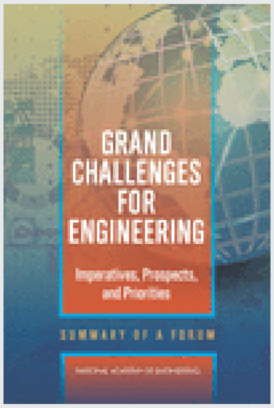

Grand Challenges for Engineering: Imperatives, Prospects, and Priorities: Summary of a Forum

DETAILS

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GRAND CHALLENGES FOR ENGINEERING

Imperatives, Prospects, and Priorities

SUMMARY OF A FORUM

Prepared by Steve Olson
for the
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Preface

Engineering has long gravitated toward great human ambitions: navigation of the oceans, travel to the moon and back, Earth exploration, national security, industrial and agricultural revolutions, communications, and transportation. Some ambitions have been realized, some remain unfulfilled, and some are yet to be determined.

In 2008 a committee of distinguished engineers, scientists, entrepreneurs, and visionaries set out to identify the most important, tractable engineering system challenges that must be met in this century for human life as we know it to continue on this planet. The committee received thousands of inputs from around the world to determine its list of Grand Challenges for Engineering, and its report was reviewed by more than 50 subject-matter experts, making it among the most reviewed of Academy studies. The 14 Grand Challenges for Engineering are to

Make solar energy economical
Provide energy from fusion
Develop carbon sequestration
Manage the nitrogen cycle
Provide access to clean water
Improve urban infrastructure
Advance health informatics
Engineer better medicines
Reverse-engineer the brain
Prevent nuclear terror
Secure cyberspace
Enhance virtual reality

Advance personalized learning
Engineer the tools of scientific discovery.

The Grand Challenges were not ranked in importance or likelihood of solution, nor was any strategy proposed for solving them. Rather, they were offered as a way to inspire the profession, young people, and the public at large to seek the solutions.

In 2010 a plan was put forth to prepare engineering students to think about careers devoted to addressing the Grand Challenges. Called the NAE Grand Challenge Scholars Program, it was the first specific action taken toward achieving solutions to the challenges on a global scale.

In 2013 the first Global Grand Challenges Summit was held in London, cosponsored by the Royal Academy of Engineering, the Chinese Academy of Engineering, and the US National Academy of Engineering in their first joint effort. In September 2015 a second Global Grand Challenges Summit was held in Beijing, with more than 800 attendees invited by the three academies. The third Global Grand Challenges Summit, to be hosted by the NAE in the United States in 2017, will be held in conjunction with a new FIRST Robotics international event aimed at engaging the world's youth on projects tied to one or more of the Grand Challenges.

The Grand Challenges are not targeted to any one country or corporate sector. Rather, they are relevant to everyone in every country. In fact, some of them bear on the very survival of society. If solving these challenges can become an international movement, all will benefit.

For the forum of the October 2015 NAE annual meeting, 7 of the 18 committee members who identified the challenges in 2008 were invited to offer their perspectives on them now:

- **Alec Broers** has chaired the Select Committee for Science and Technology for the United Kingdom's House of Lords; before that he was president of the Royal Academy of Engineering (2001–2006). A pioneer in nanotechnology, Broers was the first person to use the scanning electron microscope for fabrication of microminiature structures.
- **Farouk El-Baz** is a research professor at Boston University and director of the school's Center for Remote Sensing. He was supervisor of Lunar Science Planning for NASA's Apollo pro-

gram, and from 1978 to 1981 he was science advisor to President Anwar Sadat of Egypt.

- **Wesley Harris** is Charles Stark Draper Professor of Aeronautics and Astronautics at MIT and was previously the associate administrator for aeronautics at NASA. He has contributed to research on unsteady aerodynamics, aeroacoustics, and rarefied gas dynamics.
- **Calestous Juma** is a professor at Harvard's John F. Kennedy School of Government and director of its Science, Technology, and Globalization Project. He is the former executive secretary of the United Nations Convention on Biological Diversity and founding director of the African Centre for Technology Studies in Nairobi.
- **Dean Kamen** is founder of the DEKA Research & Development Corporation. His inventions include the wearable infusion pump, the insulin pump for diabetics, an advanced prosthetic arm for the Department of Defense, and the Segway.
- **Robert Socolow** is codirector of Princeton University's Carbon Mitigation Initiative, a multidisciplinary investigation of the use and treatment of fossil fuels in a carbon-constrained world. He has been on the Princeton faculty since 1971 as professor of mechanics and aerospace engineering.
- **Jackie Ying** is founding executive director of the Institute of Bioengineering and Nanotechnology in Singapore and editor in chief of *Nano Today,* a journal covering the field of nanoscience and technology. Previously she was a professor of chemical engineering at MIT.
- The moderator was **Dan Vergano**, a science reporter for BuzzFeed News and adjunct professor at New York University's Washington, DC, campus, where he teaches journalism.

Now is a good time for reflection on the Grand Challenges for Engineering. Has there been progress on solving them? Do changing global circumstances call for rethinking the challenges? Are we going about them correctly? Hence the theme of this meeting.

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

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I

The Grand Challenges Revisited

For the forum at the National Academy of Engineering's 2015 annual meeting, 7 of the 18 committee members who formulated the Grand Challenges for Engineering in 2008 reflected on what has happened in the seven years since. A common theme was surprise at how quickly and powerfully the idea has been embraced. "I personally had no idea, when I was part of this program, of the leverage it would have," said Robert Socolow. Added Wesley Harris, "This has been an experience that, for me, has had spiritual content."

This chapter presents an overview of the speakers' remarks, and the second summarizes the wide-ranging exchanges afterward between the presenters and forum attendees.

THE NEED FOR GLOBAL COLLABORATION

In the national shock that followed the Soviet Union's October 1957 launch of Sputnik, the old National Advisory Commission for Aeronautics, a modest organization, was expanded into the National Aeronautics and Space Administration, a major federal agency. Then came President John F. Kennedy's vow in 1961 that "This nation should commit itself to achieving the goal, before the decade is out, of landing a man on the moon and returning him safely to the earth." Not that humanity would undertake this quest—that the United States would.

US decision making post-Sputnik was driven by "political, military, technological, and even scientific competition," said Wesley Harris in his presentation. The Grand Challenges initiative must be different, he said. "It's global in intent and global in its benefit. It is blind to economic, social, cultural, and religious differences. It thrives on a win-win

outcome at all levels. It requires, it demands, it rewards cooperation and collaboration."

He envisioned the Grand Challenges as the branches of a "mighty tree with a great crown that provides shade and protection for all of humanity." But the tree also has roots "related to the things that drive us: education, government, research, and, equally important, collaboration around the globe." The Grand Challenges are "about humanity and our service to humanity within our profession."

> The Grand Challenges initiative is "global…. It is blind to economic, social, cultural, and religious differences. It thrives on a win-win outcome at all levels."

Harris proposed that engineers institutionalize the Grand Challenges in the US National Academy of Engineering while seeking support from the world's governments and recognition of the project from the United Nations. Each section of NAE members could assess and apply the Grand Challenges in their area and report back to the NAE council, he suggested. More broadly, engineers could call attention to the ways in which the Grand Challenges bear on food delivery, transportation networks, communications, and the other essential elements of modern life.

He also pointed out that, with another billion people expected to join the human family in Africa by 2050, that continent offers intellectual resources that "we cannot afford to ignore, and that we can capture through these Grand Challenges."

NEW ENVIRONMENTAL AWARENESS

Robert Socolow observed that the 14 Grand Challenges fall into four categories. The first is sustainability—maintaining air and water quality, protecting freshwater quantity, preventing sea level rise, keeping forests and other ecosystems in good condition, and minimizing artificially triggered climate change. Next is personal and community health, because, he pointed out, "as individuals we can live fulfilling lives only if we are healthy." But, he added, "people have a record of being dangerous to each other," hence the third category, vulnerability and security.

The fourth category, joy of living, does not sound like a traditional engineering concern, Socolow admitted, but "electronics deliver us music with marvelous fidelity. Air travel brings us access to the extraordinary variety of human cultures and natural settings. Electronics nurtures our curiosity by providing incredible access to information. Engineering in many forms enables many discoveries about our universe and the history of life, which we then share." Joy of living is not commonly found in an engineering course syllabus, Socolow said, but engineers should view it as part of their calling.

Joy of living is not commonly found in an engineering course syllabus, but engineers should view it as part of their calling.

He then spoke about his specialty, environmental soundness. "Human beings are modifying the global carbon cycle by burning fossil fuels at a rate that leads to the atmospheric concentration increasing by half a percent a year, with consequences that are not well understood. Nitrogen fertilizer production has more than doubled the rate at which the triple bond of the N_2 molecule is broken. For eons, nitrogen fixation had been occurring at a rate of about 100 million tons per year. Now it's over 200 million. Will that matter?"

Socolow proposed a test for today's generation of engineering students. "They will confront a new concept, unburnable fossil fuels. These are fossil fuels the next generation should decide to leave underground and not burn, in order to limit the amount of climate change. This will

entail very difficult questions. In which decades will the use of fossil fuels begin to be substantially curtailed? Will the poorest countries receive coal and oil preferentially for their development? Natural gas provides almost twice as much energy for the same amount of carbon emission, because more hydrogen comes out of the ground with each carbon atom compared to coal. So should natural gas be produced preferentially?" There is no consensus on the answers to these questions, but he predicted that "they are going to be front and center."

Greater emphasis on environmental issues calls for a change in engineering education, Socolow suggested. "A significant fraction of engineering students need to learn about Earth, Earth system science, the atmosphere, the oceans, forests, ice,…" He pointed out that these subjects are typically considered environmental studies—"no one in the engineering cohort today is taking these courses, and professors are not advising engineering students to take them. So that is an action item…. Engineering cannot exist in a vacuum any longer."

He also called for engineering professors to emphasize to their students that their profession must help the poorest. One billion people still depend on traditional biomass, which is harvested unsustainably. "Bundles of twigs for fuel are carried on people's backs long distances," Socolow said. "Cooking in tents and mud houses with unvented stoves is the number one killer associated with global energy use, due to respiratory disease."

He recalled that when he was a junior faculty member at Yale the university's president, Kingman Brewster, made the distinction between puzzle solving and problem solving. "Many of us trained as scientists and engineers basically do puzzle solving, which means there is a well-defined answer and you know it when you get it." Problem solving, he said, is more complex: it is multidisciplinary, has fuzzy edges, and has no single clearly defined solution. The sustainability of the Earth's ecosystem, for example, requires problem solving. It has many aspects, of which climate change is just one, and will require "ambition, multidisciplinarity, and humility" to solve.

> The sustainability of the Earth's ecosystem requires problem solving and "ambition, multidisciplinarity, and humility" to address.

SMALL SOLUTIONS TO BIG PROBLEMS

"Breakthroughs in small structures could help achieve several of the Grand Challenge goals," said Jackie Ying. Nanomedicine can engineer better medical devices for early diagnosis of diseases, nanoporous materi-

als could provide access to clean water, nanocatalysts can help sequester greenhouse gases, and nanocomposites can contribute to green energy.

She described some of the work being done at the Institute of Bioengineering and Nanotechnology in Singapore. For example, because of poor patient compliance when dealing with insulin delivery—patients do not want to prick their fingertips to test their blood sugar level and then inject insulin when the level is high—"we went about developing a system that is smart enough to sense when blood sugar level is high, deliver insulin, then stop delivering insulin when the blood sugar level had dropped to normal." The key was a nanomaterial that involves a two-part glucose-sensitive polymer. When glucose in the bloodstream is high, crosslinking between the two substances stops, activating insulin delivery. The system can inject a single insulin dosage, which can last for one day, or up to a triple dosage, which can keep the patient's levels normal for two days.

> Young people become excited when they realize that STEM fields are building blocks to have a positive impact on how people live.

"Here is the part that is remarkable," she explained. A self-injection of a triple dose would ordinarily cause a hypoglycemic episode. "But this material knows how to regulate delivery within the body. It can be taken orally or by nasal passage, so patient compliance is much higher and will allow you to regulate the blood glucose level very much like a normal pancreas."

Basic development of the technology led to a spinoff company that drew the notice of the pharmaceutical industry, and Merck bought the spinoff firm for $500 million. "We hope that, in Merck's hands, this nanomedicine will help us make a tremendous impact," Ying said.

As another example of work at her institute, Ying cited a microfluidic device that can shorten disease diagnosis to a couple of hours rather than days. "The whole system is just a tiny plastic cartridge that is very inexpensive," she said. "You can use it not only in hospitals but in clinics as well as checkpoints." Such devices "will have a dramatic impact in how we contain the spread of infectious diseases."

In addition, Ying observed that in her experience young people become excited when they realize that science, technology, engineering, and mathematics (STEM) are not just a matter of mastering material to earn good grades; rather, they are building blocks to have a positive impact on how people live. Her institute has a youth outreach program that includes open houses, career talks, science camps, workshops, and internships. "We have already reached out to more than 88,000 students and teachers from many schools, from elementary school all the way to university." And as the parent of a young daughter Ying said the Grand Challenges initiative "begs the question of what kind of world we want to leave our children to inherit."

The Grand Challenges initiative "begs the question of what kind of world we want to leave our children to inherit."

THE FUSION PUZZLE

"I was one of the original 14 panel members who argued strongly that fusion should be included" in the Grand Challenges, said Alec Broers. "There has been, and remains, a lot of skepticism about this technology. After all, it has been worked on for more than 60 years and has yet to reach the point that fission reached in 1942 at the University of Chicago, when the control rods were pulled out of the first fission pile and it went critical, providing net power gain."

But even considering only plasma fusion and not inertial confinement or low-temperature fusion, progress has been occurring on several fronts, Broers observed. The International Thermonuclear Experimental Reactor (ITER) project in the south of France is building a doughnut-shaped reactor the size of the Arc de Triomphe with the aim of producing half a megawatt of net output by the late 2020s. A few months before the forum, the contract was placed to deliver the superconducting wires that will compress the plasma to reach a temperature ten times that of the sun.

At the UK Culham Centre for Fusion Energy and at Princeton University, a new geometry is being explored for the fusion chamber. Instead of a torus or doughnut, as in past designs, the reactor chamber is spherical, more like a cored apple with a single conductor down the middle that carries the current from C-shaped coils. This geometry has been shown to be three times more effective in harnessing the magnetic field, which may make reactors smaller than ITER feasible, said Broers.

Finally, a small company called Tokamak Energy has spun out of Culham and is attempting to use high-temperature superconducting tapes and a spherical reactor to reach the goal of net energy output in the next five or ten years—ahead of ITER. "The experts think this aim is overoptimistic, but who knows?" Broers said.

> Engineering systems have become so complex that no single person can know everything that is happening—and "in such an environment, it's easy for ethics to get lost."

He went on to observe that engineering systems have become so complex that no single person can know everything that is happening—and "in such an environment, it's easy for ethics to get lost." He cited apparent breakdowns of ethical behavior in the automobile industry. "If there was a formal code of ethics for engineers—perhaps modeled on the codes of the medical profession—such breakdowns might be less likely."

He also pointed to the importance of the social sciences in understanding the implications of technologies. He lamented the fact that an organization akin to Alcoholics Anonymous is needed to wean people off too much use of the Internet. When designing the Web, engineers seem never to have considered that it could become an addiction, which may itself be another indication that a code of ethics would be a beneficial addition to engineering practice.

TRANSCENDING DISCIPLINARY AND NATIONAL BOUNDARIES

Calestous Juma said that the Grand Challenges structure was unusual in that "I have rarely served on a committee where the priorities are not set on the basis of the intellectual interests of the members. No member of the committee was advocating his or her own area of interest. All focused on the big global problems." In this way, the Grand Challenges "demystified engineering from being viewed by the general public as a discipline to being perceived as a way of meeting human needs and solving global problems."

He recounted his experience talking about the report at a high school in Connecticut that has a preengineering program. He challenged the students to work for a week on one of the challenges. They came up with a design for a wind power system made of tethered parachutes—an approach that closely paralleled that of a technical report from the Netherlands that Juma read several months later. "If you give these ideas to people without making them feel that you are pushing a particular field on them,…you get remarkable enthusiasm."

He also cited a competition, the Africa Prize for Engineering Innovation, established by the UK's Royal Academy of Engineering. "The criteria for the prize looked very much like the elements of the Grand Challenges, but we didn't call it Grand Challenges." The proposals submitted for the competition mirrored the NAE Grand Challenges, he said, and came from all over the continent. Even the least developed countries in Africa "have ideas," said Juma. "These are people who are using existing knowledge and expertise to solve global problems."

> What if high school students spent a full year on one of the Grand Challenges? "This could make schools more relevant for problem solving and meeting human needs."

He reported that the number of African countries with academies of science has grown from 10 to 17 just since the Grand Challenges were released. "They are relatively young, which means they are exploring new things to do. I see that as a real opportunity for this academy to engage with those academies."

One way for educational institutions to rise to the challenge, Juma proposed, is to reimagine themselves as centers of problem solving. Today, liberal arts education focuses on abstract knowledge, while trade schools prepare students for specific jobs that already exist. What if high school students instead spent a full year on one of the Grand Challenges? "This could make schools more relevant for problem solving and meeting human needs," Juma said.

INNOVATIVE WATER DISCOVERY

Farouk El-Baz offered an example of the kinds of large problems that engineering can solve. When images from various kinds of satellites became widely available in the 1970s, "we began to look at pictures of the Earth from space," he said. "What is it that we can see in these pictures, and how do we interpret them?"

> Young people view technology as a good way to address society's problems, such as access to clean water.

In 1974 Egyptian president Anwar Sadat, who wanted to more widely disperse people away from the Nile River, asked El-Baz to come to Egypt and help him with his vision of agriculture in the desert west of the river. Initial exploration and drilling for water in the desert had been largely fruitless because of difficulties interpreting geological features. Thanks to a newly designed radar imager that gave a view of the terrain beneath the desert sands,

"we began to see the passageways of former rivers in desert areas," El-Baz said. This technique (invented by a member of the US National Academy of Engineering) has been used to locate groundwater in Egypt, Chad, India, China, and elsewhere. A technological advance made it possible to look at an age-old problem "with a whole new vision."

El-Baz said he is regularly impressed that young people view technology as a good way to address society's problems, such as access to clean water. "I would like to see us concentrate our attention on trying to get young people worldwide interested in [the Grand] Challenges.... They are a lot more enthusiastic about it and a lot more open-minded about how to approach this kind of topic and find solutions to these kinds of problems." For example, he suggested commissioning a series of children's books on each of the Grand Challenges to get even young children engaged with 21st century issues. The Internet, too, is a way of putting the Grand Challenges in the hands of young people, he added, and academies of science, engineering, and medicine around the world can help spread the word.

ENVISIONING ENGINEERING ANEW

For keeping the world running, engineers deserve an A, said Dean Kamen. "For reaching out to the next generation, we should get a C, or

maybe a D." He chided his fellow engineers with a comparison of the worlds of engineering, entertainment, and athletics. "When sports teams play their championships, when the superstars of athletics get together, they don't play the Super Bowl or the World Cup privately and the only people in the stands are other athletes," he said. Yet "that's what we do" in science and engineering. "We talk to ourselves.... Then we wonder why there aren't enough kids to solve these 14 problems that we know about—and the ones that we don't know about that will probably be in their heads in 50 years."

Early in his career, Kamen decided that the worlds of sports and entertainment do a much better job of reaching out to young people than does engineering, so he decided to adopt their techniques. The FIRST Robotics program now has teams from 83 countries and 182 universities with 3,500 corporate sponsors—yet still not enough people know about it. So when will.i.am was the halftime entertainer at the Super Bowl in 2011, Kamen called and asked him to make a video that would make science and engineering cool. The singer responded, "Dean, I can't make technology cool to kids—you guys have already done that. But I can make it loud." The resulting video was loud, Kamen said, which was a deliberate choice: To compete with entertainment and sports for young people's attention, engineering needs to be flashy. The following year, Kamen presented will.i.am with the inaugural Make It Loud Award.

Kamen went on to observe that in many parts of the world, politics tends to be a divisive force. Technology, in contrast, can be a unifying force, he said, especially among young people who see science and engineering as the path out of problems. That is one reason why he thinks of the FIRST Robotics program as a collaboration rather than a competition. "Rational intelligent people who appreciate the power of technology will, in a sense, displace the nonsense of political self-inflicted wounds."

> To compete with entertainment and sports for young people's attention, engineering needs to be flashy.

This observation drew a comment from moderator Dan Vergano, who urged the engineering community to become more open to the public. "Scientists love to talk about their research," he said. "With engineers, as soon as conversation gets interesting, you shut up, saying the details are proprietary. It's only when something does not work that an engineer is free to discuss it." This is one reason, Vergano pointed out, why journalists have a harder time covering engineering than science.

II

Discussion with Forum Participants

Education, the problems the Grand Challenges address, and the role of the US National Academy of Engineering were the topics that dominated the discussion among the presenters and participants in the second half of the forum.

PREPARING YOUNG PEOPLE TO SOLVE THE GRAND CHALLENGES

The Grand Challenges can serve as an organizing principle and motivating force at all levels of education. As Dan Mote said, "You can't start early enough. That is clearly a message for us. It's all about connection and the excitement of youth."

Building on El-Baz's idea of a children's book for each of the Grand Challenges, Georges Belfort of Rensselaer Polytechnic Institute suggested producing a movie that teaches young students what engineering is and how people can create and build things. Andy Jackson of the University of Pennsylvania emphasized the importance of making sure that all teachers understand the relevance of the Grand Challenges, including social science teachers, geography teachers, and all the other teachers who influence students' educational and career choices. "Unfortunately most of our high schools, at least in the United States, don't have engineering programs," he said. "They do math, physics, science, [but] they don't know how to put it all together."

The best way to introduce the Grand Challenges, said El-Baz, is to present the problems to students and let them get enthusiastic about solving those problems. When that happens, the response of students is overwhelmingly positive, he and several other presenters said. When

Calestous Juma talks with KunMo Chung.

Juma and Harris have talked about the Grand Challenges in high schools, for example, they have been surprised by the interest shown by students. "Because it's a long-term issue, the best place to start is with people who are likely to be here in the long term," said Juma.

Ying said that when she goes to girls' schools, "their eyes light up when they realize that an engineer makes this dramatic impact on humanity for the whole globe. That's when it appeals to them."

Kamen observed that when you tell schoolchildren that there are 300 billion stars in the universe, they believe you. But "you put up a sign that says 'Wet Paint,' they have to touch it to be sure." Because whether the paint is wet is relevant to their lives. "We have to make science, technology, engineering, and math relevant and comprehensible," he said. "They have to see a need and an excitement and a path to do something…. These things can be very inviting and bring [students] in."

Ying made the same point for higher education. In many developed countries, young people educated in engineering do not want to be engineers any more. They enter engineering to get a bachelor's degree and then go into finance and banking. To make sure that more people stay in engineering, the problems they work on in class need to be "relevant to real problems," she said.

One way to integrate the Grand Challenges throughout education, said Harris, would be to credit schools from the K–12 level through higher education for incorporating the Grand Challenges into their curricula. For example, when the Accreditation Board for Engineering and Technology (ABET) comes to a college to evaluate an engineering program, it should give the program credit if it has elements that involve the Grand Challenges, he said. "Grade school, high school, engineering schools, and even industry should receive credits—tax credits, for example—if they are engaged appropriately, within their mission, in supporting and expanding the Grand Challenges."

In response to a question about whether college capstone courses could be oriented toward the Grand Challenges, Harris said, "we should not wait until the capstone design experience." MIT has demonstrated that first-year engineering students can learn design, and "there is nothing unique about MIT in that regard." He cited the example of a first-year student who suggested taking advantage of the black soldier fly (*Hermetia illucens*) in Africa, which does not transmit diseases but devours protein and converts it to fertilizer. "You don't have to write a computer code. It's already there. We took that to Ghana and it worked."

> Because the Grand Challenges are "a long-term issue, the best place to start is with people who are likely to be here in the long term."
>
> – *Calestous Juma*

The presenters and participants also discussed whether engineers should receive more than four years of higher education. As Donald Chaffin of the University of Michigan said, "I don't want a surgeon with a four-year education to operate on me. I don't want a lawyer to take my case with four years of education. Why do we expect four years of education to be sufficient to deal with these kinds of matters?"

Socolow responded that students need to be ready to participate in the Grand Challenges in many different ways. A two-year engineering education can lead to a valuable role in solving these problems. Kamen added that engineering education does not start in engineering school and does not end when a student graduates. What an engineer does with his or her knowledge matters more than how long it took to acquire that knowledge.

THE FIFTEENTH GRAND CHALLENGE?

A discussion arose about the fact that the Grand Challenges do not mention food production or population growth. As El-Baz noted, food needs are implied in the water challenge. Broers also pointed out that food security is implicit in the challenge on managing the nitrogen cycle.

On the issue of population, Socolow noted that a dichotomy exists between parts of the world where the demographic transition has not yet happened and parts where it has, with some parts of the world headed toward smaller populations and others toward larger populations. Should smaller populations be regarded as a threat, he asked, or is there a way to take advantage of them by, for example, focusing on constructive aging and medical care?

Another exchange concerned nuclear waste. Ron Latanision of the consulting company Exponent pointed out that the social science dimensions of the issue are as important as the political dimensions. "It is an extremely difficult issue," responded Broers. The amount of money that the United Kingdom is predicted to spend on the disposal of existing nuclear waste is "absolutely vast"—more than £100 billion, or about $150 billion—and the timetable now extends beyond 2100.

Moderator Dan Vergano and forum panelists.

Canada has done a better job with this question than have either the United Kingdom or United States, he observed.

In response to a question about what the fifteenth Grand Challenge will be, Kamen quoted Franklin Roosevelt: "We cannot always build the future for our youth, but we can build our youth for the future." "The future is moving much faster than it ever has before," he said. "Typically a generation or two of engineering success leaves behind unintended consequences. We made plastics, which were great, but now there is too much plastic. One car is a work of art, but a hundred million cars is a traffic jam. We typically take a generation or two to solve a problem, and then it leaves behind others. At the rate at which technology moves today, young people are going to catch up to their own problems so quickly that they won't have a generation to plan."

> "The fifteenth Grand Challenge has to be to create an environment in which people are more capable of communicating and cooperating."
>
> *– Dean Kamen*

Because of this process, many future challenges cannot be envisioned today, said Kamen. For that reason, "the fifteenth Grand Challenge has to be to create an environment in which people are more capable of communicating and cooperating," he said. "A much larger percentage of the people on this planet, whether they are practicing engineers or not, have to be competent to separate fact from nonsense so that when their governments deploy resources and assets, they do it in an intelligent way."

Added Broers, "Could I be controversial and suggest that a challenge should be to provide for the women of the world the knowledge, education, and means to control the number of children that they have?"

THE ROLE OF THE US NATIONAL ACADEMY OF ENGINEERING

The US National Academy of Engineering and other academies of engineering, science, and medicine around the world can play a pivotal role not only in identifying but solving the Grand Challenges. Other organizations have devoted considerable attention to the problems that must be solved in the 21st century for human societies to thrive, noted Janet Hering of the Swiss Federal Institute of Aquatic Science and Technology. For example, the Grand Challenges overlap with both the UN Millennium Development Goals and more recent Sustainable Development Goals.

As Juma pointed out, the Sustainable Development Goals will not be implemented "without a strong engineering component, because all of them are very much linked to solving particular problems." This would be one way for the US National Academy of Engineering to engage with academies in other countries, he added. For example, he pointed to the potential for countries in Africa to leapfrog current technologies to apply new technologies that could bring great benefit to those societies. "An interesting discussion happening across Africa right now is whether solar photovoltaics will do for energy what mobile phones have done for telecommunications," he observed.

> "The technical community thinks that politics is not its field. But being a citizen is our field!"
>
> *– Dean Kamen*

John Kassakian of MIT noted that the US National Academies of Sciences, Engineering, and Medicine have a dimension that could be used very effectively to leverage attention to the Grand Challenges: the committees they convene to address national and international con-

Audience members queue to participate in the postforum discussion.

cerns in these areas. "Many of us have served on one or more National Research Council committees, and hundreds of these committees are operating at any one time." Many of them are addressing aspects of the Grand Challenges, he said, and they offer a means of bringing critical information to students and policymakers. This work is "a valuable resource that we shouldn't overlook," he said.

Mischa Schwartz of Columbia University noticed that a number of the Grand Challenges have to do with the negative consequences of humankind on the Earth. Yet in the United States a substantial number of people, including quite a few congressmen and presidential candidates, say they do not believe in anthropogenic global warming. If policymakers do not believe in the reality of the problems that humanity faces, he asked, how can funding for the necessary research and change be sustained?

It is an important question, Socolow acknowledged. "Are we losing, particularly in the United States, the conviction that the scientific method is a privileged way of knowing?" he said. "Many people resist it. They prefer to have a religious way of knowing. We need to join that issue."

> "We have to expand our influence beyond the engineering community. We have to be actively seeking the progress" of individual nations and the world.
>
> *– KunMo Chung*

Kamen said that "democracy is a very inefficient system. It is the best one we have, but it will only work if more than 50 percent of the people get it right." Once the questions facing democracy were not technologically complex. Now, as the entire globe must start dealing with complicated technical problems, democracies need to produce enough young people with a passion to learn about science and engineering. "If [people] are not competent to deal with the world they live in, we are going to get what we deserve."

Engineers should not let ill-informed politicians get away with the nonsensical things they say, he added, but often "there is no countervailing voice, because the technical community thinks that politics is not its field. But being a citizen is our field!" Those in the technical community need to talk with students and with politicians "about the difference between facts and nonsense and what's important and what's irrelevant."

KunMo Chung, president of the Korean Academy of Science and Technology, pointed out that South Korea was one of the poorest nations in the world in the 1950s and now is doing very well. The key to South

Korea's success, he said, is that the country's first president decided to build the nation through science and technology. Leadership is essential, according to Chung. "It's not just the leadership among the engineering community alone but national leadership. The members in this room are part of that leadership. We have to expand our influence beyond the engineering community. We have to be actively seeking the progress" of individual nations and the world, he said.

The US National Academy of Engineering has helped focus the world's attention on the need to forge a path toward a sustainable, productive, and fulfilling future. By continuing to draw on the expertise of engineers, the institution can help create that future, said Mote. "We should use our convening power to maximize the impact we have."

Appendix A

Forum Agenda

Annual Meeting Forum

**Grand Challenges for Engineering:
Imperatives, Prospects, and Priorities**

Monday, October 5, 2015
9:30 a.m.–12:30 p.m.
National Academy of Sciences Building
Washington, DC

Welcome

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

Forum Discussion

Moderator: **Dan Vergano**, BuzzFeed News

Forum Participants
Alec N. Broers, House of Lords, Parliament of the United Kingdom

Farouk El-Baz, Center for Remote Sensing, Boston University

Wesley L. Harris, Charles Stark Draper Professor of Aeronautics and Astronautics, Massachusetts Institute of Technology

Calestous Juma, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University

Dean Kamen, DEKA Research and Development Corporation

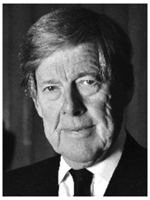
Robert H. Socolow, Princeton Environmental Institute, Princeton University

Jackie Y. Ying, Institute of Bioengineering and Nanotechnology

Appendix B

Panelists' Biographies

LORD ALEC N. BROERS, FREng FRS, was president of the Royal Academy of Engineering (2001–2006) and played a significant role in the University of Cambridge's rise as a major economic force and center of excellence for high technology and was vice chancellor from 1996 to 2003. He has always expressed strong views about the role of engineers in society, considering that any artificial barrier between engineering and the rest of science is just as damaging as the perceived division between the arts and sciences. He sees engineering and science as two sides of the same coin and believes that national engineering academies are ideally placed to drive home this message.



Lord Broers spent nearly 20 years of his career in research with IBM, working at the Thomas J. Watson Research Center in New York, the East Fishkill Development Laboratory, and corporate headquarters.

When he arrived back in Cambridge, he set up a nanofabrication laboratory to extend the technology of miniaturization to the atomic scale. He also developed his research on using electrons, X-rays, and ultraviolet light in microscopy and on making microelectronic components.

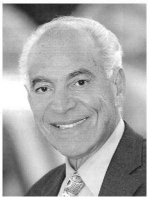
Lord Broers has served on numerous national and international committees, including the UK government's Council for Science and Technology, the NATO Special Panel on Nanoscience, and the NAE panel that selected the fourteen Grand Challenges for Engineering. He is a fellow of the Royal Society and the Royal Academy of Engineering, a foreign member of the US National Academy of Engineering and Chinese Academy of Engineering, and an honorary fellow of the Australian Academy of Technological Science and Engineering.

He has served on the board of directors of Lucas Industries, Vodafone, Plastic Logic, RJ Mears LLC, and Bio Nano Consulting and is currently on the board of FlexEnable.

On June 21, 2004, Her Majesty the Queen made him a life Peer in recognition of his contributions to engineering and higher education. He serves as a cross-bench member of the House of Lords and has chaired the select committee for Science and Technology and the Diamond Light Source.

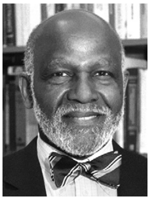
Lord Broers received a first degree in physics from Melbourne University in 1959, a degree in electrical sciences from the University of Cambridge (after arriving initially as a choral scholar), and his PhD at the University of Cambridge in 1965.

FAROUK EL-BAZ is director of the Center for Remote Sensing at Boston University and research professor in its Departments of Archaeology, Earth and Environment, and Electrical and Computer Engineering. He taught geology at Asyut University in Egypt (1958–1960) and the University of Heidelberg in Germany (1964–1966). From 1967 to 1972, he joined NASA's Apollo program as supervisor of Lunar Science Planning and served as secretary of the Lunar Landing Site Selection Committee, chair of the Astronaut Training Group, and principal investigator for Visual Observations and Photography. From 1973 to 1982 he established and directed the Center for Earth and Planetary Studies at the US National Air and Space Museum and was selected by NASA as the principal investigator for Earth observations and photography on the Apollo-Soyuz Test Project of 1975. In 1982 he became vice president for science and technology of Itek Optical Systems (Lexington, MA) until he joined Boston University in 1986 to apply remote sensing technology to archaeology, geography, and geology. He was science advisor (1978–1981) to the late Anwar Sadat, president of Egypt. He is known for pioneering work in the applications of space images to groundwater exploration in the arid lands of Egypt, Libya, Oman, Darfur, and the United Arab Emirates (UAE). He served on the board of trustees of the Library of Alexandria, Egypt, and the Geological Society of America Foundation. The latter established the Farouk El-Baz Award for Desert Research and a companion Student Research Award to encourage and reward excellence in arid land studies. He is the recipient of numerous honors and awards, including the Nevada Medal of the Desert Research Institute, NASA's



Apollo Achievement Award, the Exceptional Scientific Achievement Medal, and the Arab Republic of Egypt Order of Merit, First Class. He presently serves on the Advisory Council of Senior Scientists and Technologists of President Abdel Fattah El-Sisi of Egypt.

WESLEY L. HARRIS is Charles Stark Draper Professor of Aeronautics and Astronautics and housemaster of New House Residence Hall at the Massachusetts Institute of Technology (MIT), where he was previously associate provost (2008–2013) and head of the Department of Aeronautics and Astronautics (2003–2008).



Before coming to MIT he was a NASA associate administrator, responsible for all programs, facilities, and personnel in aeronautics (1993–1995); vice president and chief administrative officer of the University of Tennessee Space Institute (1990–1993); and dean of the School of Engineering and professor of mechanical engineering at the University of Connecticut, Storrs (1985–1990). In his early career at MIT (1972–1985) he held several faculty and administrative positions, including professor of aeronautics and astronautics.

Dr. Harris has done academic research associated with unsteady aerodynamics, aeroacoustics, rarefied gas dynamics, sustainment of capital assets, and chaos in sickle cell disease, and made seminal contributions in each field. In academia he worked with industry and governments to design and build joint industry–government–university research and development programs, centers, and institutes and transferred technology effectively. He is credited with more than 135 technical papers and presentations and has held a number of distinguished, endowed professorships and lectureships.

In addition, he has served as chair or member of various boards and committees of the National Research Council (NRC), National Science Foundation (NSF), US Army Science Board, and several state governments as well as committees of the American Institute of Aeronautics and Astronautics (AIAA), American Helicopter Society (AHS), and National Technical Association (NTA). He was a member of the board of trustees of Princeton University (2001–2005) and has been an advisor to other universities, colleges, and institutes.

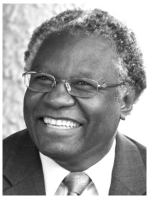
He is an elected fellow of the AIAA, AHS, and NTA for personal engineering achievements, engineering education, management, and advancing cultural diversity, and has been further recognized by election to membership in the National Academy of Engineering, Cosmos

Club, and Confrérie des Chevaliers du Tastevin as well as several honorary doctorate degrees.

He earned a bachelor of science degree (with honors) in aerospace engineering from the University of Virginia in 1964, and master's and PhD degrees in aerospace and mechanical sciences from Princeton University in 1966 and 1968 respectively.

CALESTOUS JUMA is a professor of the practice of international development and director of the Science, Technology, and Globalization Project at Harvard University's Belfer Center for Science and International Affairs, where he also directs Agricultural Innovation Policy in Africa and Health Innovation Policy in Africa projects, funded by the Bill and Melinda Gates Foundation. In addition, he is faculty chair of the Innovation for Economic Development and Technology, Innovation and Entrepreneurship in Africa executive programs as well as the Mason Fellows Program.

Dr. Juma is a former executive secretary of the UN Convention on Biological Diversity and founding director of the African Centre for Technology Studies in Nairobi. He cochaired the African Union's High-Level Panel on Science, Technology, and Innovation and was a jury member for



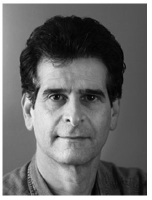
the Queen Elizabeth Prize for Engineering. He has won several international awards for his work on sustainable development and has been elected to the Royal Society of London, the US National Academy of Sciences, the World Academy of Sciences, the UK Royal Academy of Engineering, and the African Academy of Sciences. In addition, he serves on the boards of several international bodies including the Aga Khan University and the Pan-African University.

Dr. Juma has written widely on science, technology, and environment. He is editor of the *International Journal of Technology and Globalisation* and the *International Journal of Biotechnology*, and his next book, *Innovation and Its Enemies: Why People Resist New Technologies*, will be published by Oxford University Press in 2016. Pending book projects concern regional integration in Africa and innovation for economic development.

He holds a doctorate in science and technology policy studies.

DEAN KAMEN is an inventor, entrepreneur, and tireless advocate for science and technology. As an inventor, he holds more than 440 US and foreign patents, many of them for innovative medical devices that have expanded the frontiers of health care worldwide. As an undergraduate he invented the first wearable infusion pump, and in his mid-20s he founded his first medical device company, AutoSyringe, Inc., to manufacture and market the pumps; within 5 years he had added a number of other infusion devices, including the first wearable insulin pump for diabetics.

In 1981 he founded DEKA Research & Development Corporation to develop internally generated inventions and to provide R&D for major corporate clients. He led the company's development of the HomeChoice™ peritoneal dialysis system, which enables patients' dialysis in the privacy and comfort of their home. Other notable developments include the Hydroflex™ surgical irrigation pump, the iBOT™ mobility device, and the Segway® Human Transporter. An advanced prosthetic arm currently in development for DARPA should advance the quality of life for returning injured soldiers.

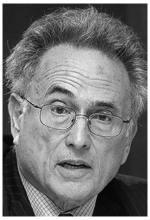


Mr. Kamen has received many awards for his efforts. In 2000 he was awarded the National Medal of Technology for inventions that have advanced medical care worldwide and for innovative and imaginative leadership in awakening America to the excitement of science and technology. In 2002 he was awarded the Lemelson-MIT Prize. He was elected to the National Academy of Engineering in 1997 and inducted into the National Inventors Hall of Fame in 2005. He is a fellow of the American Institute for Medical and Biological Engineering.

In addition to DEKA, one of his proudest accomplishments is the founding in 1989 of FIRST® (For Inspiration and Recognition of Science and Technology), an organization dedicated to motivating the next generation to understand, use, and enjoy science and technology. This year FIRST will serve more than 300,000 young people, ages 6–18, in more than 50 countries High school–aged participants can apply for more than $15 million in scholarships from colleges, universities, and corporations. Studies have shown that FIRST alumni are highly motivated to pursue careers in science and engineering, thus fulfilling Mr. Kamen's goal of inspiring the next generation of technological leaders.

ROBERT SOCOLOW is professor emeritus and (full-time) senior research scientist in the Department of Mechanical and Aerospace Engineering at Princeton University. He is the coprincipal investigator (with ecologist Stephen Pacala) of Princeton's Carbon Mitigation Initiative (www.princeton.edu/~cmi/), a 20-year (2001–2020) project supported by BP.

Dr. Socolow seeks new conceptual decade-scale frameworks useful for climate change policy. He and Pacala authored "Stabilization wedges: Solving the climate problem for the next 50 years with current technologies" (*Science*, August 13, 2004). With colleagues, he introduced the concept of "one billion high emitters," the worldwide upper and middle class whose lifestyles dominate global change. He has championed CO_2



capture and storage, energy efficiency in buildings, technological "leapfrogging" by developing countries, and policies that address the dangers of climate change "solutions," notably nuclear weapons proliferation and misuse of the land. He currently is interested in "committed emissions" and "unburnable carbon"—implications of never producing attractive fossil fuels.

Dr. Socolow was a member of the NAE's Grand Challenges for Engineering committee and the National Academies' Committees on America's Climate Choices and America's Energy Future. He chaired the Panel on Public Affairs of the American Physical Society (APS), and was editor of *Annual Review of Energy and the Environment* (1992–2002).

In 2014 he became a member of the American Academy of Arts and Sciences. He is a fellow of the APS and the American Association for the Advancement of Science. His awards include the 2009 Frank Kreith Energy Award from the American Society of Mechanical Engineers; the 2005 Axelson Johnson Commemorative Lecture award from the Royal Academy of Engineering Sciences of Sweden (IVA); and the 2003 Leo Szilard Lectureship Award from the APS "for leadership in establishing energy and environmental problems as legitimate research fields for physicists, and for demonstrating that these broadly defined problems can be addressed with the highest scientific standards."

Dr. Socolow received his BA (summa cum laude, 1959) and PhD in theoretical high energy physics (1964) from Harvard University. He was an assistant professor of physics at Yale University from 1966 to 1971.

JACKIE Y. YING received her BE and PhD from the Cooper Union and Princeton University, respectively. She joined the MIT faculty in 1992, where she was a professor of chemical engineering until 2005. She has served as the founding executive director of the Institute of Bioengineering and Nanotechnology in Singapore since 2003. For her research on nanostructured materials, she has been recognized with the American Ceramic Society Ross C. Purdy Award, David and Lucile Packard Fellowship, Office of Naval Research Young Investigator Award, NSF Young Investigator Award, Camille Dreyfus Teacher-Scholar Award, American Chemical Society Faculty Fellowship Award in Solid-State Chemistry, Technology Review's Inaugural TR100 Young Innovator Award, American Institute of Chemical Engineers (AIChE) Allan P. Colburn Award, Singapore National Institute of Chemistry–BASF Award in Materials Chemistry, Wall Street Journal Asia's Asian Innovation Silver Award, International Union of Biochemistry and Molecular Biology Jubilee Medal, Materials Research Society Fellowship, Royal Society of Chemistry Fellowship, American Institute for Medical and Biological Engineering Fellowship, and Crown Prince Grand Prize in the Brunei Creative, Innovative Product and Technological Advancement (CIPTA) Award.

Professor Ying was elected a World Economic Forum Young Global Leader and a member of the German National Academy of Sciences, Leopoldina. She was named one of the One Hundred Engineers of the Modern Era by AIChE in its Centennial Celebration. She was selected by The Muslim 500 in 2012, 2013, and 2014 as one of the world's 500 most influential Muslims, and an inaugural inductee to the Singapore Women's Hall of Fame in 2014. She is the editor in chief of *Nano Today*, which has an impact factor of 15.000.

DAN VERGANO is a science reporter for BuzzFeed News, where he covers science happenings in Washington, DC, and an adjunct professor at New York University's Washington campus, where he teaches journalism. He was formerly a senior writer-editor at *National Geographic* and before that senior science writer at *USA TODAY*. Dan was a Nieman Fellow at Harvard in 2007, where he concentrated on the intersection of science and politics. He has a BS in aerospace engineering from Penn State and an MA in science, technology, and public policy from George Washington University.