The Past Half Century of Engineering--And a Look Forward: Summary of a Forum

DETAILS

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THE PAST HALF CENTURY OF ENGINEERING –AND A LOOK FORWARD

SUMMARY OF A FORUM

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Preface

At its annual meeting on September 28–29, 2014, the National Academy of Engineering celebrated the 50th anniversary of its founding. It was a festive two days, highlighted by talks from Eric Schmidt, chair of Google; Frances Arnold, distinguished professor at Caltech; and Sally Jewell, secretary of the US Department of the Interior; along with greetings from Commander Steve Swanson and Flight Engineer Reid Wiseman from the International Space Station. The winning videos from the "Engineering for You" contest ran throughout the meeting in the west court of the Academy's headquarters in Washington, DC. Every attendee at the meeting received a copy of the anniversary essay book *Making a World of Difference: Engineering Ideas into Reality*. The meeting was a stimulating, illuminating, and fun commemoration of the benefits engineering has provided to people and society over the past half century.

Every recent annual meeting of the NAE has featured a forum of distinguished speakers who address a topic of vital interest to the profession, and this forum was one of the best yet. Seven presenters, moderated by Ali Velshi of Al Jazeera America, considered the achievements of the last 50 years and looked toward the potential achievements of the next 50. The speakers were

- Wanda M. Austin, president and CEO of the Aerospace Corporation and a member of the NAE Council;
- Corale L. Brierley, a founder of Brierley Consultancy and vice president of the National Academy of Engineering;
- Leonard Kleinrock, professor of computer science at the University of California, Los Angeles, and a developer of ARPANET;

- Robert W. Lucky, retired vice president of research at Telcordia Technologies, Inc., and previously a vice president at Bellcore;
- Arunava Majumdar, Jay Precourt Professor at Stanford University, founding director of the Advanced Research Projects Agency–Energy, and a member of the NAE Council;
- Roderic I. Pettigrew, director of the National Institute of Biomedical Imaging and Bioengineering and acting chief officer for scientific workforce diversity for the National Institutes of Health; and
- Robert E. Schafrik, retired general manager of the Materials and Process Engineering Department of General Electric Aviation.

As the speakers make clear in the following summary of their remarks, engineering is poised to make an even greater contribution to society in the next half century than it has made in the past half century. I am inspired by the important time that lies ahead for engineering. Our future, just like our past, will be delivered in great measure by engineering.

C. D. Mote, Jr.
President
National Academy of Engineering

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Learning from Adversity: Innovation on the Final Frontier

Engineers do not like to spotlight their mistakes, said Wanda Austin, president and chief executive officer of the Aerospace Corporation. They like to retain "an aura of infallibility and maybe even a little magic." But systems engineering in aerospace is hard, she said. It is rewarding but unforgiving—in aerospace, "success isn't just expected, it is absolutely required."

In the 1990s the aerospace industry experienced six launch failures, representing a considerable loss of assets. "It was a very difficult time for all of us in the industry. We were facing real adversity and were in need of real solutions."

Every one of these launch failures led to significant learning and lasting improvements, said Austin. "We took a good hard look at ourselves and improved our infrastructure, our efficiency, and our processes. As a result, we have benefited from an unprecedented stream of launch successes." Since 1999, 96 consecutive successful launches have taken place, including two from Cape Canaveral just four days apart the month before the forum.

Since 2000, the aerospace industry and government have reinvigorated all of the primary mission areas, including communications, navigation, and space-based sensors, and launched whole new constellations of satellites. Earth-observing facilities have provided huge quantities of new data about the planet on which we live. The Cassini Saturn Orbiter, the moon-mapping Lunar Reconnaissance Orbiter, the Mars Reconnaissance Orbiter, and the Mars Atmosphere and Volatile Evolution orbiter are providing fascinating information about the solar system. The Mars Curiosity Rover is studying the composition and climate of Earth's most intriguing planetary neighbor.

The aerospace industry has "been able to take the lessons we learned in the 1990s and apply them to mission success today," said Austin. "Challenging circumstances, when approached correctly, can be a tremendous catalyst for innovation."

THE POWER OF COLLABORATION

New ideas and technologies are not usually developed in isolation, Austin noted. Collaboration among government, universities, and companies has been at the core of progress in the aerospace industry.

For example, the Aerospace Corporation has been working for several years with SpaceX, one of the participants in the growing commercial space sector, on the company's effort to become certified for US Air Force missions. Another example involves science-based collaborations on the Transiting Exoplanet Survey Satellite (TESS), which is being developed by the Massachusetts Institute of Technology and NASA. TESS is a space telescope designed to locate and observe the most promising earth-like planets in the sky, after which high-powered telescopes such as the James Webb Space Telescope will characterize and evaluate their composition. Scheduled to launch in 2017, TESS "may very well be the piece of technology that discovers extraterrestrial life in our universe," said Austin.

A final example of seemingly more modest achievements in space that are still deeply critical to innovation involve what are known as CubeSats or Picosats—small orbital devices that are the product of more than 20 years of research, development, and testing. CubeSats can now perform such functions as propulsion, imaging, sensing, and attitude control. And they are invaluable educational tools, offering new perspectives on space and space flight for everyone from elected officials to young children. In response to a question about the hazards of orbital debris, Austin also noted that CubeSats are being designed for reentry so that they will not interfere with the operations of future satellites.

NEW BUSINESSES IN SPACE

Small satellites are "changing the face of space business," said Austin, by allowing new companies into the commercial sector. Shortly before the forum, Google announced that it planned to pay $500 million to acquire Sky Imaging, a company that uses small, low-cost satellites to take high-resolution images and video of Earth. Other companies, such as Planet

Labs, are creating a tremendous amount of excitement among investors and venture capitalists. Today, commercial as well as governmental investments are creating opportunities, and companies are figuring out ways to create new businesses in space. "The business potential for small satellites is anything but small," said Austin.

Advances in space technology also create new opportunities for cutting-edge developments on Earth. For example, an aerospace scientist recently received a patent for laser-scripted bone growth implants, primarily for the spine, based on laser processing techniques. "Our work touches every sector in our society," said Austin.

SUCCESS FROM ADVERSITY

"To create anything of value, we must not be afraid to fail, to make mistakes, or to change the status quo," Austin concluded. "It is my experience that challenges can always lead to opportunity." John Kennedy established the goal of going to the moon not because it was easy but because it was hard. Doing hard things teaches great lessons. Going into space, for example, provides an opportunity to learn about Earth, about its limited resources, and about the investments that need to be made to protect it.

Teams that never fail probably have missed opportunities, whereas teams that have achieved great success often do so by developing a strategy to learn from failure. As Albert Einstein said, "Anyone who has never made a mistake has never tried anything new."

The aerospace business pushes the boundaries of technology and human invention, said Austin. By confronting and overcoming challenges, it delivers tremendous benefits to humanity.

Drawing Inspiration from Hard Problems

In response to a question, Austin reflected briefly on her own life and career in engineering. "When I grew up in the inner city of New York, there were not a lot of black, female engineer role models. Fortunately, I had two parents who valued education and who never told me I couldn't do anything I wanted to do. They just told me I had to be willing to work hard." She also had a seventh grade math teacher who told her that she was good at math and that she should not let anyone tell her otherwise.

By the time Austin got to high school and college, she liked to solve hard problems, so she looked for areas that had hard problems to solve. When she got to graduate school, she had a professor who said, here is a hard problem that needs to be solved. "Voilà. The light bulb went on for me."

That kind of engagement, especially for girls, is critical, Austin said. She takes every available opportunity to go to schools and talk with students. "You never know what it is that you are going to say that is going to inspire one young person to pursue a career in engineering."

These students are our future leaders, she said. Whatever they go on to study and do, they need to be at least comfortable with technology and to understand what engineering does for society. "You have to expose them to as much as you can."

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Earth as a Resource

Every object that humans use either is made from earth resources or relies on earth resources for its production and distribution, said Corale Brierley, a founder of Brierley Consultancy. Oil and gas provide fuel for transportation and electricity for homes and businesses. Groundwater provides drinking and irrigation water. Sand and gravel are indispensable for construction. Copper is essential for electrical equipment and other devices. Electronic materials contain rare earth elements. Fertilizers consist of mined potassium and phosphorus. Geothermal energy is an emerging source of renewable energy. The earth even provides for storage and disposal of wastes.

New technologies are also changing how people think about and use earth resources. In recent decades, hydraulic fracturing and horizontal drilling have radically changed the production of energy. New techniques make it possible to drill miles into the earth beneath 10,000 feet of water-bearing rock to obtain petroleum. Tunnel boring machines are digging passages all over the world.

In the 1970s, the experience with Love Canal in Niagara Falls, New York, provided valuable lessons about environmental pollution. “We have to be extremely careful about what we put in the soil because it can pollute our groundwater,” said Brierley. Since then, research on the analysis and transport of contaminants has helped avoid similar disasters.

Solvent extraction now allows for the mining of much lower grade ore. The combination of solvent extraction and a technique known as *electrowinning* can yield a copper product that is 99.999 percent pure, Brierley observed. Biomining uses microorganisms to extract certain metals from earth materials, with 20 percent of the world’s mined copper now being produced through this technique.

And although some people think sustainability in mining is an oxymoron, "it isn't," she said, "because technology and engineering play such a huge role in maintaining our ability to extract these metals deeper and deeper in the earth and lower and lower in grade."

Technology also has made mining safer. The continuous miner has greatly reduced the number of miners who have to work underground. Many mining operations now use driverless trucks that rely on sophisticated technology to prevent injury and death to workers. In situ mining, in which minerals are extracted from rocks underground without transporting the rocks to the surface, could further reduce the exposure of workers and others to hazardous substances and situations.

TECHNOLOGIES FOR THE FUTURE

The next 50 years will demand equally dramatic improvements, said Brierley. In situ mining needs to be further developed to reduce the footprint created by mining on the earth's surface. In situ extraction can take advantage of the higher temperatures with depth in the earth, because extracting minerals tends to be easier at higher temperatures.

It also will be safer and more sustainable and will reduce the amounts of waste produced.

Technologies that enable people to "see" underground will further boost sustainability and safety. Already, ground-penetrating radar and three-dimensional seismic technology can reveal things such as objects buried under Stonehenge and the structure of volcanoes. But existing technologies still have limitations. For example, Big Bertha, the largest tunnel-boring machine in the world, got stuck under Seattle because it could not "see" a steel pipe in its path.

"What we need is a Google Map of the interior of the Earth so that we can see the geological and structural features underground," said Brierley. Just as biomedical technologies can see inside the body in real time, new technologies could visualize the fluids in the interior of the Earth with real-time accuracy.

With such technologies, the world could become a different place, Brierley concluded. Geothermal energy could reduce the need for fossil fuels. Earthquakes could be moderated or controlled. Carbon dioxide in the atmosphere could be stored underground. "Whether it is groundwater, whether it is geothermal energy, whether it is tunneling for transportation, whether it is mining, or for any of these other things, we have to be able to see what we are doing. That is where I see the great innovation technologically."

The Human Origins of Biomining

Some of the technologies Brierley discussed at the forum were of nonstandard, even humble origins. The development of biomining occurred in part because of a young woman who grew up on a cattle ranch in Montana, who rode her horse to a one-room schoolhouse and hated to clean the chicken coop. Her mother told her, "If you would go to college and if you would marry the right man, you won't have to ever clean another chicken coop." That young woman did go to college and met a young PhD student, and together they studied the microorganisms at hot springs in Yellowstone National Park, many of which have become extremely important in the mining industry. For their contributions to biomining, James and Corale Brierley were elected to membership in the National Academy of Engineering.

Brierley said that she never thought of herself as an engineer—she was a microbiologist by background. "I was just doing engineering work and applying microorganisms to mining. It wasn't until I got elected to the NAE that I discovered I was an engineer."

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The Seeds of the Internet—and Its Future

The vision that led to the Internet has existed for a long time. In 1908 Nikola Tesla envisioned a device no larger than a watch that would enable a person to communicate with anyone anywhere in the world. In the 1930s H.G. Wells wrote about a "world brain" that would serve as a depot for human knowledge. In the 1940s Vannevar Bush wrote about the Memex, a machine that would store the collective memories and creations of humanity.

In the 1960s, Leonard Kleinrock, Distinguished Professor of Computer Science at the University of California, Los Angeles, built with his colleagues a computer network that he saw as the forerunner of a system that would be always on, always available, and always accessible to anyone with any device from any location. He and the other developers of the Advanced Research Projects Agency Network, or ARPANET, had a model that they had analyzed, so they knew how it should behave. But "as engineers, we also knew what we didn't know," he added. "We had to experiment with this thing."

They built tools into their model to generate traffic, to test the model, to try to break it, and to learn from the results. "The wonders of engineering come when you try something and you discover things that you didn't anticipate. Then you find out why they behave in that way and how to fix it. The engineering approach was critical. It is not as if we designed something, built it, and let it go, because it would not have worked. We needed to correct it along the way."

The culture of the time was one of openness, he recalled. "[The model] was shared. We trusted everybody. We knew everybody that was coming into the network. We didn't put in any impediment—call that 'security measures'—to protect against bad behavior. In fact, the

gratification that we received as engineers was not to build a system to make money, but simply to solve the intriguing network engineering problem. . . . The gratification we got was when other people used the things that we designed and made available."

Once two nodes of the network were built in 1969, at UCLA and the Stanford Research Institute (SRI), Kleinrock and his colleagues decided to test it. Famous first messages, Kleinrock observed, have included "What hath God wrought," sent by Samuel Morse over the first long-distance telegraph system; "Mr. Watson, come here, I want to see you," sent by Alexander Graham Bell to his assistant over the first telephone; and "One giant leap for mankind," uttered by Neil Armstrong as he stepped onto the moon. "Those guys were smart. They understood public relations," said Kleinrock. "With ARPANET, all we wanted to do was to *log in* from the UCLA computer to the SRI computer." A programmer at UCLA typed the letter *l*. Someone on the telephone at UCLA asked whether the *l* had arrived. "I got the *l*," came the reply. A few seconds later: "Did you get the *o*?" "I got the *o*." Then the system crashed.

"So the first message on the Internet was 'lo,' as in 'lo and behold,'" said Kleinrock. "We could not have asked for a better, more succinct, more prophetic message. But nobody knows it. Hopefully someday it will be as popular as 'Mr. Watson, come here, I want to see you.'"

THE DARK SIDE OF THE INTERNET

After 25 years of growth, the first massive spam message on the Internet came from two lawyers named Canter and Siegel, who were trying to sell their services to help people get green cards. Their Internet service provider received so many emailed objections that it crashed. "The response to the first spam message was the first denial of service attack—inadvertently," Kleinrock noted.

The Internet allows anyone to reach millions of people instantly, easily, anonymously, and at no cost in money or effort. "That is a perfect formula for the dark side of the Internet."

Today, young people cannot conceive of a time when they could not share their photographs, chat with their friends, stream video, or shop online. But the Internet is a disruptive force, Kleinrock observed. As more information is digitized, as devices get smaller, smarter, faster, and cheaper, and as broadband, wireless, and wired continue to explode, disruptive events will continue to occur.

"The Internet itself is still a teenager, and it is acting like a teenager," Kleinrock said. "It is mischievous. It is erratic. It is unruly and it is disobedient. The hope is that it will mature and grow up into a properly behaved adult. We are not sure. We hope it will."

THE FUTURE OF THE INTERNET

In the future, content, technology, applications, services, and function will continue to converge in devices that everyone is carrying with them all the time. "The future will be one of extreme mobility, mass personalization, video addiction, location-based services, surprising apps, and, as we know, dramatic society and lifestyle changes."

A tipping point has recently occurred, Kleinrock observed. Engineers used to develop technology, and applications would follow. Today, applications are racing ahead of the technology, which is trying to catch up to serve the needs of the applications.

Yet the beauty of the Internet's design is that it does not preclude unanticipated services, applications, or technologies. It has accommodated the personal computer, e-mail, mobile apps, the World Wide Web, peer-to-peer sharing, blogs, social networking, and other applications, many of which have come as a complete surprise. "The technology is adaptive enough and general enough to allow these things to blossom."

Today, the Internet of things is starting to take shape. Already, much of the traffic on the Internet is generated by software agents and embedded devices. Eventually, sensors, actuators, logic, and memories will disappear into the walls, into eyeglasses, into tables, and even into people's bodies, said Kleinrock. "This room should be alive with technology. It should know I am here. It should know we are all here. If I have a conversation with Corale, it should assist us in that conversation. It should understand what we are saying and understand our background. The idea of making the environment *everywhere aware* is one of the major benefits we are going to get."

In the future, the Internet also will become increasingly invisible, so that people using it do not need to think about it. Human-computer interfaces will be far simpler than they are now, so that people will not have to do complicated typing on tiny keyboards. Computers will understand human speech, and apps will be far simpler and easier to use. In time, the Internet will become a "pervasive global nervous system."

Teaching Students to Overcome Failure

In response to a question about the education of engineers, Kleinrock said that educators need to encourage curiosity, even if it results in failure. "As teachers and faculty, we lie to our students. We present them with 4,000 years of knowledge crystallized and kernelized and lead them to believe that breakthroughs were easily accomplished. 'Here is this gem. Here is Shakespeare. Here are Maxwell's equations. . . .' The students then think, 'Well, it is easy. We will get to the frontier and we will be the next whoever.' But when they approach the frontiers of knowledge, they realize, 'My god, I can't move a thing.'"

He also labeled computers "the worst enemy of deep thinking." Students run a computer model and think they then know how a system behaves. "They have to do more than computation," he said. "They have to understand their own results and then try to extend them."

At the same time, students need to learn that they can make a difference, despite the difficulties they will encounter. "They have to be encouraged and applauded for their successes and encouraged with their failures."

These developments will not all be positive, said Kleinrock. Engineers often have the attitude that they more or less understand the systems they build, whereas natural scientists are forced to deal with a system they did not create. But as engineered systems become bigger and more complex, they are behaving in ways that engineers cannot necessarily understand or anticipate. “In all aspects of engineering, we have to step back and address complexity as an issue.”

The best prediction about the future of the Internet is that it will be unpredictable, Kleinrock concluded. “When [applications] come, they are usually unanticipated, surprising, and delightful, and they take over very quickly.”

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The Great Engineering Advances of the 21st Century

Robert Lucky's mother was born in 1902 and died in 1998. She grew up on a farm in Virginia with no electricity, no radio, and no telephone. Yet she lived to see a man walk on the moon and the rise of the Internet. "What an incredible century of change," Lucky told the forum attendees. "I was proud as an engineer of what we were able to accomplish."

Will the next century see the same amount of progress, or will technology yield diminishing returns to society's problems? "I don't know," said Lucky, but the list compiled by the National Academy of Engineering in 2003 of the 20 greatest engineering achievements of the 20th century offers some clues.

PREDICTABLE AND UNPREDICTABLE INVENTIONS

Fourteen years into the 20th century, how many of the items on that list already existed or could be foreseen?, Lucky asked.

In 1914 four of the top five items on the list were already well under way. Electrification, the top item on the list, was occurring rapidly, and AC power had become prominent. Henry Ford brought out the Model T in 1908, so the automobile, the second item on the list, already existed. The Wright brothers flew their first plane at Kitty Hawk in 1903, so the airplane, at number 3, had already been invented. And electronics, the fifth item on the list, became especially prominent when radio transmissions were used during the 1912 sinking of the *Titanic*.

Other items on the list could be foreseen with greater or lesser accuracy. The development of the automobile suggested the possibility of constructing the highway system (number eleven). Electrification

pointed toward the invention of household appliances (number 15). The mechanization of farming (number 7) was likely given the other engineering achievements of the time.

Other inventions, however, would have been difficult or impossible to foresee. Computers (number 8) and space travel (number 12) might have been vaguely foreseeable. But other inventions came out of the blue, such as the integrated circuit, the Internet, and the laser. These unanticipated inventions “had tremendous repercussions,” said Lucky. “I haven’t seen any of that yet this century.”

THE INVENTIONS OF THE FUTURE

Today, if people on the street were asked to name the greatest engineering accomplishments of the 21st century, their most likely responses would be Google, Amazon, Twitter, and Facebook, said Lucky. But these are companies, not technologies. Today the mystique of invention has a different focus. People are enthralled not by technologies but by business ideas.

Nevertheless, engineers will continue to invent, said Lucky, and he hazarded several guesses about where invention is headed.

First, wireless technologies will become increasingly prominent, he said. "The last century was a wired century—the telephone, electrification, the cable network, optical fiber. Now we have already had this transformation into a wireless world."

He also forecast the emergence of machine intelligence. He did not go so far as to predict that machines will become as intelligent as humans. "Human beings have something that machines aren't going to have this next century." But by the end of the century, intelligent machines could be widespread and doing a lot of the things that people do today.

Finally, 3D printing could transform the way products are made, Lucky predicted.

However, his most confident prediction was that inventions will continue to occur that cannot be foreseen. "Those will be the miracles that none of us, unfortunately, will be able to see."

The Changing Tools of Engineering

When engineers of his generation came of age, said Lucky in response to a question, they did not have the computer power that young engineers have today. But they had "fertile technology" that enabled massive innovation. "It was just ready to blossom at the time that we got it. I think a lot of us were lucky in that respect."

The world is now much more complex, and the number of engineers in the world makes it more difficult for any one engineer to stand out. "Nevertheless," said Lucky, "I envy them the power that they have with simulations and working with computers. Some of these kids are really great with computers. It is amazing. You go talk to the kids in schools . . . there is a lot of genius out there."

5

Energy in the 21st Century

Any discussion of energy must be viewed and framed from the perspective of three securities: national, economic, and environmental, said Arunava Majumdar, Jay Precourt Professor at Stanford University and founding director of the Advanced Research Projects Agency–Energy (ARPA-E). The growth of gross domestic product per capita and the growth of energy use have been closely correlated. "Without the use of energy, there is no modern economy," said Majumdar. "We are back in the medieval ages."

National security and economic security have been long-term concerns for energy; environmental concerns related to greenhouse gas emissions and global warming are more recent. Since the beginning of the Industrial Revolution, the average global temperature has gone up by about 1 degree. At any geographical location, some years are warmer and some years are cooler than average and it is hard to precisely predict the impact of global warming. But there is no question that globally the distribution of temperatures has shifted toward the warm end of the spectrum. As this shift continues, the tails of the distribution could have "a disproportionate effect on our economy [and] on our lives. . . . We don't understand all the details of climate change, but we know [the Earth] is warming, and the consequences of that could be severe."

The average carbon dioxide molecule emitted into the atmosphere stays in the atmosphere hundreds of years, so much of the carbon dioxide emitted since the beginning of the Industrial Revolution is still there. Over that time, the burning of fossil fuels has put about 1 trillion tonnes of carbon dioxide into the atmosphere. If all the known reserves of fossil fuels (which today have a value of about $10 trillion) were burned, the

result would be an additional 3 trillion tonnes of carbon dioxide in the atmosphere.

ENGINEERING A SOLUTION

The choice facing society is often posed as a dilemma, Majumdar observed. Should society ignore the threat to the environment and pursue economic growth, or should it keep $10 trillion worth of fossil fuels in the ground to save the environment? That is a "false choice," said Majumdar, "because it does not account for the human mind to engineer things."

The Stone Age did not come to an end because humans ran out of stones. Rather, they found better solutions to their problems. "If the Industrial Revolution was all about energy, we need to create a new Industrial Revolution," to address all three securities. Engineering will give us technological options, our insurance policy for a secure future.

The abundance of new local shale sources has separated the domestic price of natural gas from the international price of oil and thus helped bring down both carbon emissions and electricity generation costs by shifting electricity production toward the use of natural gas. Furthermore, our dependence on imported petroleum from unstable regions of the world has decreased, which has enhanced national security.

At the same time, the cost of new technologies has dropped. Within the next decade, the cost of LEDs should be competitive with the cost of compact fluorescent lamps, said Majumdar. The cost of wind energy is declining, with a resulting growth in capacity. The price of solar panels has come down dramatically, with corresponding increases in uptake. “Is this part of the new Industrial Revolution?” he asked. “Maybe.”

Energy storage is another part of the equation. The cost of lithium-ion battery systems has fallen from $1,000 to $400 per kilowatt-hour in just five years, and is continuing to drop through research that focuses on increasing the energy density of battery electrodes. Once the cost gets below $200 per kilowatt-hour, electric cars will be cost-competitive with gasoline cars, without subsidies, and will have roughly the same range. Research on the large-scale stationary storage of energy, which could be a game changer for the grid, is rapidly progressing. Further research to reduce the cost of biofuels could also be part of the solution, Majumdar said.

Nuclear power is likely to be an important source of energy, especially for base load capacity, Majumdar added in response to a question. “I can’t imagine us addressing climate change in any focused and substantive way without having nuclear.” The cost of building and financing nuclear energy has to come down so it can compete in the marketplace. Furthermore, we need to overcome some political and institutional challenges in managing nuclear wastes.

The development of a new paradigm for the design and operation of the electricity grid is critical. The architecture of the current electrical grid is still essentially the one developed at the beginning of the 20th century, with centralized generation, long-distance transmission, and local distribution. A new grid must be optimized for both centralized and distributed resources, with dynamical control and balancing of load, generation, and storage in order to maximize the use of intermittent resources such as wind and solar, reduce overall system cost and carbon emissions, and increase resilience against security and natural threats. We need engineering to design, build, and operate such a complex networked system. This is an important challenge that will require not only new technologies but also new business and financing models. “It is absolutely critical to manage this transition in the most cost-effective and reliable way."

BRINGING THE WORLD ONLINE

These technologies will be even more important as the world continues to develop. Today, about 3 billion people still have no or very limited access to electricity, and by 2050 another 2 billion people will be added to the same regions that do not have full access to electricity today. "The question is, Do we extrapolate the 20th century grid for them, or do we create a new grid?"

The current level of paralysis in the political system would argue against much getting done, but Majumdar said that he is optimistic. Even during the Civil War, the political process got things done—such as creating the National Academy of Sciences. In "the long term, I think the process has worked. I would not give up."

Enrico Fermi on the Gulf Oil Spill

Majumdar spoke briefly about his experiences with the April 20, 2010, oil spill in the Gulf of Mexico caused by the explosion on the *Deepwater Horizon* drilling rig. During the 87 days that oil flowed into the Gulf, some people speculated about the possibility of detonating a nuclear weapon to seal the well.

In an email written at 2:18 AM on June 25, Richard Garwin, an Academy member who helped developed the hydrogen bomb, wrote to the science team that was considering what to do: "This is a topic I know a good deal about. . . . Here are 7 pages in Enrico Fermi's hand from my July 1950 Los Alamos notebook—an early calculation of such containment."

As Majumdar wrote in a subsequent email: "I never thought I would encounter a historical connection between the oil spill and Enrico Fermi spanning 60 years. I am awed that Dick had his lab notebook from 60 years ago. And even more so that he remembers where things are in it!"

6

Engineering and Medicine

Roderic Pettigrew went to graduate school at the Massachusetts Institute of Technology to work on a specific project that fascinated him: a treatment for a highly lethal form of brain cancer, glioblastoma multiforme, based on an idea that was "something out of Star Trek." The treatment involved loading the stable isotope boron-10 into cancer cells and then exposing the cells to low-energy neutrons. The isotope captures neutrons and becomes boron-11, which rapidly fissions into a high-energy alpha particle and lithium. The range of these fission products in tissue is so small that their energy is delivered in a volume that is about the same size as a cell. In this way the treatment delivers "very focused radiation damage and death specifically to cancer cells and not the healthy surrounding cells," Pettigrew said.

Pettigrew's work at the interface of engineering and biology eventually led him to be named director of the NIH National Institute of Biomedical Imaging and Bioengineering. The institute was based on the idea that "biology and engineering were beginning to cross paths," he said, which promised a transformative impact on the understanding and treatment of disease. This observation was underscored by a survey of physicians on the relative importance of 30 medical innovations in the last three decades of the 20th century. Engineering and imaging claimed the top innovation and played a major role in three of the top five—MRI and CT scanning (the top innovation), balloon angioplasty, and mammography—and was critical in more than half of the top 15.

The development of MRI is "an exemplar of this process," said Pettigrew. In 1973 Paul Lauterbur, a professor of chemistry at the State University of New York at Stony Brook, published a paper in the journal *Nature* that arose from a "eureka moment." The phenomenon of nuclear

magnetic resonance was well known but had not been used for imaging. Lauterbur realized that if a magnetic field were varied spatially it would produce a signal that corresponded to a location. The English physicist Peter Mansfield showed how to efficiently analyze these signals to produce an image and developed a way to do very fast imaging. For their discoveries, Lauterbur and Mansfield received the 2003 Nobel Prize in Physiology or Medicine.

"The point here is that there is no limit to imagination," said Pettigrew. "Decades of continuous imagination and innovation led us, just 30 years down the road, to the ability to produce exquisite images of the human brain and some of its biological processes without harm."

PATHWAYS IN THE BRAIN

As another example of the intersection of engineering and biology, Pettigrew briefly described *neural tractography*, the use of imaging to trace neural tracts in the brain in three dimensions. These pathways are not directly visualized, he explained. Rather, they are computed based on the diffusion of water along axonal pathways that are quantitatively resolved in 300 isotropic directions.

The technique has "rocked the neuroscience community" by revealing the detailed wiring patterns of the brain, said Pettigrew. For example, it has revealed orthogonal wiring patterns within sheets of neurons, which Van Wedeen, the discovering neuroscientist, speculates make it easier for developing neurons to navigate through space. Such studies also may provide insights into brain plasticity when one part of the brain becomes dysfunctional and adjacent areas of the brain are enlisted to serve a lost function.

Beyond the tracking of neural pathways, reverse engineering of the brain is a "daunting challenge," said Pettigrew, but it is a challenge where engineering will continue to make progress.

CURRENT TECHNOLOGIES THAT POINT TO THE FUTURE

Pettigrew concluded by citing six current technologies (illustrated in a video[1]) that demonstrate the incredible promise of engineering to improve health:

- Regenerative medicine makes it possible to grow human liver tissue in a mouse, which then can be tested for drug toxicity to avoid the need for human testing.
- Biodegradable stents can dissolve and resorb into the body, greatly reducing the body's negative reactions to the implants.
- Tiny MRI devices combined with analytic chemistry platforms can probe virtually any biological target, including bacteria, viruses, and drugs, at very high sensitivity.
- A portable Doppler ultrasound device can be carried in the pocket and transported anywhere in the world, including disaster sites or remote regions.
- A bilayer polymer that changes shape as it absorbs moisture can be used as an energy source.
- An epidural spinal stimulation technique can return some voluntary motion to individuals who are completely paralyzed.

Pettigrew quoted Robert Goddard to make his final point: "It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow." Engineers and engineering make this

[1] The video of his presentation is available online at www.youtube.com/watch?v=Vw-kIiHhMn8.

statement true, said Pettigrew. "Engineers are in the practice of dreaming, harnessing those dreams, and turning them into a reality, giving all of us real hope for a better and brighter future."

An Engineer-Astronaut

While he was a graduate student at the Massachusetts Institute of Technology, Pettigrew became best friends with another graduate student named Ronald McNair, who was working on laser spectroscopy. "The thing that brought us together is that we had the same motivation," he said. "We both wanted to use science and engineering to improve the human condition."

When McNair graduated with his PhD, he went to work at the Hughes Research Laboratories in California. "One day he called me and said NASA was restarting its astronaut program, he was going to explore that," Pettigrew said. McNair was selected to become an astronaut, completed his training, and during his first mission operated the robot arm to move payloads in space. After this trip they were both fascinated by McNair's discoveries and new insights into the laws of nature revealed by his home videos of this voyage, which they reviewed together. Unfortunately, McNair's second mission was on the space shuttle *Challenger*, which exploded shortly after takeoff, killing all seven crew members.

"We always encouraged each other to use science and engineering to discover new things and use this knowledge to improve lives globally," said Pettigrew. "Reaching for this dream was our driver."

7

Fifty Years of Materials Science

"If the past is prologue, the future of materials will be quite exciting," said Robert Schafrik, retired general manager of the Materials and Process Engineering Department of General Electric Aviation.

Fifty years ago, when Schafrik was an undergraduate, General Electric was developing a new class of jet engines for the new Air Force C-5A strategic airlifter program. The TF39 engine was very successful, and its CF6 commercial derivative is still flying today on many wide-bodied aircraft,[1] as are similar engines designed by Pratt & Whitney and Rolls-Royce. The engine had a 25 percent improvement in fuel efficiency over early turbojet engines, based in part on a new architecture known as a high-bypass engine and in part on the implementation of many new materials. Since then fuel efficiencies have continued to improve by an average of 1 percent per year. When Schafrik asked the design engineers what proportion of that improvement was due to new materials as opposed to other engineering changes, their estimate was one-third to one-half.

To further boost fuel efficiencies, the compression ratio and burning temperature in the engine have to increase. However, the temperature in the turbine of today's jet engines is already several hundred degrees above the incipient melting point of the turbines' nickel superalloys. But engineers have found ways to "fool the metal to think the environment is cooler," Schafrik said. The turbine blades are essentially radiators with many internal cooling passages. In addition, they have cooling air flowing over the surface and an insulating layer of ceramic.

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[1] Applications for the CF6 include the Airbus A300, A310, A330; Boeing 747 and 767; McDonnell Douglas DC-10 and MD-11; and the C-5M. To date, all models of the engine have accumulated 400 million flight-hours.

Nevertheless, "designing [and] developing a new turbine blade alloy is really hard," Schafrik said. "There definitely are limits . . . to what you can do."

OVERCOMING LIMITS

One way to overcome today's temperature limits is to make engine parts out of ceramic materials that have much higher operating temperatures. For example, the new LEAP engine that will soon be introduced into service has the first application of ceramic matrix composites (CMC) in the turbine section of an engine, though on the turbine shroud rather than a rotating part of the engine. Other CMC applications are under development.

Another intriguing concept would be to move away from the Brayton thermodynamic cycle to new engine architectures, such as a number of small fans along the leading edge of an airplane's wing, with each fan powered by electricity carried in a superconducting wire. "Within 50 years, we will know what the answer is," said Schafrik. But whatever the configuration, "there will be significant challenges in materials."

What is evident from this look at materials in aviation engines is that societal benefit does result from application of new materials. Materials developments have transformed nearly every aspect of modern life, from electronics and photonics to the constructed environment, medical equipment, aerospace, and modern energy systems.

SPEEDING UP DEVELOPMENT

The development of new materials has typically taken a long time, Schafrik noted. A new class of materials like an intermetallic or ceramic matrix composite can take 20 to 30 years, and more, to move from concept to use.

He predicted that in the future development will take place in one-third the time, not only for structural materials but across the board. Already, accelerated programs on a selective basis have produced tremendous gains. Recently, a new turbine blade alloy was qualified for flight by the Federal Aviation Administration within two years of starting the program. Normally, the development of that material would have taken at least six years, Schafrik said, but the use of computational tools and an integrated design and manufacturing team greatly sped up the process. That success "gives us a road map for the future on how to conduct an accelerated program and how [to] extend that process into other areas."

Over the next 50 years, the major materials impetus will be on effectively taking advantage of new materials developments, across all application areas, to fulfill societal needs. The route to get there will involve step increases in the amount of computational modeling and quantum increases in knowledge of the underlying science behind the material that can readily be turned into predictive models. It will also lead to closer collaboration between materials experts, design engineers, and manufacturing experts.

A lot is at stake, Schafrik observed. For instance, new aircraft engines cost $1–2 billion to develop, and a field problem can easily cost hundreds of millions of dollars to solve. Other application domains encounter similar challenges, which add to the reluctance to use a new material. Current computational models are becoming proficient at predicting the properties of new materials, but more scientific research is needed to predict how materials degrade in use. "We need very smart ways to test these materials. This is beyond some of the standard tests in use now, which often are not representative of the environments that we encounter. Over the next 50 years, accelerated tests based on scientific understanding of the relevant degradation modes will enable confident predictions of long-term performance of materials, greatly reducing the risk of using them."

THE ROLE OF GOVERNMENT

As Eric Schmidt pointed out during an earlier presentation at the 2014 NAE annual meeting, the government has played a key role in stimulating innovation. That also has been the case with the development of new materials, Schafrik said, and governmental involvement will continue to be critical.

"Going forward, I think a coordinated effort by industry, government, and universities—and this will no doubt happen in the next 50 years—will be essential to accelerate the development of materials across all different spectrums of interest."

A collaborative ecosystem among sectors can bring experts together to solve problems and satisfy needs, with computational tools facilitating collaborations. "The future for materials is quite exciting," Schafrik concluded. "We have tremendous opportunity to influence the engineering world."

The Return of Supersonic Transport?

In response to a question, Schafrik speculated about the possible development of a new supersonic jet. It would be costly, he pointed out, which raises the question of whether a business case exists for such a program. But "if we wanted to do that, we do know how to do it. We could roll up our sleeves. . . . Will it be economical in 50 years? That is an intriguing possibility."

8

Expanding the Community of Innovators

During the discussion session of the forum, moderator Ali Velshi, host of "Real Money with Ali Velshi" on Al Jazeera America, briefly offered his own perspective on the future of engineering. As the presentations of the forum participants made clear, inspiration in engineering has many origins. In some cases, as with aeronautics, partnerships between government and the private sector have led to new

Left to right: Robert Schafrik, Robert Lucky, Roderic Pettigrew, Arun Majumdar, Wanda Austin, Leonard Kleinrock, C. D. Mote, Jr., Corale Brierley, and moderator Ali Velshi.

Corale Brierley and Wanda Austin.

technologies and new industries. In other cases, engineers working on their own decided to try things that no one else had tried. Sometimes national security was a driving force, or a difficult research problem, or the profit motive.

Today, said Velshi, a new source of innovation must be considered. With the connectivity of the Internet and the growing power of computing, innovation can come from anywhere, not just from those who are trained and work as engineers. The *X factor*, said Velshi, is "the kid who is dreaming right now who has no particular formal training, but has the Internet—the kid someplace in Africa or Asia who is going to get the Internet soon on a smartphone and is going to discover something."

The question for engineering, Velshi continued, is how to welcome the contributions of such innovators. "Do we figure out a way to get them into the system? Do we somehow harness the power that they have outside of that system?" Such questions could challenge traditional notions of how engineers are educated and how engineering can change the world.

In another 50 years, the National Academy of Engineering will celebrate its first century, Velshi reminded the forum attendees. The

Audience members queue to ask questions during the panel discussion.

engineers sitting in the audience and elsewhere around the world will help determine what happens during those next 50 years. "For me, this is just talk. For you, you have some influence."

Appendix A

Forum Agenda

Annual Meeting Forum
Celebrating the NAE's 50th Anniversary

The History of Engineering over the Past 50 Years
and a Look Forward

Monday, September 29, 2014
9:30 a.m.–12:30 p.m.
National Academy of Sciences Building
Washington, DC

The forum will explore the engineering accomplishments of the past 50 years and look forward to the challenges in the next 50.

Welcome

C. D. Mote, Jr., President, National Academy of Engineering

Moderator: **Ali Velshi**, Host of *Real Money with Ali Velshi* on Al Jazeera America

Forum Discussion

Forum Participants

Wanda M. Austin, President and Chief Executive Officer, The Aerospace Corporation

Corale L. Brierley, Vice President, National Academy of Engineering, and Principal, Brierley Consultancy LLC

Leonard Kleinrock, Distinguished Professor, Computer Science Department, University of California, Los Angeles

Robert W. Lucky, Corporate Vice President, Research (retired), Telcordia Technologies Inc.

Arunava Majumdar, Jay Precourt Professor and Senior Fellow, Precourt Institute for Energy, Department of Mechanical Engineering, Stanford University

Roderic I. Pettigrew, Director, National Institute of Biomedical Imaging and Bioengineering

Robert E. Schafrik, General Manager, Materials and Process Engineering Department (retired), GE Aviation

Appendix B

Biographical Information

WANDA M. AUSTIN is president and chief executive officer of the Aerospace Corporation, a leading architect of the nation's national security space programs, with nearly 4,000 employees and annual revenues of more than $850 million. She assumed this position on January 1, 2008. She is also committed to inspiring the next generation to study the STEM disciplines and making science and engineering preferred career choices. Under her guidance, the Aerospace Corporation has undertaken a number of initiatives in support of this goal, including participation in MathCounts, US FIRST Robotics, and Change the Equation.

Dr. Austin is internationally recognized for her work in satellite and payload system acquisition, systems engineering, and system simulation. She served on President Obama's Review of Human Spaceflight Plans Committee in 2009, and was appointed to the Defense Science Board in 2010 and the NASA Advisory Council in 2014.

She is a member of the National Academy of Engineering, International Academy of Astronautics, and American Academy of Arts and Sciences and a fellow of the American Institute of Aeronautics and Astronautics (AIAA). She has received numerous awards and citations, among them the National Intelligence Medallion for Meritorious Service, Air Force Scroll of Achievement, and National Reconnaissance Office Gold Medal, as well as the AIAA von Braun Award for Excellence in Space Program Management (2010), the Horatio Alger Award (2012), the NDIA Peter B. Teets Industry Award (2012), and the USC Viterbi Distinguished Alumni Award (2014).

Dr. Austin earned her bachelor's degree in mathematics from Franklin and Marshall College, master's degrees in systems engineering and mathematics from the University of Pittsburgh, and doctorate in systems engineering from the University of Southern California.

CORALE L. BRIERLEY is principal and founder (in 1991) of Brierley Consultancy LLC, which provides technical and business consultation to the mining and chemical industries and government agencies. Previously, she worked as chief of environmental process development for Newmont Mining Corporation (1990–1991), general partner at VistaTech Partnership Ltd. (1988–1999), president of Advanced Mineral Technologies, Inc. (1982–1988), chemical microbiologist at the New Mexico Institute of Mining and Technology (1971–1982), and microbiologist with Martin-Marietta Corp. (1968–1969). Her interests are in biotechnology applied to mine production; the treatment and management of metal-bearing aqueous, solid, and radioactive wastes; and market and business development in these technical areas.

Dr. Brierley was elected to the NAE in 1999 for her innovations applying biotechnology to mine production and remediation. She served as NAE Councillor from 2009 to 2014, when she was elected vice president. She has been active on a number of NAE committees, currently chairs the NRC Board on Earth Sciences and Resources, and previously chaired the congressionally mandated NRC Committee on Coal Research, Technology, and Resource Assessments to Inform Energy Policy. Her past NRC committee service includes the Panel on Technologies for the Mining Industries, Committee on Novel Approaches to the Management of Greenhouse Gas Emissions from Energy Systems, Committee on Ground Water Recharge in Surface-Mined Areas, and Committee on Review of the US Geological Survey's Mineral Resources Program (which she chaired).

Dr. Brierley is a member of the Society of Mining Engineers (SME) of the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME) and has received both the AIME James Douglas Gold Medal (2008) for distinguished achievement in nonferrous metallurgy and the SME Milton E. Wadsworth Award (2011) for distinguished contributions advancing understanding of the science and technology of nonferrous chemical metallurgy. She is a member of the International Advisory Committee for the Biohydrometallurgy Symposia (since 1983), and has served on the editorial boards for Elsevier's *Hydrometallurgy* journal since 1996 and *Minerals Engineering* journal since June 2014.

She received her BS degree in biology (1968) and MS in chemistry (1971), both from the New Mexico Institute of Mining and Technology, and her PhD in environmental sciences (1982) from the University of Texas at Dallas.

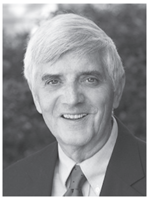
LEONARD KLEINROCK is Distinguished Professor of Computer Science at UCLA. He developed the mathematical theory of packet networks, the technology underpinning the Internet, as an MIT graduate student in 1962 (he received his PhD in 1963). His UCLA host computer became the first node of the Internet in September 1969 from which he directed the transmission of the first Internet message.

Dr. Kleinrock has served as professor of computer science at UCLA since 1963, and was department chair in 1991–1995. He has published over 250 papers and authored six books in areas including packet switching networks, packet radio networks, local area networks, broadband networks, nomadic computing, performance evaluation, intelligent agents, and peer-to-peer networks. He was a cofounder and first president of Linkabit Corporation, cofounder of Nomadix, Inc., and founder of TTI/Vanguard.

Dr. Kleinrock is a member of the National Academy of Engineering and American Academy of Arts and Sciences; a fellow of the IEEE, ACM, INFORMS, and IEC; and an inaugural member of the Internet Hall of Fame. Among his many honors, he is a recipient of the Ericsson Prize, the NAE Draper Prize, the Marconi Prize, the Okawa Prize, the Dan David Prize, and the IEEE Alexander Graham Bell Medal and Harry M. Goode Award. He was further recognized when he received the 2007 National Medal of Science, the highest honor for achievement in science, bestowed by the president of the United States.

ROBERT W. LUCKY has led premier research laboratories in telecommunications over the last several decades, first at Bell Labs and then at Telcordia Technologies, where he was corporate vice president for applied research. Since retiring he has remained active in professional activities including advisory boards, studies, and consulting.

Dr. Lucky is the author of many technical papers and several books, including *Silicon Dreams: Information, Man, and Machine* and *Lucky Strikes . . . Again: Feats and Foibles of Engineers*. However, most engineers know him through his monthly columns for IEEE's *Spectrum* magazine over the past 30 years, offering philosophical and sometimes humorous observations on engineering, life, and technology. He has been invited to speak at more than 100 universities and is a frequent speaker at technical, business, academic, and social occasions, delivering plenary and keynote addresses to conferences.



He received his PhD in electrical engineering from Purdue University, and has since been honored with four honorary doctorates as well as a number of major awards, including the Marconi Prize and IEEE Edison Medal. He is an elected fellow of the IEEE and member of the National Academy of Engineering as well as the American and European Academies of Arts and Sciences.

ARUNAVA MAJUMDAR is the Jay Precourt Professor at Stanford University, where he serves on the faculty of the Department of Mechanical Engineering and is a senior fellow of the Precourt Institute for Energy. Before joining Stanford, he was vice president for energy at Google, where he created several energy technology initiatives.

In October 2009 he was nominated by President Obama and confirmed by the Senate as founding director of the Advanced Research Projects Agency–Energy (ARPA-E), where he served 'til June 2012. From March 2011 to June 2012 he was also acting under secretary of energy and a senior advisor to the secretary of energy. He currently serves on the US Secretary of Energy's Advisory Board, the councils of the National Academy of Engineering (of which he is an elected member) and the Electric Power Research Institute, and the Science Board of the Stanford Linear Accelerator Center (SLAC) and Oak Ridge National Laboratory. He is a member of the International Advisory Panel for Energy of the Singapore Ministry of Trade and Industry and the US delegation for the US-India Track II Dialogue on Climate Change and Energy, and US science envoy to Eastern Europe in the area of energy and innovation. He is also a member of the American Academy of Arts and Sciences.

Dr. Majumdar was previously the Almy and Agnes Maynard Chair Professor of Mechanical Engineering and Materials Science and Engineering at the University of California, Berkeley, and associate laboratory director for energy and environment at Lawrence Berkeley National Laboratory. His research interests include the science and engineering of nanoscale materials and devices as well as large engineered systems.

He received his bachelor's degree in mechanical engineering at the

Indian Institute of Technology in Bombay in 1985 and his PhD from the University of California, Berkeley, in 1989.

RODERIC I. PETTIGREW, PhD, MD, is the first director of the NIH National Institute of Biomedical Imaging and Bioengineering (NIBIB) and in 2013 was also appointed NIH's acting chief officer for scientific workforce diversity. This position was established by the NIH director for the coordination and oversight of all NIH programs and activities designed to strengthen the biomedical research workforce through enhanced diversity.

Before his appointment at the NIH, Dr. Pettigrew was professor of radiology, medicine (cardiology) at Emory University and of bioengineering at the Georgia Institute of Technology; he was also director of the Emory Center for Magnetic Resonance Research, Emory University School of Medicine, in Atlanta. He is known internationally for his pioneering work at Emory University involving four-dimensional imaging of the cardiovascular system using MRI. His current research focuses on integrated imaging and predictive biomechanical modeling of coronary atherosclerotic disease.

Early on at NIBIB he jointly led a national effort with the Howard Hughes Medical Institute to create new interdisciplinary graduate training programs, and established the Quantum Projects program to achieve "medical moon shots" by pursuing high-risk, high-impact projects designed to solve major healthcare problems. Under his leadership, national collaborative and international initiatives have been issued to develop low-cost and point-of-care medical technologies.

At present he leads an effort to reduce CT radiation dose to background levels. And he has recently called for a US-India collaboration to develop unobtrusive technologies for frequent recording of blood pressure to address the worldwide problem of hypertension.

Dr. Pettigrew is a member of both the National Academy of Engineering and the Institute of Medicine. His awards include Phi Beta Kappa, the Benjamin E. Mays Award from A Better Chance Foundation, Most Distinguished Alumnus of the University of Miami, Herbert Nickens Award of the Association of Black Cardiologists, Pritzker Distinguished Achievement Award of the Biomedical Engineering Society, Distinguished Service Award of the National Medical Association, and the Pierre Galletti Award of the American Institute of Medical and Biological Engineering.

ROBERT E. SCHAFRIK recently retired as general manager of the Materials and Process Engineering Department at GE Aviation (formerly GE Aircraft Engines) in Cincinnati, a position he held since 1999. During his tenure he and his team reduced the development time for several new materials—including low rhenium turbine blade alloy, R65 (a high-temperature cast-and-wrought disk alloy), and titanium aluminide turbine blade alloy—and greatly expanded the use of composite applications in engines. He was hired in 1997 as a senior staff department engineer.

Before that (1991–1997) he staffed the National Research Council's National Materials Advisory Board (NMAB) and Board on Manufacturing and Engineering Design (BMAED), following his service as vice president of research and development at Technology Assessment and Transfer, Inc., in Annapolis (1988–1991).

Dr. Schafrik spent 20 years on active duty as a military officer in the US Air Force before retiring as a lieutenant colonel in 1988. He was chief of the Long-Term Planning Division with the Strategic Defense Initiative Organization (SDIO) at the Pentagon and, before that, chief of the Air Superiority Division for the Headquarters Air Force Systems Command (AFSC) at Andrews Air Force Base.

He chairs the NRC National Materials and Manufacturing Board as well as the External Advisory Committee for the Materials Science and Engineering Department at Ohio State University, and is a member of the Air Force Scientific Advisory Board.

He was elected to the NAE in 2013 for more than 40 years of innovation in materials for gas turbine engines.

Dr. Schafrik earned his BS in metallurgy from Case Western Reserve University, an MS in aerospace engineering from the Air Force Institute of Technology and a second MS, in information systems, from George Mason University, and a PhD in metallurgical engineering from Ohio State University.

ALI VELSHI is the host of "Real Money with Ali Velshi," a one-hour nightly business news program on Al Jazeera America. Before that he was CNN's chief business correspondent, anchor of CNN International's World Business Today, and host of CNN's weekly business roundtable "Your Money." He has reported extensively on the global financial meltdown; the financial collapses of Fannie Mae, Freddie Mac, AIG, and

Lehman Brothers; the US government's bailout plan; and the US debt ceiling and budget debate. He hosted "The Turnaround," CNN's small business improvement show; traveling across America, the show introduced troubled small business owners to high-profile mentors and helped them develop a plan for success.

His latest book, *How to Speak Money*, was coauthored with CNN's Christine Romans. He is also the author of *Gimme My Money Back*. Born in Kenya and raised in Toronto, Velshi graduated from Queens University in Canada with a degree in religion.