PKT. As Figure 3 shows, the average travel per person differs significantly at different income levels, mainly because of different costs for transportation, but also because of the size of purchasing power parity (PPP) adjustments in the socioeconomic data set (Heston et al., 2002).

While the travel-money budget translates rising per capita GDP into rising PKT per capita, the fixed travel-time budget requires that the increasing travel demand be satisfied in the same amount of time. Since each transport mode operates within a known range of speeds, the increasing per-person travel demand can only be satisfied by shifting toward increasingly rapid transport.

Figure 4 shows the continuous shifts toward faster modes of transport, from low-speed public transportation (the aggregate of buses and low-speed railways), to light-duty vehicles (automobiles and personal trucks, but, for simplicity, referred to as automobiles), to high-speed modes of transportation (aircraft and high-speed rail), again for a 51-year historical time horizon. Three distinct phases of dominance by a single transport mode can be seen. Low-speed public transportation is dominant for mobility levels of up to 1,000 km/cap; light-duty vehicles between 1,000 and 10,000 km/cap; and high-speed transport modes at even higher levels of mobility.

Similar to differences in total mobility, differences in travel costs and in urban land-use characteristics can lead to different levels in shares for transport modes at a given level of PKT per capita. However, the impact of policy measures on choice of transport mode is limited—at least on the aggregate levels shown. In Eastern Europe and the former Soviet Union, access to private automobiles was severely restricted until the transition toward a market economy in the early 1990s. Nevertheless, the modal trajectories have evolved largely within the shaded envelopes.

The Next Five Decades in World Travel Demand

If travel-expenditure shares remain approximately stable, future increases in per capita GDP will continue to cause a rise in PKT. At the same time, the fixed travel-time budget will continue to push travelers toward faster modes of transport. The highest level of travel demand would be achieved if travelers used the fastest mode of transport for their entire daily travel-time budget 365 days a year. Assuming that aircraft gradually increase their current average "door-to-door" speed from about 260 km/h (including transfers to and from the airport) to 660 km/h, the current average airport-to-airport speed for domestic flights in the United States, and a travel-time budget of 1.2 h/d for 365 d/y, the annual per-person traffic volume would result in approximately 289,000 km. At that high mobility level, most travel would be international. Prices would adjust, and so would income levels.

Hence, regional differences in per capita traffic volume at a given GDP per capita, mainly resulting from differences in land use and prices, would decline, and the 11 trajectories would ultimately converge into a single point in the far future. Given historical development, it is assumed that the GDP per capita value of that "target point" would correspond to US$(2000) 289,000. (Sensitivity analyses show that the exact location of the target point has almost no impact on the levels projected for 2050.)

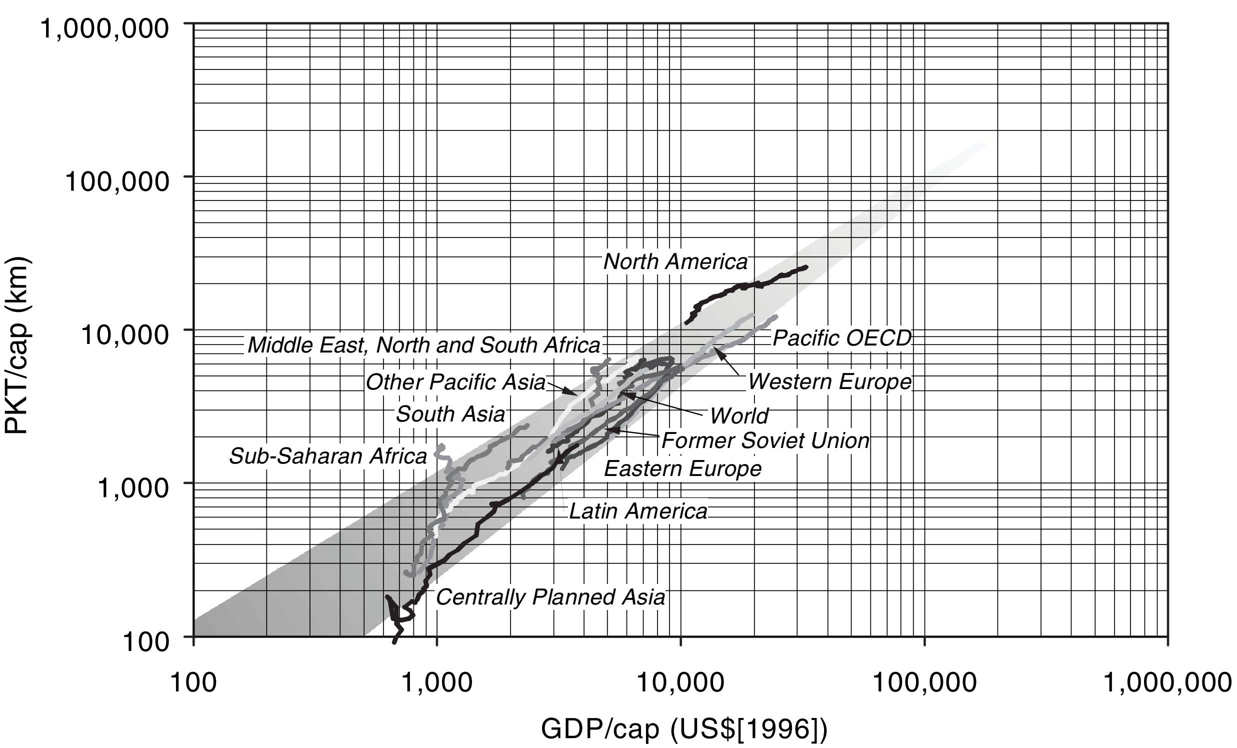

FIGURE 3 Passenger-km per capita by per capita GDP for 11 world regions and the entire world from 1950 to 2000.

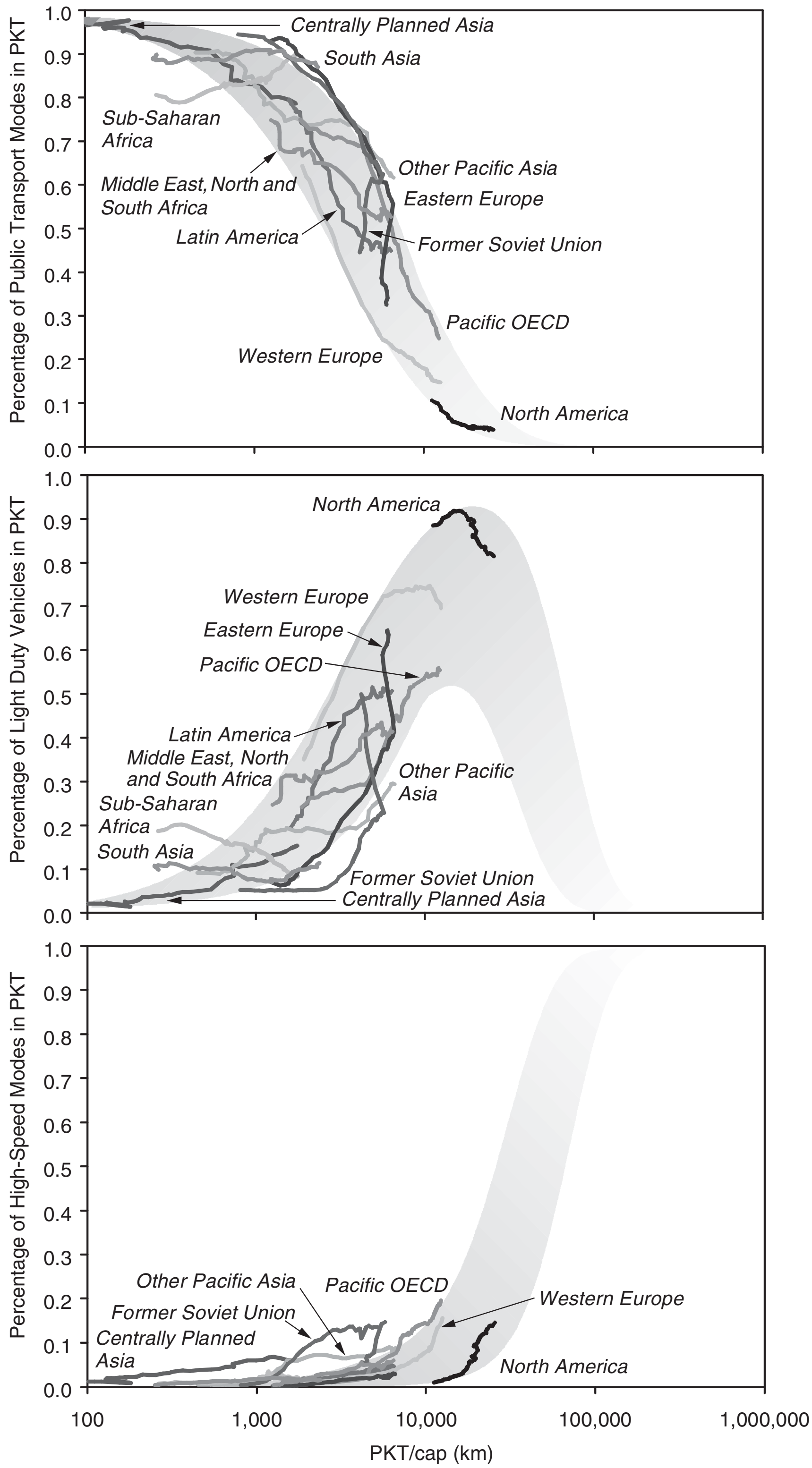

FIGURE 4 Three stages in the evolution of motorized mobility (1950–2000): the declining share of low-speed public transport modes (top), the growth and relative decline of the automobile (middle), and the rise of high-speed transportation (bottom).

This imaginary world of high-speed transportation helps in projecting future levels of PKT by approximating each of the 11 world-regional trajectories in Figure 3 by one and the same type of regression equation and by constraining one parameter of that equation so that the simulated trajectory must pass through the target point.[2] Future levels are then determined by the predicted levels of GDP/cap and population. The world-regional GDP per capita projections used here are derived from recent reference runs of the MIT Joint Program on the Science and Policy of Global Change Systems model, after slightly reducing the growth rates of industrialized regions and the reforming economies of Eastern Europe and the former Soviet Union and slightly increasing those of developing countries to match the mean values of past projections more closely (Nakicenovic, 2000; Paltsev et al., 2005). Overall, PPP adjusted gross world product per capita is projected to nearly double from US$(2000) 7,500 in 2000 to US$(2000) 14,200 in 2050. In addition to the 50 percent growth in world population, as suggested by the medium variant of the United Nations population projections (2004), gross world product would rise by a factor of nearly three.

Based on these changes in socioeconomic conditions, the stable relationship between growth in GDP and traffic volume implies that world-travel demand will increase approximately in proportion to the projected level of income, from 33 trillion passenger-km in 2000 to 105 trillion in 2050. Because of their projected higher growth in income and population, developing regions will contribute a rising share, ultimately accounting for 60 percent of world passenger-traffic volume in 2050, up from about 50 percent in 2000. (Higher growth rates of GDP in developing regions will further increase their absolute and relative importance in traffic volume.)

Given fixed travel time, future shares of low-speed public transportation modes, light-duty vehicles, and high-speed transportation systems must remain largely within the shaded envelopes in Figure 4. (The target point condition requires that high-speed transportation account for the entire traffic volume in a hypothetical world where the target point can be reached.) The precise shift in shares of transport modes, necessary to satisfy the projected travel demand through 2050, can be derived in a number of ways, but perhaps most convincingly by estimating the parameters of the functional form of statistical consumer-choice models. However, in this application, those models would require time-series data (ideally for 1950 to 2000) on speeds and travel costs for each transport mode. These data can be derived for the United States and, to a limited extent, for a few European countries and Japan, but they are not available for most countries in the world.

In 2050, light-duty vehicles and high-speed transport will account for roughly equal shares in the industrialized world.

Without these data, we can perform simplified projections by determining plausible future shares in each modal envelope at the projected level of per capita PKT, depending on whether a particular region is an early adopter or a latecomer to the diffusion of automobiles. Latecomers achieve lower shares of light-duty vehicle travel, here assumed to develop along the lower boundary of the automobile envelope in Figure 4, as they have already "leapfrogged" into high-speed travel and thus develop along the higher boundary of the high-speed transportation envelope in the same figure. (For a general introduction to diffusion theory, see Grübler, 1990.)

By contrast, future shares of high-speed transportation in the three industrialized regions and two reforming economies are estimated as the mean value of the upper and lower boundary of the envelope at the projected level of per capita GDP. The projection for the industrialized regions are then retrospectively compared to estimates from more sophisticated statistical-choice models, for which more complete speed and cost data are available. For example, the estimate of a detailed statistical-choice model for North America yields a 2050 share of 55 percent for high-speed transportation, which compares to 56 percent using the simplified approach.

[2] The general form of the regression equation is $PKT/cap = \chi \cdot (GDP/cap)^{\alpha} \cdot (P_T)^{\beta}$, with parameters χ being a constant, α the income elasticity, and β the price elasticity. However, because long-term historical data of travel costs (P_T) are available for very few countries, this factor is dropped. Thus, χ includes the averages of travel-money budget and price of travel in a particular region. Imposing the target point condition leads to an estimate of χ.

The use of statistical-choice models also allows us to conduct sensitivity tests (e.g., with regard to the stability of the travel-time budget). Should the travel-time budget increase from 1.2 to 1.5 hours per person per day (a 25 percent increase), the projected 2050 share of high-speed transportation would decline from 55 percent to 44 percent (a 20 percent decline). Although the decline in the 2050 share of high-speed transportation is significant, a 44 percent share still corresponds to three times the share for that transport mode in 2000.

In the industrialized world, light-duty vehicles and high-speed transportation modes will account for nearly the entire traffic volume in 2050 and for roughly equal shares. By contrast, in reforming economies and developing regions, automobiles will supply most of the PKT, followed by low-speed public transportation. In both meta-regions, however, high-speed transportation is also on the rise, accounting for nearly 20 percent of the 2050 passenger-traffic volume. Globally, the traffic shares of automobiles and low-speed public transport modes will decline by about 6 and 12 percentage points, respectively, below the 2000 level by 2050. At the same time, the relative importance of high-speed modes will increase from 10 percent to about 30 percent. Figure 5 summarizes the global development in PKT by major mode of transport for 1950, 2000, and 2050 (projected).

The simplified model necessarily has a number of limitations. Perhaps most important, the mode shifts in Figure 4 represent only the aggregate of two markets and do not capture substitutions in the urban and intercity transport segments. In the urban transportation segment, light-duty vehicles become more important to the cost of low-speed public transportation. By contrast, in intercity transport, automobiles are displaced by high-speed transportation modes. By disaggregating the data set into these two transportation markets and estimating (the functional form of) a nested, discrete-choice model, we could project plausible levels of shares for transport modes over time periods of more than 50 years. (Whether these projections will ultimately be achieved in reality is a different subject, which raises questions about whether such models are more valuable as tools for understanding interactions between humans and technology than for making exact predictions of the future.)

Another limitation is that the projection of future passenger mobility was performed in an unconstrained world. However, a separate analysis of potentially limiting factors, including the resource base of oil products, the need for higher aircraft speeds, the potential substitution of travel by telecommunication, increasing travel congestion, and so on, suggests that none of these constraints is likely to be binding in the next five decades. At some point in the future, however, the finite characteristics of our planet will necessarily have an impact on transportation systems.

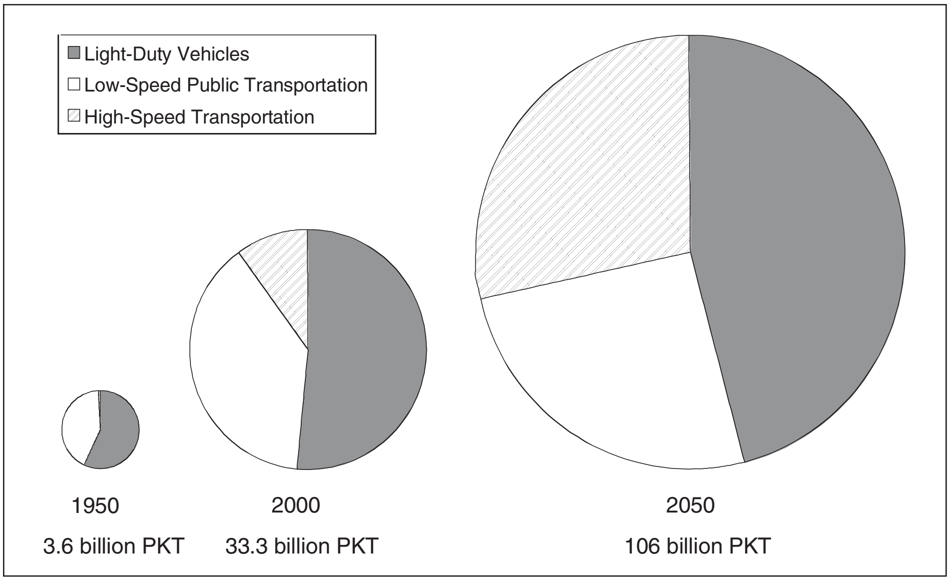

FIGURE 5 Global passenger-km traveled, by major mode of transport, in 1950, 2000, and 2050 (projected). Size of pies corresponds to PKT, which has been multiplied by nearly 10 times through 2000 and is likely to be multiplied by a factor of 30 by 2050. For comparison, GDP has grown by factors of 7 and 20, respectively.

Implications

The growth in travel demand and the shift toward faster transport modes have a number of implications. Two of the most important are for the amount of travel time spent in different transport modes and the impact on energy use and greenhouse-gas emissions.

Figure 6 shows the daily per-person travel distance by mode of transport (left) and the associated daily travel time (right) for 1950, 2000, and 2050 (projected) in North America (essentially the United States and Canada). Over the

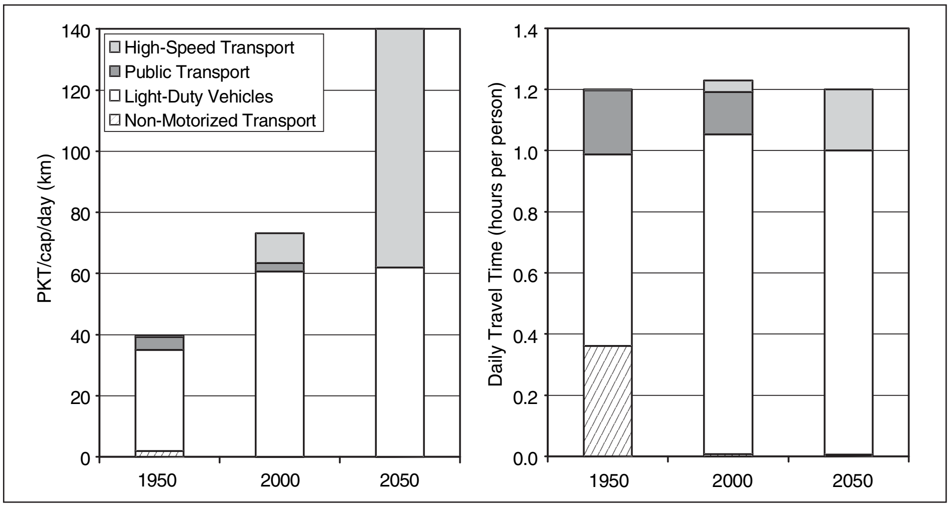

FIGURE 6 Daily per-person travel distance by mode of transport (left) and associated daily travel time (right) for 1950, 2000, and 2050 (projected) in North America.

past 50 years, the daily travel distance has more than doubled, from 30 km to 70 km, while per-person travel time has likely remained stable (no time-use data are available for 1950). Over the next five decades, based on our projection of per capita GDP, daily mobility will double again, to 140 km, with high-speed transportation accounting for 56 percent. However, despite the growing demand for high-speed transport, travelers will continue to spend most of their travel time on the road. Although automobile travel time will decrease only slightly, the main change in travel-time allocation will be a net substitution of high-speed transportation for low-speed public transportation. A traveler in 2050 will spend an average of 12 minutes per day in the air or on high-speed railways (compared to two minutes today). If the per-person travel-time budget increases to 1.5 hours per day, the average daily high-speed travel time will decrease to about 9 minutes.

Although total travel time may not be affected by the increase in travel demand, energy use and greenhouse-gas emissions will change. All factors being equal, rising travel demand will cause a proportional increase in passenger-travel energy use. Given that (synthetic) oil products are likely to continue dominating the future fuel supply of the transportation system, over the next five decades, directly released greenhouse-gas emissions will also rise, roughly in proportion to travel demand. (The increase in life-cycle greenhouse-gas emissions could be greater if there is a significant shift toward unconventional oil, such as extra-heavy oil, oil sands, or shale oil, or synthetic oil from natural gas or, especially, coal).

Changes in passenger-travel energy intensity (i.e., energy use per PKT) will also influence levels of passenger-travel energy use and greenhouse-gas emissions.

In the absence of more fuel-efficient transport modes, three trends will determine future levels of energy intensity. First, any increase in travel speed will cause an increase in energy intensity. Based on current and average U.S. data, a complete shift from low-speed public transportation to light-duty vehicles in urban travel would increase energy intensity by 25 percent. For intercity travel, a complete shift from low-speed public transportation to light-duty vehicles would increase energy intensity by almost 60 percent. A shift toward air travel would increase it by another 40 percent. In the United States, most of these changes have already taken place. If the ongoing shift from automobile intercity travel toward aircraft continues, intercity passenger-travel energy intensity will increase by 15 to 20 percent by 2050.

Second, the change to air travel for intercity transport will also increase the relative importance of urban automobile travel, which is more energy intense than intercity automobile travel because of varying engine loads and low occupancy rates. Thus, this shift will cause an increase in average automobile-travel energy intensity. However, even though the energy intensity of urban travel is twice that of intercity travel, it will probably only increase 10 percent or less, because nearly all PKT by automobiles already occurs over relatively short distances.

Third, the substitution of air transportation for intercity automobile travel mainly occurs at trip distances of less than 1,000 km, distances at which aircraft energy use is mainly determined by the energy-intensive take-off and climb stages. Aircraft energy intensity at such stage lengths can be twice as high as for trips of more than 1,000 km (Babikian et al., 2002).

In North America, the strong growth in air travel suggests that the combined effect of these three trends is determined mainly by the change in aircraft energy intensity resulting from the relative growth in different market segments. However, because the average energy

TABLE 1 Projected Percentage Change in Aircraft Energy Use by 2050.

	Low Estimate	High Estimate
Aircraft technology	–25	–45
PAX load factor	–10	–10
Direct flights	0	–11
Shift to high-speed rail	–1	–1
Totals	–33	–56

Sources: Lee et al., 2001; Jamin et al., 2004.

Note: Estimates for high-speed rail are based on 50 percent market share in 10 U.S. high-density corridors, with a cumulative great-circle distance of 16,700 km.

intensity of total air travel is lower than for automobiles and low-speed public transport modes operating in urban areas, the overall effect of these changes is likely to be negligible. Thus, total energy use and greenhouse-gas emissions will rise roughly in proportion to the growth in PKT (i.e., by 2050, 130 percent over the 2000 level, based on our assumptions of GDP growth). In Western Europe, the combination of these trends may result in passenger-travel energy intensity rising by 2050 by as much as 20 percent above the level for 2000.

The situation is fundamentally different, especially in developing countries, where the substitution of automobiles for low-speed public transportation is just beginning. Combined with a future decline in vehicle occupancy rates (mainly a consequence of increasing female participation in the labor force), the impact of these trends on passenger-travel energy intensity may be 50 to 100 percent. Compensating for this increase in energy intensity in developed countries already requires sophisticated fuel-saving technology.

In the passenger-transport sector, air travel accounts for the fastest growth in energy use and greenhouse-gas emissions. In addition to the projected ninefold increase in global air-travel demand, future levels of air-travel greenhouse-gas emissions will depend on which technologies are used, assuming that (synthetic) oil products continue to fuel air transportation. Table 1 shows the major opportunities for reductions in aircraft energy use for a given travel demand based on recent studies. Even if aircraft energy use is reduced by 33 to 56 percent by 2050, the 2000 level of carbon dioxide emissions would still be multiplied by a factor of four to six. Thus, controlling greenhouse-gas emissions from transportation will remain a significant challenge for generations to come.

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We are on the verge of a transformation in urban transportation called New Mobility.

New Mobility: The Next Generation of Sustainable Urban Transportation

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Susan Zielinski

In a classic 1950s photograph, a scientific looking man in a light suit is dwarfed by a mammoth mainframe computer he's programming. It is unlikely that the idea of a "nanopod" would have entered his mind, let alone mesh networking, GIS, or "Googling." He wouldn't have conceived of the connectivity that a mere half-century later has brought these elements together, transformed the world, and evolved into one of the fastest growing, most pervasive global industries.

Today, we are on the cusp of a comparable transformation for cities called New Mobility. Accelerated by the emergence of new fuel and vehicle technologies; new information technologies; flexible and differentiated transportation modes, services, and products; innovative land use and urban design; and new business models, collaborative partnerships are being initiated in a variety of ways to address the growing challenges of urban transportation and to provide a basis for a vital New Mobility industry (MTE and ICF, 2002).

Connectivity

An early and very successful example of integrated innovation in New Mobility is the Hong Kong Octopus system, which links multiple transit services, ferries, parking, service stations, access control, and retail outlets and rewards via an affordable, contactless, stored-value smart card. The entire

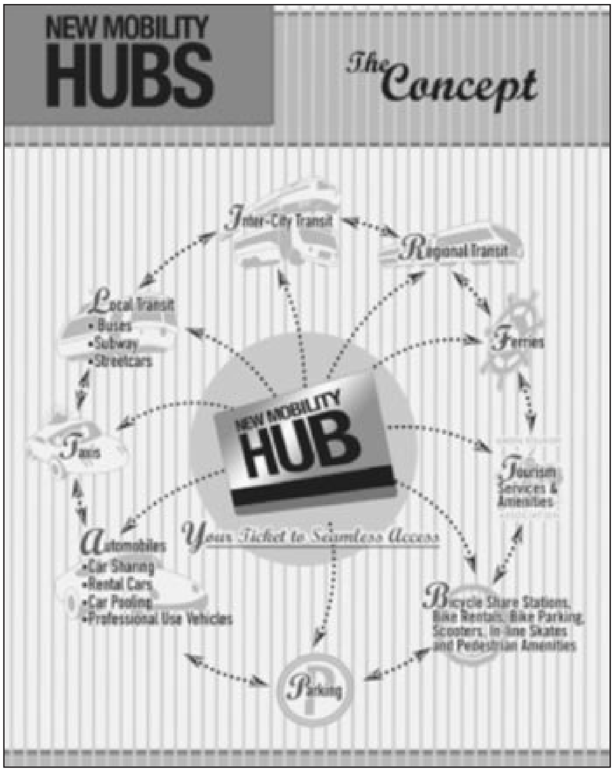

FIGURE 1 The New Mobility hub concept. Source: MTE, 2004.

system is designed and engineered to support seamless, sustainable door-to-door trips (Octopus, 2006).

A more recent innovation, referred to as New Mobility hub networks, began in Bremen, Germany, and is evolving and spreading to a number of other European cities, as well as to Toronto, Canada (Figure 1). New Mobility hubs connect a variety of sustainable modes of transportation and services through a network of physical locations or "mobile points" throughout a city or region, physically and electronically linking the elements necessary for a seamless, integrated, sustainable door-to-door urban trip (MTE, 2004). Hubs are practical for cities in the developed or developing world because they can be customized to fit local needs, resources, and aspirations. Hubs can link and support a variety of diverse elements:

- multiple transportation operators, modes, and services
- taxis and car-sharing of a variety of vehicle types and sizes
- "slugging" (Slug-Lines.com, 2006)
- free or fee-for-use bicycle sharing (Bikeshare/CBN, 2006)
- walkable, bikable, and transit-oriented spatial design and development (Kelbaugh, 1997)
- cafes and meeting places
- wi-fi amenities
- electronic fare-payment options and pricing mechanisms for all transportation modes and services
- satellite-enhanced, real-time, urban traveler information for all modes of transportation provided at on-street kiosks and by pda

Factors Driving the Development of New Mobility

The evolution of New Mobility is inspired by emerging innovations and propelled by pressing needs, not the least of which is rapid urbanization. Although a few cities are shrinking, especially in the developed world, by 2030 more than 60 percent of the world population and more than 80 percent of the North American population will live in urban regions (UN, 1996). With increasing motorization, traffic volume and congestion are already resulting in lost productivity and competitiveness, as well as health and other costs related to smog, poor air quality, traffic accidents, noise, and, more recently, climate change (WBCSD, 2001).

At the same time, sprawling, car-based, urban-development patterns can mean either isolation or chauffeur dependence for rapidly aging populations, as well as for children, youths, and the disabled (AARP, 2005; Hillman and Adams, 1995; O'Brien, 2001; WBCSD, 2001). In developing nations, aspirations toward progress and status often translate into car ownership, even as the risks and costs of securing the energy to fuel these aspirations rise (Gakenheimer, 1999; Sperling and Clausen, 2002; WBCSD, 2001).

Engineering for New Mobility

The factors described above have created not only compelling challenges for engineering, but also opportunities for social and business innovation. New Mobility solution building is supported by new ways of thinking about sustainable urban transportation, as well as emerging tools and approaches for understanding, implementation, and commercialization. In this article, I focus on three frontiers of thinking and practice for New Mobility: complexity; accessibility; and new business models.

Complexity

Tools for Understanding

A variety of tools and approaches have been developed to support the analysis and modeling of complex urban transportation systems. At least three types of complementary systems analysis (top-down, bottom-up, and simulations) can be applied to transportation and accessibility. Top-down analyses generally start with self-generated variables or hypotheses and develop a causal-loop diagram using software that highlights patterns, dynamics, and possible intervention points. Once a basic analysis is complete, more in-depth data gathering and modeling can be done. Some of the most extensive transportation-related work of this kind has been undertaken by Professor Joseph Sussman at M.I.T. (Dodder et al., 2002; Sussman, 2002; Sussman and Hall, 2004). Figure 2 shows a passenger-transportation subsystem for Mexico City.

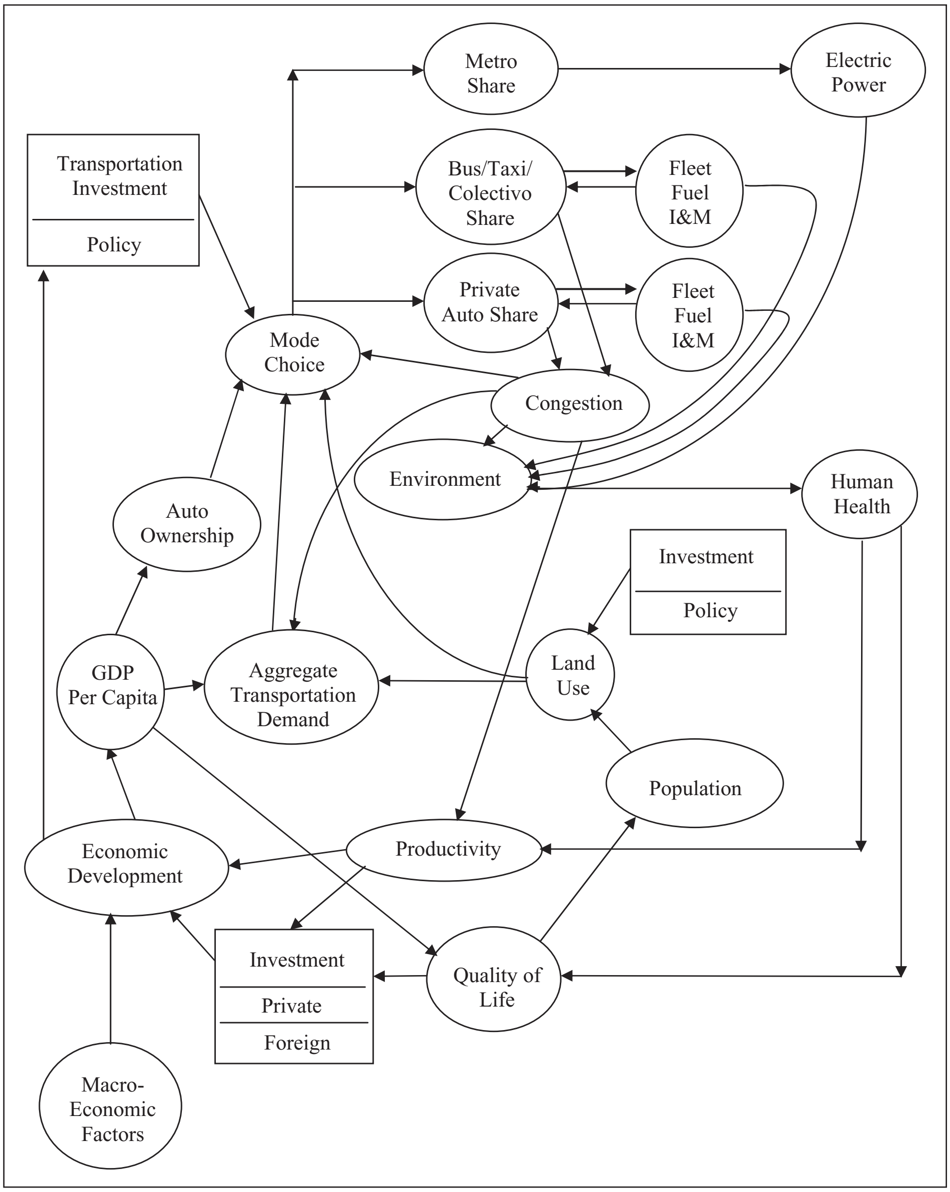

FIGURE 2 Part of a larger analysis showing a passenger-transportation subsystem for Mexico City. Source: Dodder et al., 2002.

Bottom-up, or agent-based, models, are computer-based models that use empirical and theoretical data to represent interactions among a range of components, environments, and processes in a system, revealing their influence on the overall behavior of the system (Axelrod and Cohen, 2000; Miller and Roorda, 2006; Miller and Salvini, 2005; Zellner et al., 2003). Ethnographic research can also be applied to transportation as a bottom-up research tool. By giving subjects documentation tools (e.g., cameras) over a fixed period of time, patterns of behavior can be observed without interference by researchers.

Simulations and scenario-building software can draw from and build upon both top-down and bottom-up analyses. Simulations graphically depict and manipulate transportation and other urban dynamics to inform decision making and identify opportunities for innovation. MetroQuest (2006) is a good example of an effective urban-transportation simulation tool.

Sophisticated Solution Building

Complex transportation challenges call for sophisticated solutions. "Single-fix" approaches (e.g., alternative fuels alone, pricing mechanisms alone, or policy changes alone) cannot address the serious urban challenges and conditions noted above. Informed by complex systems

SMART

UNIVERSITY OF MICHIGAN

SMART (Sustainable Mobility and Accessibility Research and Transformation), an interdisciplinary initiative at the University of Michigan in Ann Arbor, is grounded in complexity theory and practice. The goal of the project is to move beyond purely technical and mobility-based approaches to urban transportation to address challenges and opportunities raised by the complex interactions of social, economic, environmental, and policy factors. A project of CARRS (Center for Advancing Research and Solutions for Society), SMART brings together experts on issues, theoretical approaches, and practical and policy applications to tackle the complexity, sophistication, impacts, and opportunities related to urban transportation and accessibility, particularly for growing urban populations worldwide. SMART works collaboratively across disciplines and sectors to:

- catalyze systemic and fundamental transformations of urban mobility/accessibility systems that are consistent with a sustainable human future
- harness emerging science on complex adaptive systems to meet future mobility and accessibility needs in an ecologically and socially sustainable way and identify "tipping points" to guide the evolution of such systems
- inform and develop integrated New Mobility innovation and business models
- provide diverse academic opportunities related to sustainable urban mobility and accessibility
- contribute to a growing multidisciplinary, multi-stakeholder, global network of applied learning in sustainable mobility and accessibility

analysis, systems-based solution building involves "connecting the dots," that is, enhancing or transforming existing conditions with customized, integrated innovations in products, services, technologies, financing, social conditions, marketing, and policies and regulations (ECMT, 2006; MTE and ICF, 2002; Newman and Kenworthy, 1999). Sophisticated solution building usually involves multisector interdisciplinary collaboration.

A good example of systems-based solution building is the New Mobility hub network described above. Hub networks can catalyze engineering and business opportunities related not only to the design and implementation of individual product and service innovations, but also to the engineering of physical and digital connections between them.

Accessibility

Over the past 50 years, measures of regional and economic success have become increasingly linked to (motorized) mobility and speed of travel (TTI, 2005). This association originated in the West and has been widely adopted in cities of the developing world. However, transportation is only a means to an end, or a derived demand, so measures and applications of accessibility do not focus on how fast or how far one can travel in a certain period of time. Instead, they focus on how much can be accomplished in a given time frame and budget or how well needs can be met with available resources. For example, on a typical day in Los Angeles, you may drive long distances at high speeds to fit in three meetings. In Bremen, Germany, a more accessible place, you may be able to fit in five meetings and a leisurely lunch, covering only half the distance at half the speed and for half the price (Levine and Garb, 2002; Thomson, 1977; Zielinski, 1995).

Accessibility can be achieved in at least three ways: wise land use and design; telecommunication technologies that reduce the need for travel; and seamless multimodal transportation. Among other benefits, connected accessibility options can help address the demographic, equity, and affordability needs of seniors, children, the poor, and the disabled. At the same time, integrated accessibility can help build more adaptable and resilient networks to meet the challenges of climate change and emergency situations in cities. Dynamic and flexible accessibility and communications systems can support quick responses to unforeseen urban events.

The University of Michigan's SMART/CARSS project (2006) is currently developing an accessibility index to compare and rate accessibility in metropolitan regions, as a basis for urban policy reform and innovation (see sidebar).

New Business Models

In a 2002 study by Moving the Economy, the current value and future potential of New Mobility markets were measured in billions of dollars (MTE and ICF 2002). New Mobility innovations and opportunities go beyond the sectoral bounds of the traditional transportation industry. They encompass aspects of telecommunications; wireless technologies; geomatics; e-business and new media; tourism and retail; the movement of goods; supply chain management (Zielinski and Miller, 2004); the design of products, services, and technologies; real estate development; financial services; and more.

New Mobility innovations not only improve local competitiveness and quality of life (Litman and Laube, 2002; Newman and Kenworthy, 1999), they also provide promising export and economic development opportunities for both mature and "base-of-the-pyramid" markets (Hart, 2005; Prahalad, 2004). Because urban transportation represents an increasingly urgent challenge worldwide, and because urban mobility and accessibility solutions can, in most cases, be adapted and transferred, regions, nations, and enterprises that support New Mobility (supply-side) innovation, as well as industry clustering and the development of new business models, stand to gain significantly from transportation export markets in the coming years (MTE and ICF, 2002).

Engineering and Beyond

New Mobility has the potential to revitalize cities and economies worldwide and can open up a wealth of engineering and business opportunities. But obstacles will have to be overcome, not all of them related to engineering. For example, increased motorization and the high social status it represents in developing countries, along with seemingly unstoppable urban sprawl in the West, are challenges that must be addressed on psychological and cultural levels, as well as infrastructural and economic levels. Progress toward a positive, integrated, and sustainable future for urban transportation will require more than moving people and goods. It will also involve the complex task of moving hearts and minds.

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Coping with disruptions in demand requires different strategies than coping with disruptions in supply.

Managing Disruptions to Supply Chains

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For as long as there have been supply chains, there have been disruptions, and no supply chain, logistics system, or infrastructure network is immune to them. Nevertheless, supply-chain disruptions have only recently begun to receive significant attention from practitioners and researchers. One reason for this growing interest is the spate of recent high-profile disruptions, such as 9/11, the West Coast port lockout of 2002, and hurricanes Katrina and Rita in 2005.

Another reason is the focus in recent decades on the philosophy of "lean" supply chains, which calls for slimmed-down systems with little redundancy or slack. Although lean supply chains are efficient when the environment behaves as predicted, they are extremely fragile, and disruptions can leave them virtually paralyzed. Evidently, there is some value to having slack in a system.

A third reason for the growing attention paid to disruptions is that firms are much less vertically integrated than they were in the past, and their supply chains are increasingly global. A few decades ago, many firms manufactured

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products virtually from scratch. For example, IBM used to talk, only slightly hyperbolically, about sand and steel entering one end of the factory and computers exiting the other. In contrast, today's firms tend to assemble final products from increasingly complex components procured from suppliers rather than produced in-house. These suppliers are located throughout the globe, many in regions that are unstable politically or economically or subject to wars and natural disasters. In his recent book *End of the Line*, Barry Lynn (2006) argues that this globalization has led to extremely fragile supply chains.

Supply-chain disruptions can have significant physical costs (e.g., damage to facilities, inventory, electronic networks) and subsequent losses due to downtime. A recent study (Kembel, 2000) estimates the cost of downtime (in terms of lost revenue) for several on-line industries that cannot function if their computers are down. For example, the cost of one hour of downtime for Ebay is estimated at $225,000, for Amazon.com, $180,000, and for brokerage companies $6,450,000. Note that these numbers do not include the cost of paying employees who cannot work because of an outage (Patterson, 2002) or the cost of losing customers' goodwill. Moreover, a company that experiences a supply-chain disruption can expect to face significant declines in sales growth, stock returns, and shareholder wealth for two years or more following the incident (Hendricks and Singhal, 2003, 2005a, 2005b).

Disruptions in supply or demand tend to cascade through the system.

The huge costs of disruptions show that business continuity is vital to business success, and many companies are actively pursuing strategies to ensure operational continuity and quick recovery from disruptions. For example, Wal-Mart operates an Emergency Operations Center that responds to a variety of events, including hurricanes, earthquakes, and violent criminal attacks. This facility receives a call from at least one store with a crisis virtually every day (Leonard, 2005). Other firms have outsourced their business continuity and recovery operations. IBM and SunGard, the two main players in this field, provide secure data, systems, networks, and support to keep businesses running smoothly during and after disruptions.

Supply chains are multi-location entities, and disruptions are almost never local—they tend to cascade through the system, with upstream disruptions causing downstream "stockouts." In 1998, for example, strikes at two General Motors parts plants led to shutdowns of more than 100 other parts plants, which caused closures of 26 assembly plants and led to vacant dealer lots for months (Brack, 1998). Another, scarier, example relates to port security (Finnegan 2006):

> *National-security analysts estimate that if a terrorist attack closed New York Harbor in winter, New England and upstate New York would run out of heating fuel within ten days. Even temporarily hampering the port's operations would have immeasurable cascading effects.*

Nevertheless, very little research has been done on disruptions in multi-location systems. Current research is focused mostly on single-location systems and the local effects of disruptions. The research discussed below is a step toward filling this gap.

Underlying Concepts

Supply uncertainty (SU) and demand uncertainty (DU) have several similarities. In both cases, the problem boils down to having too little supply to meet demand, and it may be irrelevant whether the mismatch occurs because of too much demand or too little supply. Moreover, firms have used similar strategies—holding extra inventory, using multiple suppliers, or improving their forecasts—to protect against both SU and DU.

These similarities offer both good and bad news. The good news is that supply chains under DU have been studied for decades, and we know a lot about them. The bad news is that much of the conventional wisdom about DU is exactly wrong for SU. Thus, we need research on supply chains under SU to determine how they behave and to develop strategies for coping with disruptions in supply.

Related Literature

In the early 1990s, researchers began to embed supply disruptions into classical inventory models, assuming that a firm's supplier might experience a disruption when the firm wished to place an order. (See Nahmias [2005] for an introduction to inventory theory and Zipkin [2000] for a more advanced treatment.) Examples include models based on the economic order quantity (EOQ) model (Berk and Arreola-Risa, 1994; Parlar and Berkin, 1991), the (R,Q) model (Gupta, 1996; Parlar, 1997), and the (s,S) model (Arreola-Risa and DeCroix, 1998). All of these models are generally less tractable than their reliable supply counterparts, although they can still be solved easily using relatively simple algorithms.

More recent literature has addressed higher level, strategic decisions made by firms in the face of disruptions. For example, Tomlin (2006) explores strategies for coping with disruptions, including inventory, dual sourcing, and acceptance (i.e., simply accepting the risk of disruption and not protecting against it), and shows that the optimal strategy changes as the disruption characteristics change (e.g., disruptions become longer or more frequent). Tomlin and Snyder (2006) examine how strategies change when a firm has advance warning of an impending disruption. Lewis, Erera, and White (2005) consider the effects of border closures on lead times and costs. Chopra, Reinhardt, and Mohan (2005) evaluate the error that results from "bundling" disruptions and yield uncertainty (another form of SU) when making inventory decisions.

Only a very small body of literature is focused on disruptions in multi-location supply chains. Hopp and Yin (2006) investigated optimal locations for capacity and inventory buffers in a multi-location supply chain and concluded that as potential disruptions become more severe, buffer points should be located closer to the source of disruptions. Kim, Lu, and Kvam (2005) evaluated the effects of yield uncertainty in a three-tier supply chain. They addressed the consequences of the decision maker's risk-aversion, an important factor when modeling infrequent but high-impact events.

A growing literature addresses disruptions in the context of facility location. Here, the objective is to choose locations for warehouses and other facilities that minimize transportation costs to customers and, at the same time, account for possible closures of facilities that would necessitate re-routing of the product. Although these are multi-location models, they focus primarily on the local effects of disruptions (see Snyder et al. [2006] for a review). We discuss these models in greater detail below.

Supply Uncertainty vs. Demand Uncertainty

In the sections that follow, we discuss the differences between SU and DU in multi-echelon supply chains. (An *echelon* is a "tier" of a supply chain, such as a factory, warehouse, retailer, etc.). We consider several studies, each of which examines two possible answers to a question of supply-chain design or management. Each study demonstrates that one answer is optimal for SU while the opposite answer is optimal for DU. Some of these results may be proven theoretically. Others are demonstrated using simulation by Snyder and Shen (2006).[1]

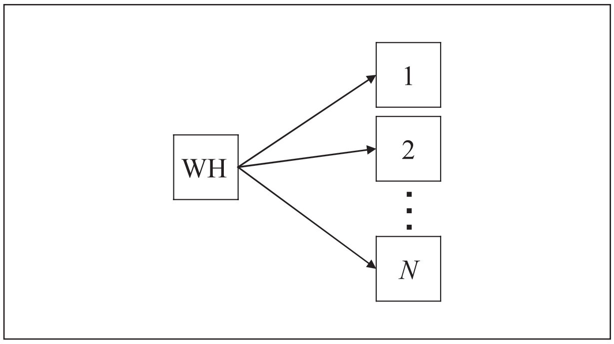

FIGURE 1. One-warehouse, multi-retailer system.

Centralization vs. Decentralization

Consider a system with one warehouse that serves N retailers (Figure 1). Under DU, it is well known that if the holding costs are equal at the two echelons and transportation times are negligible, then the optimal strategy is to hold inventory at the warehouse (a *centralized* system) rather than at the individual retailers (a *decentralized* system). This is because of the *risk-pooling* effect, which says that the total mean cost is smaller in the centralized system because cost is proportional to the standard deviation of demand. The standard deviation, in turn, is proportional to the square root of N in the centralized system but is linear in the decentralized system (Eppen, 1979). Although the assumptions of equal holding costs and negligible lead times are unrealistic, the risk-pooling effect and the insights that arise from it are applied widely in supply-chain planning and management.

Now consider the same system under SU (with deterministic demand). In this case, if inventory sites are subject to disruptions, it may be preferable to hold inventory at the retailers rather than at the warehouse. Under this decentralized strategy, a disruption would affect only a fraction of the retailers; under a centralized strategy, a disruption would affect the whole supply chain. In fact,

[1] Although we use terminology suggestive of private-sector supply chains (e.g., "firms" and "retailers"), the results discussed in this paper are also applicable to noncommercial supply networks (e.g. military, health care, and humanitarian networks).

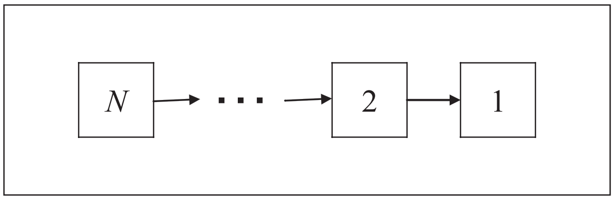

FIGURE 2. Serial system.

the *mean* costs of the two strategies are the same, but the decentralized strategy results in a smaller *variance* of cost. This is referred to as the *risk-diversification* effect, which says that disruptions are equally frequent in either system, but they are less severe in the decentralized system (Snyder and Shen, 2006).

Inventory Placement

In a serial system (Figure 2), a common question is which stages should hold inventory. Under DU, the tendency is to push inventory as far upstream as possible (to the left in Figure 2), because the cost of holding inventory tends to increase as one moves downstream in a supply chain. Under SU, however, the tendency is reversed. It is preferable to hold inventory downstream, where it can protect against disruptions elsewhere in the supply chain. For example, this might mean that a manufacturing firm should hold inventory of raw materials under DU but of finished goods under SU.

Hub-and-Spoke vs. Point-to-Point Networks

Figure 3 shows two possible networks for a firm with a single factory that wants to distribute its product to multiple retailers. The network in Figure 3a is a *hub-and-spoke* network, with intermediate warehouses that hold inventory and distribute it to retailers. The network in Figure 3b is a *point-to-point* network in which the warehouses are bypassed and retailers hold the inventory. Many firms operate hub-and-spoke networks because of economies of scale and other savings from consolidating inventory locations. Even absent economies of scale, however, the hub-and-spoke network is optimal under DU because of the risk-pooling effect (there are fewer inventory-stocking locations, hence a smaller total inventory requirement). Under SU, however, the point-to-point network is preferable because of the risk-diversification effect (increasing the number of stocking locations reduces the severity of disruptions).

A relevant analogy comes from the airline industry. Large U.S. carriers have primarily adopted a hub-and-spoke model because of the economies of scale it offers regarding airport infrastructure and the scheduling of flight connections. However, when a disruption (e.g., a thunderstorm) occurs at a hub, it can affect the carrier's entire domestic flight network. In contrast, smaller carriers have tended to adopt point-to-point networks that allow flight schedules to be somewhat more flexible and reactive.

Supplier Redundancy

Consider a single firm with a single supplier trying to determine the value of adding backup suppliers. Suppose that each supplier has sufficient capacity to meet the mean demand plus a few standard deviations. Under DU, backup suppliers have little value because they would fill in only when demand exceeds capacity, which happens infrequently. Under SU, however, backup suppliers play a vital role because they provide capacity both to meet demand *during* a disruption to the primary supplier and to ramp up supply *after* a disruption.

Facility Location

Classical facility-location models choose locations for plants, warehouses, and other facilities to minimize transportation cost or achieve some other measure of proximity to both suppliers and customers (Daskin, 1995; Drezner and Hamacher, 2002), typically ignoring both DU and SU. A recent model finds that under DU the optimal number of facilities decreases because of the risk-pooling effect and economies of scale from consolidation (Shen, Coullard, and Daskin, 2003). Conversely, when facilities face potential disruptions (i.e., under SU) the optimal number of facilities increases because of the risk-diversification effect (Snyder and Daskin, 2005). A model currently under development incorporates both DU and SU, thus balancing these competing tendencies (Jeon, Snyder, and Shen, 2006).

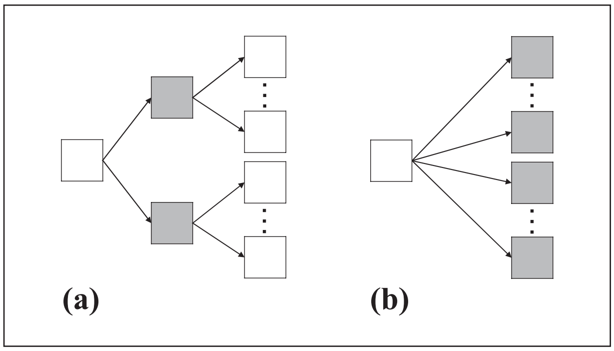

FIGURE 3. 3a. Hub-and-spoke network. 3b. Point-to-point network. Sites that hold inventory are shaded.

Cost of Reliability

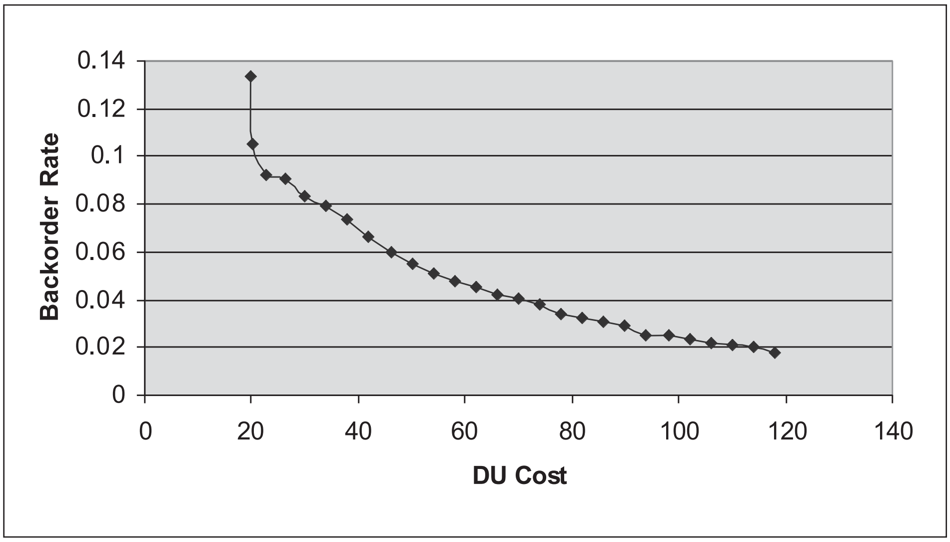

FIGURE 4. Trade-off curve.

A firm that is used to planning primarily for DU may recognize the importance of planning for SU but may be reluctant to do so if it requires a large up-front investment in inventory or infrastructure. Fortunately, a small amount of extra inventory goes a long way toward protecting against disruptions. Figure 4 shows the trade-offs between the vulnerability of a system to disruptions (on the *y*-axis, measured by the percentage of demands that cannot be met immediately) and the cost under DU (on the *x*-axis, measured in the cost the firm is used to considering).

Each point in Figure 4 represents a possible solution, with the left-most point representing the optimal solution if there are no disruptions. This solution is cheap but very vulnerable to disruptions. The left-hand portion of the curve is steep, suggesting that large improvements in reliability are possible with small increases in cost. For example, the second point shows 21 percent fewer stockouts but is only 2 percent more expensive. This trend is fairly common and has been identified in other contexts, including facility location with disruptions (Snyder and Daskin, 2005).

Conclusions

Studies of SU and DU in multi-echelon supply chains show that the two types of uncertainty require different strategies in terms of centralization, inventory placement, and supply-chain structure. In fact, the optimal strategy for dealing with SU is, in many cases, the exact opposite of the optimal strategy for DU. However, we are not suggesting that firms are currently doing everything wrong. Rather, we are arguing that although DU leads to certain tendencies in supply-chain management (e.g., centralization), SU suggests opposite strategies that should also be considered when making supply-chain decisions. Fortunately, it can be relatively inexpensive to shift the balance enough to account for SU, in the sense that the trade-offs between the two types of uncertainty are favorable.

In virtually all practical settings, both DU and SU are present, and the optimal strategy must account for interactions between them. For example, since upstream inventory is cost effective under DU but downstream inventory is most helpful under SU, a firm may wish to adopt a hybrid strategy that combines the advantages of both. For example, many firms hold inventory of both raw materials (upstream) and finished goods (downstream), with raw material inventory accounting for the bulk of the firm's inventory holdings but finished goods inventory acting as a key buffer against uncertainty. Alternately, a hybrid strategy may involve holding inventory near the middle of the supply chain (rather than at both ends). For example, Dell holds inventory of sophisticated components, assembling them into finished goods only after orders are placed.

It is our hope that researchers will continue investigating the causes and effects of supply-chain disruptions, as well as strategies for coping with them. One important area for future research is the development of analytical tools for understanding the interdependence of risks faced by a supply chain. A single event (e.g., an economic downturn or a bird-flu pandemic) might cause multiple types of disruptions (e.g., a shortage of raw materials and absenteeism among the firm's own workforce), and these risks may be subtly related. In other words, the supply chain's total risk may not be a simple sum of its parts.

Another promising avenue for future research is to develop strategies for designing resilient supply chains. How can a supply chain's infrastructure be designed so that buffers are located in the right places and in the right quantities to protect against disruptions and other forms of uncertainty? What forms should these buffers take (e.g., inventory, capacity, redundant supply)?

Many of the analytical models for designing and managing supply chains under uncertainty assume that the decision maker has some knowledge of the risk of disruption, for example, the probability that a disruption will occur or the expected duration of a disruption. In practice, these parameters can be very hard to estimate. Therefore, we suggest, as a third area for future research, the development of models that are insensitive to errors in these parameters.

Acknowledgments

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NAE News and Notes

NAE Newsmakers

Madan M. Bhasin, senior scientist, Dow Chemical Company, was awarded the **Herbert H. Dow Medal** on August 30, 2006, "for significant contributions to the advancement of catalysis, particularly for ethylene oxide." The Dow Medal is the highest award the company awards its scientists and researchers.

Six NAE members were inducted into the **Consumer Electronics Industry Hall of Fame: Donald L. Bitzer**, Distinguished University Research Professor, Computer Science Department, North Carolina State University; **Robert W. Galvin**, Chairman Emeritus, Motorola Inc.; **Andrew S. Grove**, senior advisor to Executive Management, Intel Corporation; **George H. Heilmeier**, Chairman Emeritus, Telcordia Technologies Inc.; **Nick Holonyak Jr.**, John Bardeen Chair Professor of Electrical and Computer Engineering and Physics, University of Illinois; and **Gordon E. Moore**, Chairman Emeritus, Intel Corporation.

Arup K. Chakraborty, Robert T. Haslam Professor of Chemical Engineering, Chemistry, and Biological Engineering, Massachusetts Institute of Technology, is the first engineer ever to receive the **National Institutes of Health Pioneer Award**, which includes a $2.5 million grant from NIH for biomedical research.

Lloyd S. Cluff, Geosciences Department, Pacific Gas & Electric Company, received the **2006 WSSPC** (Western States Seismic Policy Council) **Award in Excellence for Lifetime Achievement in Earthquake Risk Reduction** for his achievements during his 45-year career in earthquake geology. Dr. Cluff is a world-renowned expert in the field, a well published research scientist, a champion of public policy on earthquake safety, an inspiring educator, a sought-after consultant, a president and board member of many professional organizations, and a successful business leader.

Chung K. Law, Robert H. Goddard Professor of Mechanical and Aerospace Engineering, Princeton University, received the **2006 Alfred Egerton Gold Medal** from the Combustion Institute. The award was presented to Dr. Law for "distinguished, continuing, and encouraging contributions to the field of combustion."

Alan Lawley, Emeritus Professor, Department of Materials Science and Engineering, Drexel University, became an **Honorary Member of the American Institute of Mining, Metallurgical and Petroleum Engineers (AIME)**. Dr. Lawley was cited for his "services to education, government, research, and editorial activities, especially in powder metallurgy, and for professional service culminating as president of the Minerals, Metals & Materials Society (1982) and AIME (1987)." Dr. Lawley has also been invited by the Metal Powder Industries Federation to **co-chair PM 2008**, the World Congress on Powder Metallurgy and Particulate Materials, in Washington, D.C.

Gordon E. Moore, Chair Emeritus, Intel Corporation, received the sixth annual **Nierenberg Prize for Science in the Public Interest** presented by the Scripps Institution of Oceanography, University of California, San Diego. The bronze medal and $25,000 were presented to Dr. Moore at a ceremony on September 14, 2006.

Cherry A. Murray, deputy director for science and technology, Lawrence Livermore National Laboratory, has been elected **vice president of the American Physical Society** (APS) for 2007. Following Dr. Murray's year as vice president, she will become president-elect, president, and then immediate past president. Dr. Murray will be a member of the council and executive board of APS for four years and will chair both bodies during her term as APS president.

Elaine S. Oran, senior scientist for reactive flow physics, Naval Research Laboratory, is the recipient of the **2006 Society of Women Engineers Achievement Award**. Dr. Oran was recognized for pioneering a computational technology that unifies engineering, scientific, and mathematical disciplines into a methodology for solving reactive-flow problems. The award was formally presented on October 13, 2006.

Gavriel Salvendy, Chair Professor and head of the Industrial Engineering Department, Tsinghue University, Beijing, and professor, School of Industrial Engineering, Purdue University, received the **Friendship Award** presented by the People's Republic of China on

September 29, 2006. The award is the highest honor the Chinese government confers on foreign experts.

NAE President **Wm. A. Wulf** and two NAE members have been named by U.S. Commerce Secretary Carlos M. Gutierrez to the newly formed Deemed Export Advisory Committee. **Norman Augustine**, retired chairman and CEO of Lockheed Martin Corporation, will co-chair the group with Robert Gates, president of Texas A&M University. **Ruth David**, president and CEO of Analytic Services Inc., will also serve on the 12-member committee of business and academic leaders.

2006 Annual Meeting

Wm. A. Wulf, John-Paul Clarke (Gilbreth Lecturer), John A. Armstrong, and Craig R. Barrett.

Wm. A. Wulf, Karen D. Hagedorn (Gilbreth Lecturer), John A. Armstrong, and Craig R. Barrett.

NAE members, foreign associates, and guests gathered in Washington, D.C., this October for the 2006 NAE Annual Meeting. The meeting began on Saturday afternoon, October 14, with an orientation session for new members. This was followed by the NAE Council dinner in the Great Hall of the Academy honoring the 76 new members and nine foreign associates.

NAE chair **Craig R. Barrett** opened the public session on Sunday, October 15, with brief remarks about the importance to a democracy of an educated public and a review of the recent National Academies report, *Rising Above the Gathering Storm* (see p. 49). President **Wm. A. Wulf** then addressed the group in a talk about his anticipated return to teaching at the University of Virginia when his 11-year tenure as NAE president ends in June 2007. Dr. Wulf argued for the importance of technological literacy to a democracy and for teaching undergraduate courses for all students to provide them with the basic concepts of engineering and tools of analysis they will need to make informed decisions in a technology-dependent society (see p. 51). The induction of the NAE Class of 2006 followed President Wulf's address.

The program continued with the presentation of the 2006 Founders Award to **Shu Chien** and the Arthur M. Bueche Award to **Chauncey Starr**. Dr. Chien, University Professor of Bioengineering and Medicine and director, Whitaker Institute of Biomedical Engineering, Department of Bioengineering, University of California, San Diego, was recognized "for outstanding contributions to elucidating the engineering foundation of cardiovascular dynamics, and integrating engineering and biomedical sciences for the development of the biomedical engineering profession." Dr. Starr, President Emeritus, Electric Power Research Institute Inc.(EPRI), received the Bueche Award for "leadership in the development of nuclear power, contributions to the creation of the field of risk analysis, and leadership in electric power R&D as the founding president of EPRI." Drs. Chien (see p. 54) and Starr (see p. 57) then delivered their acceptance remarks.

John S. Lamancusa, professor of mechanical engineering and director of the Learning Factory, Pennsylvania State University, a member of the team that received the 2006 Gordon Prize, which is awarded in recognition of new modalities and experiments in education that develop effective engineering leaders, delivered a lecture describing the prize-winning program. The team also included Jens E. Jorgensen, Professor Emeritus of Mechanical Engineering, University of Washington; Lueny Morell, professor of chemical engineering, currently director of university relations for Latin America, Hewlett Packard Company; Allen L. Soyster, professor and dean of the College of Engineering, Northeastern University; and Jose L. Zayas-Castro, professor and chair of the Industrial and Management Systems Engineering Department, University of South Florida. The Gordon Prize was awarded at an awards ceremony in Washington, D.C., last February. The Gordon Prize acceptance speech appeared in the summer 2006 issue of *The Bridge*.

After a break, **John A. Armstrong**, vice president for science and technology at IBM (retired), introduced the Armstrong Endowment for Young Engineers Gilbreth Lecturers. These lectures recognize outstanding young engineers who have given presentations at the Frontiers of Engineering symposia. John-Paul Clarke, associate professor of aerospace engineering and director of the Air Transportation Laboratory at Georgia Institute of Technology, spoke on the global impact of air transportation. Karen D. Hagedorn, operations technical manager, Reservoir U.S. Production for ExxonMobil Production Company, spoke on the use of modeling in petroleum reservoir development and production enhancement.

The final speaker was Calestous Juma, professor of the Practice of International Development, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University. The title of his talk was "Redesigning African Economies: The Role of Engineering in International Development." The day ended with a reception for members and their guests.

At the Annual Business Session on Monday morning, members had an opportunity to raise issues relevant to specific NAE activities and the engineering profession at large. The business session was followed by a symposium, "Engineering for the Threat of a Natural Disaster," moderated by William H. Hooke, senior policy fellow and director, Atmospheric Policy Program, American Meteorological Society, and chair, Disasters Roundtable, National Research Council.

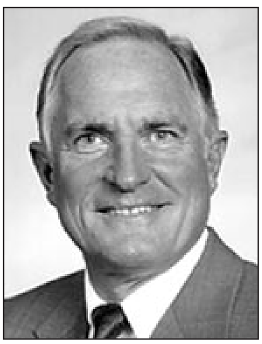
Class of 2006.

Speakers included **Lloyd S. Cluff**, director, Geosciences Department, Pacific Gas & Electric Company; Melvyn Green, president, Melvyn Green and Associates Inc.; **John T. Christian**, consulting engineer; Les Harder, chief, Division of Floor Management, California Department of Water Resources; and Mary C. Comerio, chair, Department of Architecture, University of California at Berkeley.

On Monday afternoon, members and foreign associates participated in NAE section meetings at the Keck Center. The final event of the meeting was the annual reception and dinner dance, held at the Ritz-Carlton, Washington. Music was provided by the Radio King Orchestra.

The next annual meeting is scheduled for September 30–October 1, 2007.

Comments by NAE Chairman Craig Barrett



Craig R. Barrett

These remarks were delivered on October 15, 2006, at the NAE Annual Meeting.

Let me start by welcoming you all here . . . especially the Class of 2006. My heartiest congratulations to you on your accomplishments and my compliments to your significant others and family members, because I know they sacrificed to get you here. This morning, I want to make some brief comments, which I can outline in just a few words. I will talk about two presidents, one book, and a fortune cookie, in that order.

The first president, **Bill Wulf**, has been the president of the National Academy of Engineering for the last 11 years, and this is the last Annual Meeting over which he will preside. I want to express the appreciation of the NAE Council and membership to Bill for his tenure. He entered the academy at a tumultuous time, and he has brought stability to the organization, worked with the National Academy of Sciences and Institute of Medicine to create the National Academies, and brought the National Academy of Engineering into the forefront of national debates on a number of very serious topics. I want to extend my personal thanks to Bill for his service to the organization over the last 11 years.

Because we are in Washington, D.C., I thought it proper to invoke the words and thoughts of another president, one of our previous leaders, Thomas Jefferson. Many of you may know the history of Thomas Jefferson and that he was very interested in education. In his writings, you will find that he talked about three aspects of education that he thought were important. First was the need for an educated populace; the basis of any democracy, he said, is a citizenry that can make intelligent decisions. The key to making intelligent decisions is for voters to have a good, strong education. Jefferson was a very strong proponent of education as the foundation, or cornerstone, of an effective democracy.

The second aspect of education he emphasized was the recognition that knowledge is power. Perhaps he meant something slightly different from what we mean today when we talk about a knowledge-based society or a knowledge-based economy. Jefferson was referencing people who had knowledge and power because they could interpret world and domestic events, make intelligent decisions, and move forward. If you fast-forward 200 years to today, we are talking about a knowledge-based economy in which knowledge provides economic growth and economic stimulus. Economic growth and competitiveness are really the basis for world power today and are very important for the United States.

The third aspect of education was the importance of science, not only for economic growth and development, but also for national defense. If you take those three thoughts expressed by Jefferson in the early 1800s and apply them to the early twenty-first century, I think you will find that they have continuity and meaning today, just as they did 200 years ago.

My next topic is a book. This particular book, which represents the work of all three academies in the National Academies, was published approximately one year ago. It is called *Rising Above the Gathering Storm*. Its subject is U.S. competitiveness, and it incorporates the thoughts of Jefferson. Bill Wulf was on the committee that wrote that document, and it incorporates Bill's thoughts as well. *Rising Above the Gathering Storm* is about what the United States must do to maintain its competitiveness around the world as we go forward into the twenty-first century. The recommendations of that study can be summarized in three main points.

First, we must improve the understanding of the American populace of math and science, which will mean improving K–12 education in math and science. Everyone in this audience of engineers and people associated with engineers knows the relatively sorry state of our K–12 educational system. You all know that, on average, when our youngsters graduate from high school, they rank relatively low compared to their international counterparts on those topics. *Rising Above the Gathering Storm* includes a detailed discussion about improving K–12 math and science education.

Second, it talks about the importance of research and development, again bringing Jefferson's ideas forward. Science and research are important not only to national defense, but also to economic competitiveness in general. *Rising Above the Gathering Storm* recommends that the federal budget for research and development of the National Science Foundation be doubled, that the Department of Energy's research budget be increased, and that we invest in the future—the ideas that will become the next-generation products, services, and companies.

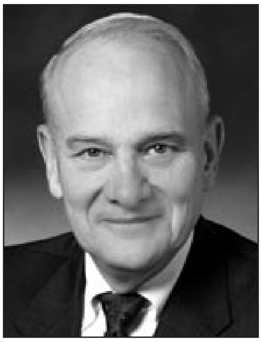
The last main point in the report is that the United States should not only be more competitive, but should also be the center for investments in innovation. You can think about investments in innovation in two areas. One kind of investment is to continue to attract the best and brightest minds from around the world, not only to study in our universities, but also to stay and work in the United States. We must continue to make the United States the most attractive place for the best and the brightest by providing an environment that promotes the second kind of investments in innovation. I mean investments in research and development, in new companies and start-ups, and in growing economic wealth in the United States.

If you have not seen the report, I invite you to look it up on the National Academies website. The reason I bring it up and the reason I invoke Thomas Jefferson's philosophy is that everyone here today has a certain responsibility—to speak out about what is in the best interest of our democratic society and what is in the best interest of this country going forward. I hope we can enlist all of you as spokespersons in the campaign to bring the suggestions of *Rising Above the Gathering Storm* through the legislative process to implementation in our economy.

The suggestions in that report have been incorporated into pending legislation in Congress. But, as you know, when we're talking about the legislative process, pending can be a very, very long word. Because of your stature as members and others associated with the National Academy of Engineering, your opinions carry great weight. I encourage you to exercise your democratic prerogative and speak out in support of those suggestions to your congressmen and your senators and urge them to pass this legislation.

This brings me to my final topic, a fortune cookie . . . a good way to end any speech. I was sitting in a Chinese restaurant in Mountain View, California, about six years ago—the restaurant is called Chef Chu's, my favorite Chinese restaurant. I always look forward to the fortune cookie at the end of the meal, and when I popped open this fortune cookie, I found it included a pertinent bit of wisdom. The fortune said, "The world is always ready to receive talent with open arms." Today, your talent is being received with open arms by the National Academy of Engineering. But even more important, if you look around the world today, wherever great talent exists, the world is ready to receive it with open arms. That is a measure of the competitive nature of the world today and the competitive challenges facing the United States. So, as the fortune cookie said, "Welcome to the National Academy of Engineering. We are very pleased to have you here today."

President's Address



Wm. A. Wulf

These remarks were delivered October 15, 2006, at the NAE Annual Meeting.

It is an immense honor to welcome once again our new members and foreign associates. I know you must feel honored as well; my own induction is one of my fondest memories. The academy is renewed and enriched by each new class, so please accept my sincere, heartfelt welcome. The knowledge and experience you bring to NAE enables us to continue to play a unique and invaluable role in service to our democracy. I also want to acknowledge the families and friends of the members of the new class. I know that none of those being inducted would be here if it weren't for their support.

As most of you know, I will be stepping down from the presidency at the end of next June after 11 years. So, when I was thinking about what to talk about today, there was a fleeting temptation to reflect on the progress we have made in those 11 years. But I decided not to do that. Instead, I want to talk about what I plan to do next—and, maybe, enlist some help from you.

Along with our sibling organizations, NAS and IOM, NAE operates under a congressional charter that calls upon us, "whenever asked," to advise the nation on issues of science, engineering, and health. Often our advice concerns the state of knowledge as it relates to a public policy issue, such as how engineering methods can be used to improve the delivery of health care, or if storing nuclear waste at Yucca Mountain is safe, or whether it is feasible to service the Hubble Space Telescope robotically.

The United States is the most technologically sophisticated (and thus technologically dependent) country in the world. Consequently, many of our most important public policy issues have a significant technical component. Thus, for more than 10 years, NAE (and I) has been at the nexus of science, engineering, and public policy.

It is good that the National Academies are here to inform debates about these policies, but it is also disconcerting that the vast majority of Americans do not have the background to participate in these debates. Thomas Jefferson often said that a democracy cannot survive without informed citizens. His point was that, to be wise stewards of our democracy, citizens must, at the very least, understand the issues. It would be even better if they understood the alternatives available to address those issues and were able to evaluate those alternatives. Most Americans cannot do that for the issues we face today, such as alternative energy sources, the levees in New Orleans, the possibility of a hydrogen economy, privacy in this technological age, zero-emission cars, electronic voting machines, and on and on.

Despite efforts by the National Academies, I see policy makers every day expounding on national and homeland security, energy, and dozens of other technical issues about which they haven't a clue! I interact with journalists who, in my view, miss the real issues in a story because they have no knowledge of technology, and thus compound their own ignorance by misdirecting the public's attention. I put up with advocates of all stripes proposing technologically nonsensical solutions to very real problems.

I worry about people having to make personal decisions—whether or not to disarm an air bag, for example—about which they have fragmentary information and no disciplined thought process on which to rely. Mostly, these are good, intelligent people who want to do the right thing. They simply do not have the knowledge they need to function in a technological society. In other words, they are technologically *illiterate*! They are not dumb, just uninformed.

I'm going to be using the phrase *technological literacy* from here on, so perhaps I should say a few words about what it means. First, when I use the word *technology*, I do *not* mean only computers and telecommunications, even though that seems to be a common use of the word today. A flint knife was high technology in its day. The chair you are sitting on is technology. The appliances that made your breakfast are technology. The vehicles that brought you here are technology. When I use the word technology, I mean the vast array of objects and processes that humans make to satisfy their wants and needs.

Second, *literacy*. I am fond of a definition of *cultural literacy* given by E.D. Hirsch many years ago. He said that in every society there is a body of information that members of that society must share to be able to communicate and make sense of the world. A culturally literate person in that society knows that body of information. In that sense, then, technological literacy is based on a body of information that people must share to be able to communicate and cope with our technological society.

NAE has had a Program on Technological Literacy for much of my tenure here. Working with the International Technology Education Association, we produced a set of standards for technological literacy in K–12 that was published in 2000. We produced a report, *Technically Speaking*, in 2002 that defined the concept of technological literacy and made a case for why every American needs to be technologically literate.

At the request of the Department of Education, we hosted a workshop in 2004 for state education officials; about two-thirds of the states sent representatives. One state, Massachusetts, now requires that engineering and technology be part of the curriculum in all K–12 grades, and, as of 2004, 27 percent of states will require at least one K–12 course in technology. In April 2005, we hosted a National Science Foundation (NSF) workshop to discuss existing approaches to teaching technological literacy to undergraduate students. I will just observe that not many attempts have been made, but they exhibit an amazing diversity of goals and approaches.

In 2005, I testified before the National Assessment Governing Board (NAGB), the group that defines the National Assessment of Educational Progress examination, or NAEP. I (and others) asked them to include technology assessment questions in the science portion of the NAEP, and they have done that for the 2009 test! About 10 percent of the exam will be on technology. Even better, NAGB is conducting a feasibility study of a completely independent examination on technological literacy. That will take a while to implement, of course, so the target for the first exam is 2012. But that is real progress!

This August we released another report, *Tech Tally*, that addresses the question of how to measure technological literacy. A lot has been done on assessing scientific literacy, but not technological literacy. We are working on disseminating this material to as many audiences as we can. For example, in October, we will present the results of *Tech Tally* to the ASTC—Association of Science-Technology Centers (museum personnel)—and the day after this meeting, we will present the results to the House STEM (science, technology, engineering, and mathematics) caucus.

NSF has requested a proposal from us to actually *conduct* an assessment of adult technological literacy. In addition, NAE member and former chair of NAE, **Steve Bechtel**, is funding our work on developing guidance for the creation and implementation of K–12 engineering curricula and instructional practices.

One of the important things we did in 1999 was to compile a list of the 20 greatest engineering achievements of the twentieth century—"greatest" being defined in terms of impact on people's lives, not technological gee whiz. The list is stunning! My grandfather was a teenager in 1900, and looking at the list I am awestruck by how different his life was from mine. In 1900 barely anyone had electricity or an automobile, and there were just a few tens of miles of paved road in the entire United States. The first airplane had not been flown. The average life expectancy was 46 . . . now it's 76, largely thanks to clean water and sanitation. There was no radio or television, and few people had telephones. Of course there were no cell phones, computers, or Internet. Fifty percent of Americans lived on farms; now only 2 percent do because of agricultural mechanization. And the list goes on! With the support of **Bob Pritzker**, that list was transformed into a coffee-table book. And now, even as we speak, it is the basis for a PBS television show in the making.

Other NAE members have also been working to inform the public. For example, **Sam Florman** and **Henry Petroski** are great popular authors on engineering. **John Lienhard** produces short pieces on engineering for NPR. **David Billington** teaches the most popular course at Princeton on engineering. **Elsa Garmire** is writing a college text on technological literacy. And **Francois Castaing** has led the transition of the Detroit Science Center to emphasize engineering and technology.

In short, both the organization and NAE members have been active and, I think, effective in working to improve the technological literacy of Americans. However, I often feel that this exercise is a bit like steering a supertanker. One has to have the helm over hard for a long time before the bow swings. But I think it's beginning to move!

So, now to the point I said I was

going to make at the beginning of this talk—what I am going to do next. I plan to return to the University of Virginia after a leave of 11 years. And when I do, I am going to develop an engineering course for liberal arts majors!

My objective will be to give students the knowledge and mental tools they need to be good citizens in a technology-intensive democracy—to make them technologically literate. My objective will *not* be to make them into engineers—so no equations, for example. It's the concepts behind the equations that matter! I plan to use contemporary public policy issues as a context for discussions of engineering concepts.

You may be wondering why my focus is on an *engineering* course for liberal arts majors rather than on a science course. It's because engineering is usually most relevant to public policy. I am fond of the contrast that Theodore von Karmen made between science and engineering. He said, "Science is about understanding nature, about understanding what is. Engineering is about creating *what has never been*."

Public policy questions are most often about whether there is a technological solution to some problem. The public policy question about global climate change, for example, is *not* about whether anthropological CO_2 is causing climate change. Although that would be nice to know, even if we had a 100 percent certain answer, that wouldn't *fix* anything. The real question is whether we can create technology that will enable us to continue our present lifestyle while reversing the buildup of greenhouse gases in the atmosphere. And, if we can't create that technology, or if it is already too late, can we create technology that will enable us to survive in a radically altered environment?

Let me give you a quick example of the kind of issue I want students to be able to analyze and what they need to know to do that. Some years ago, given a rather dire air pollution situation, California mandated that a certain percentage of cars in the state had to be "zero-emission" (i.e., electric) vehicles. Should other states also adopt this policy?

To the non-engineer, the notion of zero-emission cars sounds appealing. To the engineer, however, the question raises at least two red flags. First, electricity has to be *made* somewhere. A zero-emission car is part of a larger system that includes an electricity generation plant and transmission lines. Maybe a zero-emission car will just move the emissions from the location of the car to the location of the generating plant. Whether you view that as good or bad probably depends on where you live.

Second, nothing works perfectly (that's the essence of the second law of thermodynamics). Maybe the imperfect conversion of the chemical energy in coal to electricity *will add* to the losses in the transmission line, which *will add* to the losses in charging the car's batteries, which *will add* to the imperfect conversion of electricity into rotary motion. Thus, when you add these up, the result may be *lower* efficiency than if you simply burned gasoline directly. If so, that would mean zero-emission cars *will add more* emissions to the atmosphere than gasoline-powered cars.

Well, maybe, and maybe not—we'd have to do the computations to find out. The point is that informed citizens, faced with a public policy question like this one, ought to at least know enough to ask these questions. To do that, they don't need a B.S. in engineering. In this case, they only need to be aware of two things: (1) everything is embedded in a larger system, and policy questions like this must take a "big enough" part of that system into account; and (2) nothing works perfectly, and if you string many imperfect things together, you may make things worse!

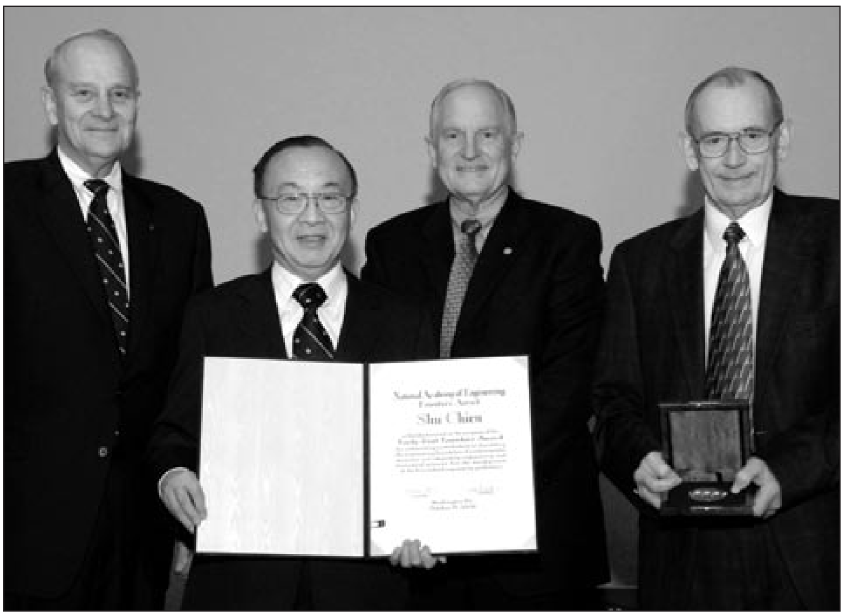
Informed citizens don't have to be able to do the calculations of the overall efficiency of the system supporting the zero-emission car. If they ask the question, we can find an expert to do the calculation. Thus, I will consider the course a success if, at the end, students (1) recognize the technical information they need to inform themselves on a public policy issue, (2) know how to find that information, and (3) reach reasonable, informed conclusions. Frankly, I hope they will also be able to recognize when a politician tries to pull the wool over their eyes with overly simplistic descriptions of technologies. Hydrogen and ethanol are two of my current favorites on that score!

An obvious question is which engineering concepts I should teach. The honest answer is that I don't know yet, and I would be happy to get help from the engineers in the audience. I hoped there was a book on great concepts in engineering, but, if it exists, I haven't found it yet. So, on long, boring plane rides I have been playing with this question, and I have come up with a list of candidates. It includes obvious things like design, systems, the first and second laws of thermodynamics, control and feedback, safety margins vs. fail-soft design, risk analysis and communication, and so on. But the thing about lists is that you never know what you've left off. So I would be grateful for *your* lists. Indeed I'd appreciate *any* thoughts you have on this subject.

In other contexts, I have observed that schools of engineering, like other professional schools, target all of their courses to their own majors. However, faced with this crucial issue—individuals need sufficient technological literacy to be functional citizens of a democracy—engineering schools have an *obligation* to educate *every* college student. So, what I am going to do next is to tilt with that windmill!

Thank you.

2006 Founders Award Acceptance Remarks



Wm. A. Wulf, Shu Chien, Craig Barrett, and Paul Peercy.

The 2006 NAE Founders Award was presented to Shu Chien, University Professor of Bioengineering and Medicine, and Director, Whitaker Institute of Biomedical Engineering, Department of Bioengineering, University of California, San Diego, "for outstanding contributions to elucidating the engineering foundation of cardiovascular dynamics, and integrating engineering and biomedical sciences for the development of the biomedical engineering profession." These remarks were delivered on October15, 2006, during the NAE Annual Meeting.

It is a great honor for me to receive this most prestigious Founders Award. The National Academy of Engineering is the most honorific academy in engineering, and the Founders Award is a major award of this austere body composed of the best and most respected engineers. The past awardees are all great leaders in engineering who have upheld the ideals and principles of NAE through professional, educational, and personal achievement and accomplishment. I am deeply humbled and privileged to be included among these giants. I wish to express my most sincere gratitude to the members who nominated me and to the Awards Committee for choosing me as the recipient of the Founders Award.

I am probably the only awardee who does not have a degree in an engineering discipline. When I was elected to NAE, I was already honored beyond what I deserved. To be selected as the Founders awardee is beyond my wildest dream. I wish to express my deep appreciation for NAE's grand view emphasizing interdisciplinary research that builds bridges between engineering and biomedical sciences. I would also like to use this opportunity to illustrate, especially to young colleagues, that learning is not limited to what we are taught in school, but that learning is a lifelong process that never ceases.

I was born in Beijing, China, in 1931, the second of three sons to Shih-liang Chien and Wan-tu Chang. In elementary and junior high schools, I discovered that I liked mathematics very much. Numbers, geometry, and the quantitative aspects of how things work fascinated me. After the end of WWII, the Chinese government had a temporary rule that allowed junior-year high school students to take the nationwide college entrance examination. When I went to register for the exam, however, I found out that a key subject for math majors was analytical geometry, which would be taught in my senior year. Among all possible majors, I chose premedical studies because medicine is a very rewarding profession that enhances the quality of people's life. To my surprise, I passed the exam and was admitted to my first preference, the premed program of Peking University in Beijing.

As the civil war in China escalated in late 1949, Beijing was under siege and shelling. The Nationalist Government sent two airplanes to evacuate professors from universities in Beijing. In retrospect, it was truly remarkable that my father, a professor of chemistry at Peking University, and my mother were able to leave with their three sons (Robert, I, and Fred) and only five duffle bags on a few hours of notice. We went to Taiwan in January 1950, and I transferred to National Taiwan University College of Medicine.

After graduation, I decided to come to the United States to pursue either graduate education or clinical training. After considerable deliberation, I decided to study for a Ph.D. in physiology at Columbia University College of Physicians and Surgeons (P&S), with Magnus Gregersen as my advisor. In addition to biomedical courses at P&S, because of my interest in math, I also took courses related to engineering at Columbia and at City College of New York (CCNY). Therefore, I did get my engineering education without enrolling as an engineering student.

After the completion of my Ph.D. study with a thesis on the role of the sympathetic nervous system in hemorrhage, I remained in the department at Columbia as junior faculty. I then realized that biophysical factors also contribute to the compensatory responses to hemorrhage. In the early 1960s, I started to work on blood rheology with Magnus, Shunichi Usami, and Bob Dellenback, thus beginning to link our research to engineering. These studies culminated in the publication of three back-to-back papers in *Science* in 1967 on the roles of deformability and aggregation of red blood cells in governing blood viscosity.

These papers triggered the most important collaboration of my career, with **Richard Skalak**, then professor of civil engineering and engineering mechanics at Columbia. Dick was on sabbatical leave with P.-I. Brånemark at the University of Gothenburg; he wrote to express his interest in these papers. In 1968, I went to Gothenburg to attend a meeting and met Dick for the first time thousands of miles away from Columbia. Our wonderful discussions there initiated a fruitful collaboration that lasted for 30 years, during which we worked together to publish 60 full-length papers and edit a 900-page textbook, *Handbook of Bioengineering*.

I am deeply indebted to Dick for the knowledge in engineering that I learned from him and for making it possible for me to apply my interests in math to biomedical research. I was blessed to have Dick as a friend and colleague till his passing in 1997. Ours was a true example of interdisciplinary collaboration in which each gains from working with the other, and the total is much greater than the sum of the parts.

In the 1970s, I initiated several new directions of research that emanated from blood rheology, each combining biomedical experiments with engineering modeling. These include the study of viscoelastic properties of individual blood cells (Dick, Paul Sung), the mechanism of cell aggregation (Dick, Kungming Jan, Amy Sung), and the roles of cell deformability and aggregation in regulating microcirculatory flow dynamics in vivo (Shunichi, Herb Lipowsky, **Geert Schmid-Schöbein**).

My ability to get into these new areas is attributable to my wonderful colleagues, including basic bioscientists, engineering scientists, and clinical investigators, who provided guidance for the clinical relevance of our research. In the mid-1970s, I also started to work on the role of fluid mechanics in macromolecular transport across vascular endothelium, in collaboration with **Shelly Weinbaum** and Bob Pfeffer of CCNY, following their return from sabbatical leaves with Colin Caro of the Imperial College of London. I was most fortunate to have worked for 30 or more years with Dick and Shelly starting at Columbia, and later with **Y.C. Bert Fung** at UCSD—three extraordinary bioengineering scientists!

In the early 1980s, recognizing that molecular biology provides extremely powerful tools to probe physiological and bioengineering problems, I began to learn molecular biology by taking courses and reading on my own. Our lab at Columbia (Amy Sung) began to perform molecular biology research on red cell membrane. I fostered the application of molecular biology to physiology and bioengineering by giving lectures and organizing symposia and workshops for the American Physiological Society, International Society for Biorheology, Microcirculatory Society, and Biomedical Engineering Society. I have had the pleasure and privilege of contributing to the activities of these societies and the Federation of American Societies for Experimental Biology, International Union of Physiological Sciences, and American Institute for Medical and Biological Engineering, as well as several institutes abroad, such as the National Health Research Institutes and Academia Sinica in Taiwan.

In the mid-1980s, UCSD was

recruiting faculty in bioengineering to succeed Ben Zweifach and Bert because of their pending retirements. In 1987–1988, when I was taking a sabbatical leave from Columbia to establish a new Institute of Biomedical Sciences for Academia Sinica in Taiwan, I was pleasantly surprised when I was asked to go to UCSD. After long deliberations, with my wife K.C.'s consent and because Dick was willing to move together with me, we went to La Jolla in 1988. It was a wonderful decision, because the new environment in a young university offered great challenges and opportunities. What has transpired since then is actually much more than what I could have envisioned. I am most fortunate to have worked in two great universities, Columbia and UCSD.

At UCSD, I began to consolidate our research programs to focus on mechanotransduction in vascular endothelial cells and smooth muscle cells (i.e., how mechanical forces, such as the shear stress due to flow and the circumferential stretch due to pressure, act on these cells to modulate their transduction of signals and expression of genes). These studies have considerable importance because the molecular and genetic basis of cellular responses to mechanical forces is a fundamental problem at the interface of biology and engineering. These investigations also have significant clinical implications because they may shed light on the mechanisms by which atherosclerotic lesions have preferential locations in the vascular tree and may generate novel therapeutic approaches.

These studies were facilitated by the joining of John Shyy and Julie Yi-shuan Li and many superb postdoctoral and predoctoral trainees, as well as the collaboration of outstanding colleagues at UCSD and elsewhere. Our research led to the identification of several molecules in the endothelial cell that can serve as mechano-sensors and the elucidation of a number of signaling pathways that mediate the effects of mechanical forces on gene and protein expression as well as their functional consequences.

We have formulated the notion that shear flow or stretch with a definite direction can trigger the adaptive remodeling of the endothelium to alter its intracellular mechanics and molecular signaling in the straight part of the aorta, thus maintaining homeostasis in the face of the external mechanical stimuli. In contrast, the disturbed flow and non-directional stretch in branch points and curvatures have opposite effects and are atherogenic, thus explaining the regional predilection for atherosclerotic lesions.

An analogy can be drawn between these findings and our lives. That is, it is important for us to have direction. When we face a branch point, instead of staying in a stagnation zone, we need to make our decision, grasp the opportunity, and move forward with vigor, determination, and perseverance.

The administrative leaders at UCSD (especially NAE members **Bob Conn** and **Frieder Seible**) and my colleagues in bioengineering have afforded me the opportunity of developing bioengineering on the campus and beyond. Together with colleagues in the Jacobs Schools of Engineering, Medicine, and Natural Sciences, as well as those in neighboring institutions in La Jolla, I was able to establish the Institute of Biomedical Engineering in 1991 (named Whitaker Institute in 1998) to foster interdisciplinary research and fruitful interaction with industry. By winning the Development Award from the Whitaker Foundation in 1993, we were able to establish the infrastructure needed to form the Department of Bioengineering the next year. With the Whitaker Foundation Leadership Award granted in 1998 and gifts from the Powell Foundation and von Liebig Foundation, we constructed the Powell-Focht Bioengineering Hall in 2002. Besides these foundations, I am grateful for support from the National Institutes of Health, National Science Foundation, Beckman Laser Foundation, Howard Hughes Medical Institute, Senyei Family Foundation, Taiwan Semiconductor Manufacturing Foundation, Wallace H. Coulter Foundation, and many generous donors (Joan and **Irwin Jacobs**, Ernie and Su Huang, **David Lederman**, Louise and **Dane Miller**, and others). In 2004, with the collaboration of colleagues on all 10 campuses in the University of California (UC) system, we established the System-wide Multi-campus Research Unit, the Bioengineering Institute in California, to carry out collaborative activities in bioengineering across the UC system.

On many occasions in my life, I have been very fortunate to make the right decisions, but none was more important than my marriage to my dear wife, K.C. We met in our medical school days and married in New York in 1957. In more than 49 years of our marriage, K.C. has given me unreserved love, care, and support. She has played a major role in whatever I have done, and she deserves at least one-half of the credit for anything I have accomplished. K.C. and I are extremely blessed by having two marvelous daughters, May and Ann, with Len and Steve as our wonderful sons-in-law, and six most lovely granddaughters. We are truly grateful!

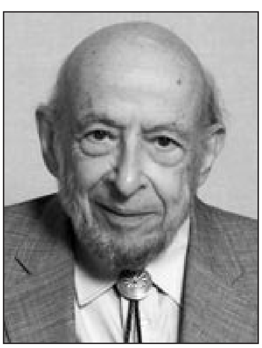
Looking back at my life, I could have chosen many different paths at several branch points. If I had gone into mathematics, I probably would not have met K.C., and I would have missed out on our happy life together. If my parents had not decided to take that plane to fly out of Beijing in 1949, my life would have been totally different. There are many other "ifs." What if I had chosen clinical medicine instead of physiology and bioengineering? What if I had chosen to stay at Columbia instead of going to UCSD?

There is no need to answer these questions. What is important is that I am extremely fortunate and happy to be where I am, especially today. If I had not taken the paths I took, I would never have had the chance to receive this most prestigious award. Even with all the paths I have chosen to take, I still do not believe I should have this chance.

Finally, I would like to say that any ability I possess was given to me by my parents, both in my genetic inheritance and my upbringing, as well as by the education and wonderful help from my teachers, colleagues, and students. I am grateful to all of them, and to all of you here at this ceremony. I sincerely feel that there is no reason for me to be proud of what I have accomplished, but I have every reason to be grateful for the abilities given to me and the extraordinary support, advice, and encouragement I have received from all of my family, friends, and colleagues.

Thank you all most sincerely from the bottom of my heart!

2006 Bueche Award Acceptance Remarks



Chauncey Starr

The 2005 Arthur M. Bueche Award was presented to Chauncey Starr, President Emeritus, Electric Power Research Institute Inc. (EPRI), for "leadership in the development of nuclear power, contributions to the creation of the field of risk analysis and leadership in electric power R&D as the founding president of EPRI." These remarks were delivered on October 15, 2006, at the NAE Annual Meeting.

I deeply appreciate the opportunity to accept the Arthur M. Bueche Award at the annual NAE meeting, even though it's by recorded tape. Although I'd much prefer being with you in person, physical limitations make travel too difficult for me.

It is an honor to be added to the list of Arthur M. Bueche awardees, most of whom I knew from chairing NAE committees. Art Bueche was a professional friend, who co-chaired with me the 1977 World Electrotechnical Congress in Moscow, sponsored by the USSR Ministry of Electricity. That event was illustrative of the international bonding technology provides. At the congress, Art spoke about electricity applications, and I reviewed electricity-supply options.

My ties to NAE started with my early participation in its preformation struggles with existing professional societies, each certain it could expand to include NAE's objectives. I was vice president of NAE from 1970 to 1974 and temporary acting head during that period. These historical ties have kept me interested in NAE's growth, and I find it particularly rewarding that NAE is now a nationally recognized member of the Academies complex. I still wear with pride my 40-year membership pin of the class of 1965.

My personal experience has been in the electrification of the United States, which has been called a major twentieth-century engineering accomplishment. However, the electricity network is now in need of updating with innovative engineering, innovations that must include the Academies' full spectrum of concerns for science, engineering, and health.

Thus, I found refreshing the recent Academies report, *Rising Above the Gathering Storm*, which provides guidance for a multidecade national education program. The report stimulated me to urge the Academies to explore vital long-range topics more often and not wait for current events to motivate "tasking" by a slow-moving Congress. I realize this will require funding, but I believe the Academies could raise funds for explorations of significant issues.

The crucial importance of electricity supply to our nation underscores the urgent need for the Academy's anticipatory attention. The electrical kilowatt-hour (kWhr) has become an essential commodity for our daily existence, as contrasted with the luxury status of electricity a century ago. The formation of the Electric Power Research Institute (EPRI) in 1972 reflected recognition of electricity's vital national role. I had the honor and pleasure of being EPRI's founding president and am now a retired and active emeritus.

Most challenging to me are projections (~2 percent/year) that in several decades we will have to supply twice as many kWhrs of electricity as we do today. Continued routine expansion of our present network of localized private, public, and government utilities could eventually result in a congested network and a sub-optimum asset mix. The Edison Electric Institute (EEI) has recently urged that a national efficiency program be initiated to achieve a modernized national grid and minimize such an outcome. I suggest that NAE undertake a "Gathering Storm" exploration of such a program, covering the complete scope of future efficiency options for our electricity network, from primary resources to end use. It takes decades to commercialize new power equipment, and more time to optimize network subsystems and eventual consumer adaptations. Thus, the search for innovative technologies should begin now.

Unfortunately, daily pressures on utilities to optimize their capital assets discourage them from funding long-term R&D programs. Therefore, such programs will require political, public, regulatory, and technology collaborative support. The biggest obstacles will be the high cost of achieving high-efficiency targets and the cost of restructuring today's decentralized utility systems into a national network. In the final accounting, end users always pay for the integrated costs. The practical question today is who will pay for the intermediary subsystem improvements to a national network, all heavily influenced by regional utility economics —like a highway with a sequence of independent toll stations.

Nevertheless, I am optimistic that we can achieve integrated national efficiency by taking innovative steps. Some innovations shape events that over time lead to functional system changes on a huge scale. Traditionally, the major concerns of utilities have been generation, transmission, and local distribution of electric power, but storage has been a minor concern. At present, there is a low level of interest in the bulk storage of kWhrs, but this area provides opportunities for a wide range of innovations. The missing bulk-storage capability is the primary reason the distribution of electricity is different from the distribution of fossil fuels. The gasoline tank in every auto and at every gas station is a distributed storage system. We need the kWhr equivalent of the gas tank.

The missing capability of storing kWhrs is the factor that forces the supply/demand "instant-matching" that dominates present electricity networks. Storage would make the intermittency of renewables, such as solar and wind power, less of a handicap. On a familiar small scale, the transportability of the common laptop computer shows how storage enables a new function to become a common end-use system. Consider the impact of a much-improved automobile storage battery with a 10-year lifetime, high energy density, minimal maintenance, short recharging time, and low cost. Provided it could power a 180-mile range, it would shift many automobiles from gasoline-dependent cars to electric "plug-in" cars. DaimlerChrysler's plug-in hybrid Sprinter van and several electric-hybrid car enthusiasts are assembling demonstration vehicles that have some of these virtues. This is a start, but we are still some years from achieving a commercial electricity-storage package.

EEI has made the plug-in car a specific industry goal. When it is finally commercialized, it might significantly minimize the oil-import factor in both foreign policy and internal environmental economics. On a longer time scale, a successful plug-in car might create a precedent for a national electricity system based on storage to supplement today's supply/demand instant-matching system (i.e., a hybrid network system).

This would eventually result in a major change in our national network. It is important to note that utility executives need not be concerned that the suggested storage-based supplemental system would conflict with their responsibilities today. They will continue to be the producers of kWhrs. The slow time scale of R&D will ensure that accommodation to any supplementary change will also be slow.

All innovative projects need stable R&D leadership and patient funding with a steady growth rate—a familiar combination. I believe NAE is capable of sponsoring such practical efforts. To repeat my message, it is time for NAE to assume a leadership role in multidecade R&D technologies for an efficient energy future. I have suggested kWhr storage as a target and a long-term national hybrid network as a subject for a "Gathering Storm" study. I hope these suggestions will elicit questions worth discussing.

Again, I thank NAE for honoring me with the Arthur M. Bueche Award and for allowing me to suggest these fresh endeavors.

U.S. Frontiers of Engineering 2006 Symposium

Lloyd Watts from Audience Inc. describes the development of a realistic, real-time model of the human auditory pathway with a view toward building a machine that can hear like a human being.

The 2006 U.S. Frontiers of Engineering (FOE) Symposium was held on September 21–23 at the Ford Research and Innovation Center in Dearborn, Michigan, the second year the symposium has been held at a corporate research site. Participants were able to get a first-hand look at a corporate research facility, and the host company helped defray a substantial amount of symposium costs.

The 2006 symposium, attended by 105 engineers, covered four major topics: intelligent software systems and machines; the nano/bio interface; personal mobility for the 21st century; and supply-chain management applications with economic and public impact. The first session, "The Rise of Intelligent Software Systems and Machines," began with an observation that scientists have spent decades trying to model the complexity and efficiency of the human brain, or the evolutionary process that created it, in an attempt to create *intelligent systems*, that is, systems that can adapt their behavior to their environments. The four talks covered the commercialization of auditory neuroscience, or the development of a machine that can hear; the creation of intelligent agents in machine-learning games (see p. 5); the co-evolution of computers and social sciences; and how computational cognitive models can improve human-robot interaction.

The subject of the second session, "The Bio/Nano Interface," was how engineering has changed as researchers have harnessed biomolecular processes, such as self-assembly, catalytic activity, and molecular recognition. The first two speakers described approaches to solving nanotechnology problems by biomimetics (see p. 14). They were followed by two speakers who described how nanotechnology is being used to address biotechnology problems in cancer detection and other clinical applications (see p. 19).

The third session, "Engineering Personal Mobility for the 21st Century," was premised on the idea that providing people in the developing world with cost-effective, energy-efficient, environmentally sustainable personal mobility, on the same level that people in the developed world enjoy, is one of the grand challenges for the twenty-first century. Presentations focused on the history and evolution of personal mobility, the energy and environmental challenges of current forms of personal mobility, and prospective technologies that can transform personal mobility for this and future generations (see p. 33).

The subject of the final session was "Supply Chain Management Applications with Economic and Public Impact." Effective supply-chain management (SCM) has become a significant source of competitive advantage for private companies (e.g., Dell Computer and Wal-Mart). Recently, researchers and practitioners have begun to focus on the public impact of SCM, exploring relationships between SCM and health care, housing policy, the environment, and national security. Presentations addressed problems in SCM, such as fast implosion, the special needs of the military, affordable housing and sustainability, and the risk of supply-chain disruptions (see p. 39).

Participants spent part of the first afternoon at a "get-acquainted session," a popular event at which

On a tour of the Rouge Plant, symposium participants visit the observation deck, from which they can view Ford's living roof, the largest in the world.

small groups of participants present a slide describing their research or technical work and answer questions. In this way, attendees were able to get to know more about each other relatively early in the program. On the second afternoon, participants were taken on a tour of Ford's Rouge Plant. The tour included films about the history of the plant and how automobiles are manufactured; a visit to the observation deck with views of the largest living roof in the world; and a tour of the plant, in operation, where Ford F-150s are assembled.

Another tradition of U.S. FOE symposia is the Thursday evening dinner speech, which this year was given by **Dale Compton**, Lillian M. Gilbreth Distinguished Professor of Industrial Engineering, Emeritus, at Purdue University, and former vice president of research at Ford. In addition to describing some of the history of Ford research, Dr. Compton talked about the current situation in industrial research and highlighted some of the technical and nontechnical problems facing our country today. He emphasized the critical importance of innovative approaches to our continued competitiveness and national prosperity.

Julia M. Phillips, director of the Physical, Chemical, and Nano Sciences Center at Sandia National Laboratories, chaired the organizing committee and the symposium for this year. She will continue in this role for the 2007 symposium, which will be held September 24–26 at Microsoft in Redmond, Washington.

Funding for the 2006 U.S. Frontiers of Engineering Symposium was provided by Ford Motor Company, Air Force Office of Scientific Research, Defense Advanced Research Projects Agency, U.S. Department of Defense (DDR&E-Research), National Science Foundation, Microsoft Corporation, Cummins Inc., and Dr. **John A. Armstrong**.

NAE has sponsored U.S. FOE symposia since 1995, as well as bilateral programs with Germany, Japan, and India. FOE meetings give outstanding engineers from industry, academe, and government at a relatively early point in their careers (participants are 30 to 45 years old) an opportunity to learn about cutting-edge developments, techniques, and approaches in many fields. In this way, NAE hopes to encourage and support interdisciplinary explorations and facilitate the establishment of contacts and collaborations 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, NAE Program Office, (202) 334-1571 or *jhunziker@nae.edu*.

Workshop on Offshoring of Engineering

On October 24 and 25, 2006, NAE hosted a public workshop to gather data on the phenomenon of offshoring of engineering and explore its implications for the U.S. engineering enterprise. Policy makers, industry representatives, academic experts, and other thought leaders expressed a wide range of opinions and perspectives and discussed the outlook for U.S. engineering in the global engineering marketplace. About 130 people attended the workshop, and many more participated by webcast.

In recent years, intense debate has arisen about "offshoring," the transfer of engineering and other high-skill work from the United States to developing economies. Those who consider offshoring a signal that U.S. technological leadership is threatened warn of long-term erosion in the quality of U.S. engineering and, ultimately, a lower standard of living if current trends continue. Others consider offshoring the inevitable "next stage" of globalization. They argue that the United States is well positioned to reap the benefits of more efficient global innovation networks.

Everyone agrees that offshoring represents a significant challenge to U.S. engineers, but hard data to support either argument has been difficult to come by. To address this need, NAE has established a committee of prominent industry and academic experts, chaired by NAE member **William Spencer**, SEMATECH (retired), to investigate the implications of offshoring. The project sponsors are the National Science Foundation and the United Engineering Fund.

The October workshop, the centerpiece event in the committee's study process, featured keynote addresses by **Charles Vest**, President Emeritus, Massachusetts Institute of Technology, and **Robert Galvin**, Chairman Emeritus, Motorola Inc., and NAE-commissioned research papers on offshoring in the software, semiconductor, personal computer, automotive, construction and engineering design, network systems, and pharmaceuticals industries. The presentations were followed by panel discussions on the implications of offshoring for the engineering profession and workforce, as well as for engineering education and management. The research papers will be published in a volume with the committee's report on the workshop next year.

Grand Challenges for Engineering

GRAND CHALLENGES
FOR ENGINEERING

From urban centers to the remote corners of Earth, the depths of the oceans to the far reaches of space, humans have sought to transcend barriers, overcome challenges, and create opportunities to improve life in our part of the universe. Engineering, science, and technology have truly shaped our world.

A few years ago, we published *A Century of Innovation*, a coffee-table book that highlighted great engineering achievements in the last century that have improved the quality of life—most of which we now take for granted. Technology has made it possible for us to provide an abundant supply of food and safe drinking water for much of the world. We rely on electricity for many of our daily activities, and we can travel the globe with relative ease. Goods and services can be delivered wherever they are needed. Growing computer and communications technologies are opening up vast stores of knowledge and entertainment.

As remarkable as these engineering achievements were, great challenges and opportunities still lie ahead. NAE has enlisted a blue-ribbon committee to develop a technological road map that charts a path to the future as a basis for public analysis and debate. The committee will be chaired by **William Perry**, University Professor of Engineering at Stanford University and former U.S. secretary of defense. The project is sponsored by the National Science Foundation.

The Grand Challenges for Engineering Committee will develop a ranked list of world challenges that can be addressed, at least in part, by engineering, drawing upon many sources of expertise (including NAE members and foreign associates, the NAE international Frontiers of Engineering Program, and engineering societies worldwide). Ideas from the broader public will also be welcome.

The committee will also identify areas of engineering research and innovation with the potential to address aspects of each challenge, suggest avenues of exploration, and explain it all in a way that will be easily understood by the lay public. The results of the committee's deliberations will be revealed at an event in Washington, D.C., in fall 2007.

To participate in the discussion or submit ideas, please visit the Grand Challenges for Engineering website at: *www.engineeringchallenges.org*, where essays and committee member profiles are also available.

Visiting Scholar and New Mirzayan Fellows

NAE Visiting Scholar

Alec Yasinsac

Alec Yasinsac is an associate professor of computer science at Florida State University (FSU). He joined the faculty of the FSU Computer Science Department in August 1999 after a 20-year career in the U.S. Marines as a data systems and communications officer. Having completed tours of active duty in Japan, Korea, North Carolina, California, and Virginia, he has operational experience in software development, information systems management, network engineering, and information security. Alec received his doctoral degree in computer science from the University of Virginia, where his thesis advisor and mentor was **Wm. A. Wulf**. His major research interests are network and wireless security, cryptography, intrusion detection, and security protocols.

Alec has published more than 35 refereed conference, symposium, and journal papers in the past five years. His work is presently funded by the National Science Foundation, U.S. Department of Defense, Army Research Office, and several industrial partners. He is an advisor to three doctoral students, three master's students, and one undergraduate thesis student. He has taught more than 75 college courses in mathematics, computer science, and information security.

Born and raised in the mountains of North Carolina, Alec earned a B.S. in mathematics from Appalachian State University. He earned an M.S. in computer science from the Naval Postgraduate School while he was on active duty in the Marines. He spent three weeks of his sabbatical at NAE learning about the work of the National Academies and assisting in the development of new NAE initiatives, including the Grand Challenges for Engineering Project.

Mirzayan Fellows

Peter Jordan

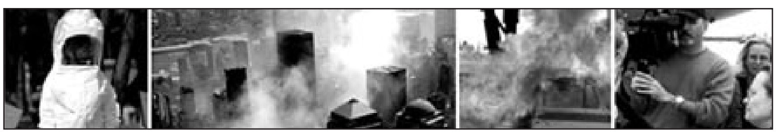
Peter Jordan is completing his Ph.D. in physiology and biophysics at the Weill Graduate School of Medical Sciences, Cornell University. In his research, which is funded by a predoctoral fellowship from the Howard Hughes Medical Institute (HHMI), he uses computational modeling to elucidate the mechanisms underlying cardiac arrhythmias. Prior to attending Cornell, Pete received his undergraduate degree in mechanical engineering from Queensland University of Technology in Australia and spent one year as a graduate student in biomedical engineering at the University of British Columbia. He is also completing a part-time M.A. in theology and religious studies, a reflection of his strong interest in the implications of interactions between science and religion in the formation of public policy.

During his time at NAE, Pete was a science and technology policy fellow at the Center for the Advancement of Scholarship in Engineering Education (CASEE). He worked on projects designed to increase participation in engineering and improve understanding of the value of research on engineering education.

Aaron Weaver

Aaron Weaver is pursuing a Ph.D. in mechanical engineering at the University of Michigan; he received his B.S. in mechanical engineering from Ohio State University. The goal of his research on the repair process of bone after fracture is to determine the effect on healing of external forces and micromotions at the fracture site. Through his coursework and research experience, Aaron has become interested in the policy of science education, especially in (1) improving communication between the public and the scientific community so that the public is better educated on the current state of science, and (2) educating the next generation of scientists to ensure that there is a strong base of enthusiastic scholars to conduct future scientific research. Aaron was a science and technology policy fellow at the Center for the Advancement of Scholarship in Engineering Education (CASEE) at NAE. During this fellowship, he reviewed articles for inclusion in the Peer Reviewed Research Offering Validation of Effective and Innovative Teaching (PR^{2}OVE-IT) website, which is aimed at disseminating techniques professors used to teach the next generation of scientists.

News and Terrorism Workshops Held in Columbus and Seattle



News and Terrorism: Communicating in a Crisis workshops were held in Columbus, Ohio, on July 20 and Seattle, Washington, on October 3. Engineers, scientists, and medical professionals from each region joined journalists, government officials, and representatives of private industry to participate in terrorism exercises, share perspectives, and discuss each other's roles in a disaster. The discussions centered on keeping the public informed and providing accurate news coverage during disasters.

Each workshop began with a scenario featuring a terrorist attack—a dirty bomb in the Columbus workshop and aerosolized anthrax in the Seattle workshop. A panel representing a cross-section of key players responded to events in the scenario as they unfolded. Afterward, experts critiqued the panelists' performances and participants discussed panelists' decisions and the issues raised by the scenario. Participants were then briefed on ways to protect themselves when covering various types of attacks.

Finally, smaller breakout groups met to discuss ideas and issues such as the need for private industry to have access to government decision makers, the media's preparedness for its role as first responder, and how to build trust between journalists and engineering and science experts.

These two workshops were the most recent in a series of 12 National Academies workshops sponsored by the U.S. Department of Homeland Security and led by the NAE Program Office. For additional details or information on future workshops, contact 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, which are available in PDF format at: *http://www.nae.edu/factsheets*.

Grants Awarded for Research on Vaccine Production

Four young academic engineers have been awarded $20,000 "starter grants" to pursue research on various aspects of engineering for production of an influenza vaccine. The grants, given in the name of NAE, are a result of an NAE/IOM Joint Topical Meeting on "Vaccine Production: Potential Engineering Approaches to a Pandemic," that was held on April 10 and 11 at Case Western Reserve University. The meeting attracted approximately 275 participants and another 1,000 by webcast. Six articles based on presentations given at the meeting were published in the fall 2006 issue of *The Bridge*.

Financial support for the meeting, provided by industry, federal agencies, and the state of Ohio (co-sponsors are listed on the website, *http://www.vaccine2006.org*), included money for 23 travel scholarships for young academic engineers to attend the conference and for the starter grants, for which the NAE/IOM steering committee held an open competition. The award winners were: Thomas H. Epps III, Chemical Engineering Department, University of Delaware, enhancing the potency of influenza vaccine with cross-linkable, nonionic block copolymer adjuvants; Sarah H. Harcum, Department of Bioengineering, Clemson University, the feasibility of alternative cell culture substrates; Blaine Pfeifer, Tufts University, cellular engineering to improve vaccine production and efficacy; and Chenming (Mike) Zhang, Department of Biological Systems Engineering, Virginia Tech, the role of transgenic plants in combating an influenza epidemic.

Leading Philanthropists Inducted into Einstein Society

Wm. A. Wulf, Jeong Kim, Cindy Kim

Dale Compton, Wm. A. Wulf, Jeanne Compton

Four leading donors to NAE and the National Academies were honored during the annual meeting in Washington, D.C. Jeanne and **Dale Compton** and Cindy and **Jeong Kim** were inducted into the Einstein Society, the highest recognition for donors to the National Academies.

The Einstein Society was created in 2005 to recognize members and private donors who make cumulative lifetime donations of $100,000 or more to NAE, National Academy of Sciences, Institute of Medicine, or National Research Council. To date, the society has 102 members, 34 of whom are NAE members.

In appreciation of their exemplary commitment, NAE president **Wm. A. Wulf** presented the honorees with replicas of the original maquette of the Einstein monument located on the front lawn of the National Academies Building on Constitution Avenue in Washington, D.C. Created by sculptor Robert Berks, each replica maquette has Berks' signature and is engraved with the donor's name as well as the following quotation from Albert Einstein: "The right to search for truth also implies a duty. One must not conceal any part of what one has recognized to be true."

For information about becoming a member of the Einstein Society, please contact the Office of Development at (202) 334-2431.

Einstein Society

The Einstein Society recognizes the generosity of members and friends who have made cumulative lifetime contributions of $100,000 or more to the National Academies. NAE members are in bold.

John Abelson
Bruce and Betty Alberts
Rose-Marie and Jack R. Anderson
Anonymous
John and Lise Armstrong
Holt Ashley*
Richard C. and Rita Atkinson
Norman R. Augustine
William F. Ballhaus Sr.
Craig and Barbara Barrett
Eleanor F. Barschall
Jordan and Rhoda Baruch
Warren L. Batts
Stephen D. Bechtel Jr.
Kenneth E. Behring
C. Gordon Bell
Elwyn and Jennifer Berlekamp
Diane and Norman Bernstein
Elkan Blout
Harry E. Bovay Jr.
David G. Bradley
Donald L. Bren
Sydney Brenner
Fletcher and Peg Byrom
James McConnell Clark
Dale and Jeanne Compton
Roman W. DeSanctis
George and Maggie Eads
Richard Evans
Harvey V. Fineberg and Mary E. Wilson
George and Ann Fisher
Harold K. and Betty A. Forsen
William L. and Mary Friend
Eugene Garfield
T.H. Geballe
William T. Golden
Corey S. Goodman
Bernard M. Gordon
David Grainger
Jerome H. and Barbara N. Grossman
Corbin Gwaltney
Margaret A. Hamburg and Peter F. Brown
William M. Haney III
Michael and Sheila Held
The William R. Jackson Family
Robert L. and Anne K. James
Thomas V. Jones
Kenneth A. Jonsson
Yuet W. Kan
Jeong and Cindy Kim
Mrs. Leon K. Kirchmayer
Frederick A. Klingenstein
Daniel E. Koshland Jr.
William W. Lang
Gerald and Doris Laubach
Tillie K. Lubin*
Whitney MacMillan
William W. McGuire
Burton and DeeDee McMurtry
Richard and Ronay Menschel
Ruben F. Mettler*
Dane and Mary Louise Miller
The Honorable* and Mrs. G. William Miller
George and Cynthia Mitchell
Ambrose K. Monell
Gordon and Betty Moore
Joe and Glenna Moore
Richard M. Morrow
Philip Needleman
Gerda K. Nelson
Ralph S. O'Connor
Peter O'Donnell Jr.
Kenneth H. Olsen
Doris Pankow
Jack S. Parker
Shela and Kumar Patel
Percy Pollard
Robert A. Pritzker
Dr. and Mrs. Allen E. Puckett
Michael P. Ramage
Simon Ramo
Carol and David Richards
Walter L. Robb
Hinda G. Rosenthal
George Rowe Jr.
Jack W. and Valerie Rowe
Mrs. Joseph E. Rowe
Mrs. Fritz J. Russ
William J. Rutter
Jillian Sackler
Bernard G. and Rhoda Sarnat
Sara Lee and Axel Schupf
Shep and Carol Ruth Shepherd
Melvin I. Simon
Georges C. St. Laurent Jr.
Ted Turner
Leslie L. Vadasz
Roy and Diana Vagelos
John C. Whitehead
Wm. A. Wulf and Anita K. Jones
Alejandro Zaffaroni

*Recently deceased

Calendar of Meetings and Events

November 8	Japan Region Meeting of Foreign Associates Atsugi, Japan
November 9–11	Japan-America Frontiers of Engineering Symposium Tsukuba, Japan
December 1	NAE Committee on Membership Meeting Irvine, California

2007

January 19	Grainger Challenge Committee Meeting
January 31	NAE Finance and Budget Conference Call
February 7–8	NAE Council Meeting Irvine, California
February 8	NAE National Meeting
February 20	NAE Awards Ceremony and Presentation Dinner Union Station, Washington, D.C.
March 15	NAE Regional Meeting Atlanta, Georgia

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

In Memoriam

MANSON BENEDICT, 98, Institute Professor, Emeritus, Massachusetts Institute of Technology, died on September 18, 2006. Dr. Benedict was elected to NAE in 1967 for "work in nuclear engineering."

FREDERICK BILLIG, 73, president, Pyrodyne Inc., died on June 1, 2006. Dr. Billig was elected to NAE in 1995 for "analytical and experimental contributions on supersonic/hypersonic combustion and ramjet engine technologies."

UMBERTO P. COLOMBO, 78, councillor, Italian National Council for the Economy and Labor, died on May 13, 2006. Professor Colombo was elected a foreign associate of NAE in 1989 for "contributions to the development of inorganic materials, electrotechnologies, and alternative energy sources."

P. OLE FANGER, 72, senior professor, International Center for Indoor Environment and Energy, Technical University of Denmark, died on September 18, 2006. Dr. Fanger was elected a foreign associate of NAE in 2001 for "significant interdisciplinary research on the influence of indoor environments on human comfort, health, and productivity."

R. PETER KING, 68, Professor Emeritus, University of Utah, died on September 11, 2006. Dr. King was elected to NAE in 2003 for "the development of techniques for quantifying mineral liberation and for leadership in Internet education about mineral processing."

HENDRICK KRAMERS, 89, past member, Board of Management, Akzo Nobel N.V., died on September 17, 2006. Dr. Kramers was elected a foreign associate of NAE in 1978 for "leadership in Dutch industry, education, and professional societies and research on chemical reactor design, separation processes, and process controls."

M. EUGENE MERCHANT, 93, senior consultant, TechSolve, died on August 19, 2006. Dr. Merchant was elected to NAE in 1975 for "contributions in machine tool research and development."

PHILLIP S. MYERS, 90, Emeritus Distinguished Research Professor, University of Wisconsin, died on October 18, 2006. Dr. Myers was elected to NAE in 1973 for "contributions to the understanding of ignition and heat transfer problems of internal combustion engines and their environmental impact."

FRANK R.N. NABARRO, 90, Honorary Research Professorial Fellow, School of Physics, University of the Witwatersrand, died on July 20, 2006. Professor Nabarro was elected a foreign associate of NAE in 1996 for "contributions to the understanding of crystal plasticity."

DUDLEY A. SAVILLE, 73, Stephen C. Macaleer '63 Professor of Engineering and Applied Science, Princeton University, died on October 4, 2006. Dr. Saville was elected to NAE in 2003 for "advancing our understanding of electrokinetic and electrohydrodynamic processes and their application to the assembly of colloidal arrays."

MILTON C. SHAW, 91, Professor of Engineering, Emeritus, Mechanical and Aerospace Engineering Department, Arizona State University, died on September 7, 2006. Professor Shaw was elected to NAE in 1968 for "contributions to chemical synthesis, lubrication and bearing design, and machine-tool design and performance."

RONALD SMELT, 91, retired vice president and chief scientist, Lockheed Corporation, died on February 17, 2005. Dr. Smelt was elected to NAE in 1971 for "the development of ingenious mathematical solutions to practical problems of aircraft and space-vehicle design and testing."

ALVIN M. WEINBERG, 91, Distinguished Fellow, Oak Ridge Associated Universities, died on October 18, 2006. Dr. Weinberg was elected to NAE in 1975 for "contributions in reactor design, development, and safety and understanding of how nuclear power must help meet world energy demand."

MAX T. WEISS, 83, retired corporate vice president, Northrop Grumman Corporation, died on June 10, 2006. Mr. Weiss was elected to NAE in 1986 for research into the use of ferrites in microwave components and for "extensive contributions to the research, engineering, and development of military space systems."

JAMES W. WESTWATER, 86, retired professor of chemical engineering, University of Illinois, died on March 31, 2006. Dr. Westwater was elected to NAE in 1974 for "contributions to boiling heat transfer by high-speed photography at great magnification."

DEAN E. WOOLDRIDGE, 93, retired president, TRW Inc., died on September 20, 2006. Dr. Wooldridge was elected to NAE in 1977 for "contributions to physical electronics, analog computers, and the management of research and development."

LEO YOUNG, 80, retired director for research, Office of the Secretary of Defense, U.S. Department of Defense, died on September 14, 2006. Dr. Young was elected to NAE in 1999 for "contributions to microwave technology and to the management of national security research."

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.)*

Beyond Bias and Barriers: Fulfilling the Potential of Women in Academic Science and Engineering. Women scientists and engineers face barriers to success in every field of science and engineering, a record that deprives the country of an important source of talent. Without a transformation of academic institutions to bring down such barriers, the future vitality of the U.S. research base and economy is in jeopardy. Eliminating gender bias in academia requires overarching reform now, including decisive action by university administrators, professional societies, federal funding agencies and foundations, government agencies, and Congress. If implemented and coordinated across public, private, and government sectors, the recommended actions will help to improve workplace environments for all employees while strengthening the foundations of America's competitiveness.

NAE members **Alice M. Agogino**, Roscoe and Elizabeth Hughes Professor of Mechanic Engineering, University of California at Berkeley, and **Elaine Weyuker**, fellow, AT&T Laboratories, Florham Park, N.J., were members of the study committee. Hardback, $50.95.

The Fuel Tax Alternatives for Transportation Funding: Special Report 285. This Special Report by the Transportation Research Board is a study of the viability of existing revenue sources, the merits of present transportation-finance arrangements, and potential directions for the reform of transportation finance. According to the report, fuel taxes can remain the primary funding source for the nation's highways for at least another decade, but eventually they should be replaced by a system of metering road use and charging accordingly, which would benefit both travelers and the general public. In addition, the committee that developed the report suggests that although the current funding system helps maintain existing highways and build new ones and ensures that users pay most of the costs, it does not help transportation agencies alleviate congestion or target investment to the most valuable projects.

NAE member **Thomas D. Larson**, consultant and former administrator, Federal Highway Administration, was a member of the study committee. Paper, $30.00.

Assessment of the Benefits of Extending the Tropical Rainfall Measuring Mission: A Perspective from the Research and Operations Communities, Interim Report. The Tropical Rainfall Measuring Mission (TRMM), which was launched in 1997 by the National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency, is a satellite-based program that placed a unique suite of instruments, including the first precipitation radar, in space. The instruments are used to monitor and predict tropical cyclone tracks and intensity, estimate rainfall, and monitor climate variability (precipitation and sea surface temperature). The data collected by TRMM for the past seven years are used by the Joint Typhoon Warning Center, National Center for Environmental Prediction, and National Hurricane Center, among other organizations worldwide. In July 2004, NASA announced that it would terminate TRMM in August 2004. At the request of the National Oceanic and Atmospheric Administration (NOAA), the White House, and the science community, NASA agreed to continue TRMM operations through the end of 2004. Meanwhile, NASA asked a National Research Council committee to assess the benefits of keeping TRMM in operation beyond that date. After holding a workshop with a number of experts in the field, the committee found that TRMM would make significant contributions to operations and science if the mission were extended and strongly recommended that it be continued, with one caveat—cost and risk of the program should be reexamined before a final decision is made.

NAE member **Eugene M. Rasmusson**, Research Professor Emeritus, Department of Atmospheric and Ocean Science, University of Maryland, chaired the study committee, and NAE member **Kristina B. Katsaros**, retired director, Atlantic Oceanographic and Meteorological Laboratory, NOAA, was a member of the study committee. Paper, $27.25.

Critical Technology Accessibility. In 2003, the Defense Intelligence Agency asked the National Research Council to form a standing committee to help the agency develop study topics. One issue identified by the committee was the growing U.S. dependence on foreign suppliers of critical technology as a result of increased globalization. Two important topics for study emerged: (1) the risk of refusing critical products from foreign sources; and (2) how the United States can ensure that it has access to critical products and technologies in the future. This report addresses both topics and provides an analysis of a strategic approach to managing the consequences of the trend toward globalization. Finally, the report offers recommendations for implementing this strategy and for ensuring U.S. access to critical technologies.

NAE member **Robert J. Hermann**, senior partner, Global Technology Partners LLC, chaired the study committee. Other NAE members on the committee were **Anthony J. DeMaria**, chief scientist, Coherent–DEOS LLC, and **Edsel D. Dunford**, retired president and chief operating officer, TRW Inc. Paper, $18.00.

Instrumentation for a Better Tomorrow: Proceedings of a Symposium in Honor of Arnold Beckman. On November 15, 2004, the National Academies sponsored a symposium at the Beckman Center in Irvine, California, in honor of Arnold O. Beckman on practical applications of scientific instrumentation, which was the focus of much of Beckman's work. The first section in this volume includes two presentations, a remembrance by Arnold Beckman's daughter, Pat, and an overview of Beckman's life and accomplishments by Arnold Thackray, president of the Chemical Heritage Foundation. The next section includes presentations on applications of instrumentation in seven areas: organic chemistry, molecular and systems biology, synchrotron x-ray sources, nanoscale chemistry, forensics, and clinical medicine. The volume concludes with a summary of a panel discussion on the changing relationship between instrumentation and research.

NAE members on the oversight board were **Erich P. Ippen**, Elihu Thomson Professor of Electrical Engineering and professor of physics, Massachusetts Institute of Technology, and **Julia M. Phillips**, director, Physical, Chemical, and Nano Sciences Center, Sandia National Laboratories. Paper, $18.00.

Transportation Knowledge Networks: A Management Strategy for the 21st Century: Special Report 284. This Special Report by the Transportation Research Board addresses how transportation information should be managed and provided. The report provides strategic advice to the federal government and states for a sustainable administrative structure and funding mechanism that will continue to meet the information-service needs of the transportation sector. The report identifies the core services that should be provided, describes how those services should be provided, and identifies funding options to support them.

NAE member **Francis B. Francois**, retired executive director, American Association of State Highway and Transportation Officials, chaired the study committee. Paper, $26.00.

Visualizing Chemistry: The Progress and Promise of Advanced Chemical Imaging. Scientists and engineers have long relied on imaging techniques to study objects invisible to the naked eye. Now they are pushing the limits of technology in pursuit of chemical imaging—techniques of visualizing molecular structures and chemical composition in time and space as they actually unfold, from tiny biological systems to the vast expanses of distant galaxies. Chemical imaging also has a variety of everyday applications, ranging from medical diagnosis and treatments to the study and design of material properties in new products. However, we must continue our efforts to improve our understanding and manipulation of complex chemical structures and processes. By linking technological advances in chemical imaging with a science-based approach to using these new capabilities, it is likely that we will achieve breakthroughs in our understanding of basic chemical processes in biology, the environment, and manufactured products. This report provides a review of the current state of chemical imaging technology, identifies promising future developments and their applications, and suggests a research and educational agenda that could lead to breakthrough improvements.

The report highlights the advances that would have the greatest impact on critical problems in science and technology.

NAE member **Watt W. Webb**, professor of applied physics and S.B. Eckert Professor in Engineering, Cornell University, was a member of the study committee. Paper, $50.00.

Tank Waste Retrieval, Processing, and On-site Disposal at Three Department of Energy Sites: Final Report. Congress asked the National Academies to evaluate the U.S. Department of Energy's (DOE's) plans for cleaning up defense-related radioactive wastes stored in underground tanks at three sites: the Hanford Site in Washington state, the Savannah River Site in South Carolina, and the Idaho National Laboratory. DOE plans to remove the waste from the tanks, separate out high-level radioactive waste to be shipped to an off-site geological repository, and dispose of the remaining lower activity waste on site. The report concludes that DOE's overall plan is workable, as long as important challenges can be overcome, including the removal of residual waste from some tanks, especially at Hanford and Savannah River. The report recommends that DOE pursue a more risk-informed, consistent, participatory, and transparent process of making decisions about how much waste to retrieve from tanks and how much to dispose of on site. The report offers several detailed recommendations for improving technical aspects of DOE's tank cleanup plans.

NAE member **Frank L. Parker**, Distinguished Professor of Environmental and Water Resources Engineering, Vanderbilt University, chaired the study committee. Other NAE members on the study committee were **Hadi A. Abu-Akeel**, senior vice president and chief engineer (retired) and technical advisor, FANUC Robotics America Inc., and **Milton Levenson**, retired vice president, Bechtel International, and independent consultant. Paper, $58.50.

Condensed-Matter and Materials Physics: The Science of the World Around Us. An Interim Report. As part of the 2010 Physics Decadal Survey Project, the U.S. Department of Energy and National Science Foundation requested that the National Research Council assess opportunities for the next decade in condensed matter and materials physics (CMMP). The final study will include a review of recent accomplishments and new opportunities; identify potential impacts of CMMP; consider how CMMP may contribute to national needs; assess priorities for tools and facilities; analyze current research and funding; and make recommendations for realizing the full benefit of CMMP. This interim report provides a summary of the early assessment of eight important challenges facing CMMP research in the coming decade and a brief review of the international situation. The final report will include a detailed discussion of these challenges and provide recommendations for addressing them.

NAE members **Mildred S. Dresselhaus**, Institute Professor of Electrical Engineering and Physics, Massachusetts Institute of Technology, and **William J. Spencer**, Chairman Emeritus, SEMATECH, are co-chairs of the Committee on CMMP 2010. Free pdf available online at: *http://www.nap.edu/catalog/11730.html.*

Decadal Survey of Civil Aeronautics: Foundation for the Future. The U.S. air transportation system is very important for our economic well-being and national security. The nation is also the global leader in civil and military aeronautics, a position that must be maintained to ensure a strong future for the domestic and international air transportation system. However, this will require a strong commitment. Congress and the National Aeronautics and Space Administration (NASA) requested that the National Research Council undertake a decadal survey of civil aeronautics research and technology (R&T) priorities to help NASA fulfill its responsibility of preserving U.S. leadership in aeronautics technology. This report provides strategic objectives for the next decade of R&T, identifies high-priority challenges for both NASA and non-NASA researchers, and provides an analysis of key barriers to reaching the strategic objectives. The report also stresses the importance of synergy between civil aeronautics R&T objectives and national security objectives.

NAE member **Paul G. Kaminski**, chairman and chief executive officer, Technovation Inc., and senior partner, Global Technology Partners, chaired the study committee. Other NAE members on the committee were **Eugene E. Covert**, T. Wilson Professor of Aeronautics, Emeritus, Massachusetts Institute of Technology (MIT); **Ilan Kroo**, professor, Department of Aeronautics and Astronautics, Stanford University; and **Nancy G. Leveson**, professor of aeronautics and astronautics and professor of engineering systems, MIT. Paper, $43.50.

Alternatives to the Indian Point Energy Center for Meeting New York Electric

Power Needs. Since September 11, 2001, many in the New York City area, concerned about the consequences of an attack on the Indian Point nuclear power plants located about 40 miles from Manhattan, have called for their closure. This would require some way to replace the 2,000 MW of power supplied by the plants. Congress directed the U.S. Department of Energy to request a study by the National Research Council of options for replacing the power currently supplied by the Indian Point plants. This report provides a detailed review of both demand and supply options for replacing that power and for meeting expected increases in demand in the region. The report also provides an assessment of institutional considerations and expected impacts of these options. Finally, the report provides an analysis of scenarios for implementing the replacement options using simulation modeling.

NAE member **Lawrence T. Papay**, consultant, and retired senior vice president, Integrated Solutions Sector, Science Applications International Corporation, chaired the study committee. Other NAE members on the committee were **James R. Katzer**, independent consultant and retired manager of strategic planning and program analysis, ExxonMobil Research and Engineering Company; **James S. Thorp**, Hugh P. and Ethel C. Kelly Professor of Electrical and Computer Engineering, and head, Department of Electrical and Computer Engineering, Virginia Polytechnic Institute and State University; and **John A. Tillinghast**, president, Tiltec Inc. Paper, $40.75.

Future Air Force Needs for Survivability. Many have proposed that more stealth technology be used to improve the survivability of future Air Force systems. Others have suggested that, considering the high cost and maintenance required for stealth technology, increased speed would be more effective. To help the Air Force address these issues, the National Research Council was asked to investigate combinations of speed and stealth that would provide U.S. aircraft with a high survival capability in the medium term (about 2018) and to identify changes in planned R&D to enable such aircraft. This report provides a review of stealth technology development; a discussion of possible future missions and threats; an analysis of the technical feasibility of achieving various levels of stealth and different speeds by 2018 and of relevant near-term R&D needs and priorities; and a discussion of speed and stealth trade-offs in the face of evolving threats.

NAE member **Seth Bonder**, Bonder Group, was a member of the study committee. Paper, $27.25.

Defense Modeling, Simulation, and Analysis: Meeting the Challenge. Modeling, simulation, and analysis (MS&A) is one of the pillars of a strategy for transforming the U.S. military. However, MS&A has not kept pace with new demands arising from rapid changes in defense processes and missions or with rapid changes in the technologies available to meet those demands. To help address those concerns, the U.S. Department of Defense (DOD) asked the National Research Council to identify shortcomings in current practices of MS&A and suggest where and how they should be resolved. This report provides an assessment of the changing mission of DOD and the environment in which it must operate, an identification of high-level opportunities for MS&A research to address the expanded mission, approaches for improving the interface between MS&A practitioners and decision makers, a discussion of training and continuing education of MS&A practitioners, and a discussion of the need for coordinated military science research to support MS&A.

NAE members **David M. Maddox**, consultant, Arlington, Virginia, and **Stephen M. Pollock**, Herrick Emeritus Professor of Manufacturing, University of Michigan, were members of the study committee. Paper, $18.00.

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