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The mission of the National Academy of Engineering is to advance the well-being of the nation by promoting a vibrant engineering profession and by marshalling the expertise and insights of eminent engineers to provide independent advice to the federal government on matters involving engineering and technology.
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The National Academy of Sciences was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The National Academy of Engineering was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The National Academy of Medicine (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the National Academies of Sciences, Engineering, and Medicine to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at www.nationalacademies.org.
Once again the winter issue of The Bridge is focused on the NAE Frontiers of Engineering (FOE) symposium. Jennifer West, chair of the organizing committee for the 2019 program, which was held at Boeing in North Charleston, SC, assembled a superb program that is highlighted in these pages.

We also include an op-ed from Sam Florman. Sam is a civil engineer, retired general contractor, and author who is well known in the engineering world. He has provided me with important feedback since the beginning of my tenure as editor of The Bridge. When Cameron and I interviewed Sam for the winter issue in 2015, I began by wondering aloud what word best described his influence on me and The Bridge. He suggested that I just identify him as one of my many advisors. It is true that I have many advisors, but Sam—who is approaching his 95th birthday—is a special advisor. I am especially grateful to him for his wise counsel and friendship. In this issue, he adds another thoughtful statement to his many contributions, reminding us that in our fall 2002 issue he wrote that “The problems of the Information Age—who should control the Internet and how—are still too new for us to predict their resolution.” What had begun as a platform for making information available throughout the planet now manifests in Sam’s view as “a most insidious, widespread source of calamity: our electronic world of communication.” And 17 years later his question remains unanswered.

We continue our interview series with engineers who add to our culture in ways that go beyond their engineering backgrounds. In this case, we talk with Gary Taubes, who got his MS in aerospace engineering but has made his name as an author and investigative journalist on subjects as diverse as scientific fraud and the health dangers of sugar consumption.

With this issue we introduce two new regular columns. The NAE’s new president, John Anderson, will offer his perspective on topics of interest to members and other readers, starting in this issue with his thoughts on a concise definition of engineering. And in a new column called Invisible Bridges, Guru Madhavan, Norman R. Augustine Senior Scholar and director of NAE programs, will close out each issue with musings about engineering’s connections and influences in society, building on the name of this publication.

The spring 2020 issue, edited by Warren Washington and Tony Busalacchi, will focus on climate change. Given the record-breaking high tides in Venice as well as other impacts in this country and around the world, it is certainly timely.

Finally, I am pleased to point out that The Bridge will celebrate its 50th anniversary in 2020. We are planning a special issue with a view toward anticipating the nature of the engineering enterprise over the next 50 years.

As always, I welcome your comments and feedback at rlatanision@exponent.com.
President's Perspective

What Is Engineering?

“A scientist studies what is, whereas an engineer creates what never was.”

– Theodore von Kármán

The National Academy of Engineering carries the flag of the engineering profession in the United States. But when I asked the NAE for a definition of “engineering” eight years ago, I was referred to the famous quote by von Kármán. Inspiring, but not definitive. Visual artists, composers, and ditch diggers also create “what never was.”

The origin of the word engineer is in the Latin ingeniator: one who devises. It is associated with ingenious and ingenuity. The French word for those who practice our profession is ingénieurs; in Swedish, it's ingenjörs.

I think it is time we try to define engineering in an operational sense. A start is to suggest important words that characterize the profession—for example, create, design, systems, processes, artifacts (products). Skill sets and knowledge bases also shape the definition and practice of our profession; examples include computation, science, operations. The goal is to “create” a concise definition of engineering.

Here are a few expressions:

- Engineering is “The systematic application of scientific knowledge in developing and applying technology.” (AAAS 1989, p. 26)
- “Engineering involves the knowledge of the mathematical and natural sciences (biological and physical) gained by study, experience, and practice that are applied with judgment and creativity to develop ways to utilize the materials and forces of nature for the benefit of mankind.” And an engineer is “A person who is trained in and uses technological and scientific knowledge to solve practical problems.” (ITEA 2007, p. 238)
- “Engineering is a systematic and often iterative approach to designing objects, processes, and systems to meet human needs and wants.” (NAGB 2014, p. 1-4)
- Engineering is the act of creating artifacts, processes, or systems that advance technology and address human needs using principles of the sciences, mathematics, computing, and operations.

We can benefit from a short but substantive phrase to use when asked “What is engineering?,” whether by a cabdriver or at a cocktail party or when talking with members of Congress. It is important that the general public, including lawmakers and influencers, appreciate the essence of engineering, its contributions, and the fact that it is a separate and just as influential partner with the sciences.

Let me know what you think. Send comments or suggestions to me via Bridge managing editor Cameron Fletcher (CFletcher@nae.edu). I am always pleased to hear from our readers, on this as well as bold, forward-looking ideas for the programs of the National Academy of Engineering.

1 Quoted in NRC (2001, p. 1).

2 I tip my hat to Howard Stone, who introduced me to this etymology and continues to enlighten audiences about it (Stone 2019).
References


Visions of the Future

This year’s US Frontiers of Engineering Symposium was hosted by Boeing, September 25–27 in North Charleston, SC, and brought together a very diverse group of talented young engineers representing the best and brightest from academia, industry, government, and nonprofit sectors across all engineering disciplines. The event was an opportunity for the invited participants to learn about cutting-edge and impactful engineering developments and to network and engage in intellectual discussions crossing traditional boundaries in engineering.

The focus areas for the meeting were

• Advanced Manufacturing in the Age of Digital Transformation
• Engineering the Genome
• Self-Driving Cars: Technology and Ethics
• Blockchain Technology.

The meeting was introduced by John L. Anderson, president of the National Academy of Engineering, and by Perry J. Morrissette, senior engineering manager for Boeing Commercial Airplanes.

The first session, on advanced manufacturing, was cochaired by Jim Aske and Li Chun Chang of Boeing and Tarik Dickens of Florida State University. Gabriel Burnett (Boeing) presented a clear vision for the future in his talk “21st Century Engineering Systems.” Chris Lang (NASA Langley) then discussed “Computational Materials for the Design and Qualification of Additively Manufactured Components.” This was followed by a stimulating talk by Chris Hubicki (Florida State University) on “Robots That Walk,” previewing the future of manufacturing, and perhaps also gymnastics! The session ended with a thought-provoking talk by Pamela Kobryn (Air Force Research Laboratory) on the concept of the “Digital Twin,” which is designed to simulate the future performance of a system based on knowledge of its past and projected use.

A breakout session after lunch provided small groups with the opportunity to connect and discuss their research, conversations that hopefully will lead to many new interdisciplinary collaborations. Sohi Rastegar, head of the Office of Emerging Frontiers and Multidisciplinary Activities at the National Science Foundation, then gave a short talk, “Where Are the Emerging Frontiers of Research and Innovation?”

The second session, “Engineering the Genome,” was chaired by Charles Gersbach (Duke University) and Renee Wegrzyn (DARPA). The first two presentations were held Wednesday afternoon, and the session continued with two more talks Thursday morning. Kris Saha (University of Wisconsin, Madison) gave a wonderful overview of how technologies like CRISPR work and why there are off-target impacts, in his talk “Genome Editing with Precision and Accuracy.” Omar Akbari (University of California, San Diego) followed with a vision for eradicating malaria-bearing mosquitoes using genome editing, in his talk “Using CRISPR to Combat Human Disease Vectors.” In the third talk, “Microbes and Manufacturing: Moore’s Law Meets Biology,” Patrick Boyle (Ginkgo Bioworks) described the maturation of synthetic biology and impacts in fields ranging from food production to aerospace. Closing the session, Samantha Maragh (NIST) discussed efforts toward “Empowering Genome Editing Through Standards,” a critical step for widespread applications of these technologies.

On Wednesday evening, the participants enjoyed a fascinating lecture by Joan Robinson-Berry, vice president of engineering, modifications, and maintenance at Boeing Global Services. We were left with a moving message about the importance of diversity and inclusion in engineering.

The third session, “Self-Driving Cars: Technology and Ethics,” was chaired by Chris Heckman (University...
of Colorado Boulder) and Hae-Jong Seo (NVIDIA). Dr. Heckman provided some background for the audience in his talk “Autonomous Vehicles: Challenges and Opportunities.” Tae Eun Choe (Baidu) talked about the “Perception of Low-Cost Autonomous Driving,” introducing perception algorithms in Apollo, the largest open autonomous driving platform. John Basl (North-eastern), an associate professor of philosophy, provided interesting perspectives on the use of hypothetical scenarios (“trolley cases”) to program autonomous vehicles for accident responsiveness, in his talk “Why Everyone Has It Wrong about the Ethics of Autonomous Vehicles.” Dora Sadigh (Stanford) gave the final talk of the session, “Influencing Interactions in Autonomous Driving,” discussing how to accomplish safe and seamless interactions between autonomous vehicles and human-driven vehicles.

On Thursday afternoon, the group was treated to a fantastic set of tours at Boeing. The facility in South Carolina is integral to the fuselage fabrication and final assembly of the 787 Dreamliner. The group was able to see the manufacturing of the composite fuselage, the integration of fuselage sections, and the final assembly processes. We also visited a rapid prototyping facility where engineers and mechanics work together to design and build new tools useful to the assembly processes. This was a truly impressive visit!

The final session, “Blockchain Technology,” was held Friday morning and chaired by Petr Novotny (IBM) and Elaine Shi (Cornell). Dr. Shi started the session with some fundamentals in her talk “Blockchains: An Introduction.” Hong Wan (North Carolina State University) gave a talk entitled “Blockchain beyond Cryptocurrency: An Overview,” discussing differences between public and private blockchains and a variety of potential applications. Jacob Leshno (University of Chicago), an economist, talked about “Cryptocurrencies as Marketplaces,” showing how a decentralized system like Bitcoin could provide an alternative for services previously available only through trusted firms, allowing for exciting new economic models for the future.

The next US Frontiers of Engineering Symposium will be held September 14–16, 2020, hosted by the National Renewable Energy Lab in Golden, Colorado. I encourage you to nominate outstanding young engineers to participate in this program so that we can continue to facilitate cross-disciplinary exchange and promote the transfer of new techniques and approaches across fields in order to sustain and build US innovative capacity.
Computational modeling supports the qualification efforts necessary to realize the full potential of additive manufacturing for designing and manufacturing aerospace components.

Computational Materials for the Design and Qualification of Additively Manufactured Components

Christopher G. Lang

NASA is developing next-generation computational materials capabilities to support the qualification of additively manufactured metallic structural components for aerospace applications. The quality of these parts directly depends on a wide range of process parameters, including build conditions and feedstock properties. Computational materials research aims to develop a fundamental understanding of the dependence of the part properties and performance on the process parameters and to apply that understanding to efficient qualification practices.

Integrated multiscale modeling methods allow prediction of the process-structure-property relationships, including the effect of defects. This paper primarily focuses on the powder bed fusion process and its application to aerospace flight systems, with discussion of in situ monitoring, process-to-microstructure linkages including residual stress, and microstructure-to-performance linkages. Computational materials research for additive manufacturing (AM) processes will enable efficient and accurate design, manufacture, and certification of future aerospace flight systems.

Introduction

Although AM technology has recently experienced considerable growth and publicity for its potential to significantly transform the manufacturing industry, its promise is limited in application because of a lack of confidence
in part quality. Improvements in material properties, consistency, and process control are necessary for AM to realize the advertised potential of enhanced performance, reduced cost, and increased manufacturing speed; for example, the application of AM to fracture-critical flight components requires extensive qualification efforts.

Additive manufacturing encompasses a variety of materials (e.g., metals, polymers, and ceramics) and processes (e.g., powder bed, blown powder, wire fed, laser, and electron beam). Part quality and consistency depend on numerous process-specific parameters that are selected or adjusted for each component.

**Laser Powder Bed Fusion**

I focus on the laser powder bed fusion (LPBF) process for metallic AM, although many of the approaches are applicable to a wide range of materials and manufacturing processes. The LPBF parameter space consists of laser power, scan speed, laser spot size, scanning strategy, feedstock, part geometry, and machine conditions. The selection of process parameters determines the resulting microstructure and component properties.

Various libraries of process parameters for a given machine and material have been determined through physical testing by AM suppliers or individual laboratories, with additional testing required for each new part geometry or powder supply. An integrated computational materials engineering (ICME) approach reduces the amount of physical testing and informs design engineers about detrimental performance expected for specific process parameters (Turner et al. 2015).

NASA is developing AM rocket engine components for human spaceflight. To address the immediate need for a consistent framework specific to the production and evaluation of LPBF processes, standards have been released by Marshall Space Flight Center (MSFC 2017a,b) for materials, process control, personnel training, inspection, and acceptance requirements. Concurrently, an ICME approach to the design and qualification of aerospace AM materials and their components is being developed at NASA and provides a path toward rapid manufacturing and qualification.

Improved control and understanding of the AM process offer improved consistency and more complex design such as multiple alloys and functionally graded material components. When combined with in situ process monitoring, computational modeling enables the development and integration of manufacturing process capabilities and constraints as well as qualification considerations such as inspection requirements in the component design.

**Computational Modeling of the AM Process**

Process modeling is used to develop an understanding of the relationship between the process parameters, feedstock, microstructural and porosity evolutions, and resulting mechanical properties by solving the governing equations for the physics of the process. Determination of the temperature history, deformations due to residual stress, microstructure evolution, and porosity are among the goals of current process simulation efforts.

**Physics**

Modeling of the AM process requires a multiscale approach to accurately account for the physics at multiple length scales from microstructure to component. An accurate temperature history and melt pool geometry are necessary to understand the microstructure, defect formation, and residual stress formation. The temperature history is predicted by numerical models at different levels of fidelity. Various physics—melting, evaporation, fluid flow, recoil pressure, powder packing density, and surface tension—are incorporated to improve the model accuracy. To accommodate accuracy and computational resource requirements, thermal models are generally restricted to a low number of scan tracks and powder layers.

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**Integrated computational materials engineering reduces the amount of physical testing and informs design engineers about expected performance of specific process parameters.**

Simulation of residual stress formation requires a scale-up to efficiently account for the numerous layers in an AM build. A promising approach for predicting residual stress is the modified inherent strain method,
which computes the strain at the scan track scale and imposes the strains in a layer-by-layer fashion to a part scale mechanical analysis (Liang et al. 2018). Phase-field and kinetic Monte Carlo models are used to simulate grain structures dependent on feedstock and temperature history.

Porosity

Two sources of porosity during the LPBF process are lack of fusion and keyholing. The melt pool transitions from conduction mode to keyhole mode for increased laser power and reduced scan speed. Keyhole mode occurs when a vapor cavity forms with a high aspect ratio of depth to width as compared to conduction mode (Trapp et al. 2017). In contrast, lack of fusion porosity occurs when insufficient power and overlap of successive melt pools are applied to fully melt the powder. A balance for avoiding lack of fusion and keyhole porosity is determined by the selected process parameters (Tang et al. 2017).

In Situ Process Data

For the design and qualification of AM components, experimental data are required to capture critical events and behavior during the manufacturing process. To that end,

• Powder bed systems are being equipped with sensors and measuring devices to record data during the manufacturing process.
• System monitoring provides critical data necessary for understanding process events, performing feedback control, diagnosing machine operation, and validating computational models.
• Key process measurements include temperature history, melt pool dimensions, and defect formation.

Collection of in situ data provides a component build history that can be used to identify critical events during the process that may affect part quality.

Dynamic x-ray radiography (DXR) at the Argonne National Laboratory Advanced Photon Source provides high-speed cross-section videos of the LPBF process (Zhao et al. 2017). The real-time imaging yields data relative to the laser position, including melt pool dimensions, keyhole behavior, solidification rate, and porosity formation. DXR data help characterize the melt pool and solidification behavior for various feedstock compositions and baseplate material as well as varying laser parameters.

Summary

Computational modeling supports the qualification efforts necessary to realize the full potential of additive manufacturing for designing and manufacturing aerospace components. A large design space exists for AM, and an ICME approach to process and component design will support qualification efforts through improved process understanding and control for application- and material-specific needs. Simulation tools that assist in choosing parameters for process control and designing AM-specific components will lead to microstructures that help attain and even exceed design specifications.

Micromechanical simulations characterize part performance for process-specific microstructures including the effect of defects. Integrated computational modeling and in situ process monitoring efforts provide a path toward accelerated design and qualification of aerospace components.

References


Legged robots can both contribute to and benefit from the reliability of modern manufacturing processes.

Robots That Walk:
What the Challenge of Locomotion Says about Next-Generation Manufacturing

Why study walking and running robots, and bipedal robots in particular? Because robots can go where people can’t or shouldn’t go because it isn’t safe, such as malfunctioning nuclear power plants, or the staircases and corridors of burning buildings—places designed to be navigated by bipedal humans.

In addition to disaster response and exploration applications, the study of bipedal robotics informs the design and control of assistive devices. Robotic prosthetic legs and exoskeletons can enable walking and running for patients who have lost the ability to do so, or perhaps even superhuman performance (e.g., lifting or conveying immensely heavy loads).

More broadly, the challenge of engineering bipedal robots yields general lessons across autonomy-related fields including manufacturing. While manufacturing has excelled in extreme repeatability of its processes in controlled environments (famously measuring quality in “sigmas”), legged robotics grapple with uncontrolled environments. If manufacturing is to push its capabilities or venture into remote and uncontrolled locations, it may be beneficial to learn from the field of legged robotics.

This paper summarizes four lessons that were essential to recent advances in walking and running robots and illustrates how they can be applied to manufacturing.
• Bipedal roboticists have designed robots with underactuation and compliance for improved agility and efficiency, and automated manufacturing facilities can similarly lower capital and energy costs.

• Walking and running controllers are being designed for robustness to unknown terrain, and manufacturing can use similar robust control to operate on parts of unknown shape and softness.

• Locomoting robots that rely on self-stable and emergent behaviors provide an example of decreased reliance on heavy computation and ways to find surprising effective behaviors not programmed by their control engineers.

• And finally, the need to change locomotion behaviors on the fly—for example, to change speeds or tasks—has driven the development of task-flexible control algorithms that can make robots more versatile (e.g., for tasks like carrying packages).

Underactuation and Compliance

Legged robots have made enormous strides in terms of agility and stability—Boston Dynamics’ Atlas (figure 1) can do backflips—but energy economy is a longstanding challenge in legged robotics. Humanoid robots typically require an order of magnitude more energy to walk than an equivalently sized person. This drastically limits the range that robots can travel on a limited energy supply, pushing legged roboticists to find ways to do more with less energy.

One efficiency-driven approach, underactuation, involves building bipedal robots with fewer motors, forcing the controller to do the same task using less power. Underactuation can also reduce robot weight as well as stiffness due to highly geared drive transmissions. These combined improvements often lead to increased efficiency: A simple underactuated walker called the Cornell Ranger was able to walk 40 miles on a single battery charge.1

Another approach to increased efficiency comes in the form of compliance, or elasticity in the robot. Robots traditionally are built with highly rigid bodies, in part to make control algorithms simpler. Humans, however, have elastic tendons in their legs that can store and return energy otherwise lost to heat while walking. Following this example, robots like DURUS (figure 2) have spring-legged feet that reduce the energy cost of locomotion by 70 percent over previous humanoid robots (Hereid et al. 2018).

For the field of manufacturing, assembly-line manipulators may save on energy costs by omitting actuators and including flexible linkages.

Robustness to Unknown Terrain

The terrain of the outside world is messy. Not only can it be uneven or rocky, it can be soft like soil, sand, or snow. This means that vision alone cannot always reveal all the necessary properties of oncoming terrain to inform control. Real-world environments call for robots that are robust to unknown terrain. Figure 1 shows the Atlas humanoid from Boston Dynamics walking over a snow bank, an effective example of terrain robustness.

1 Reported by PI Andy Ruina (http://ruina.tam.cornell.edu/research/topics/locomotion_and_robotics/ranger/Ranger2011/).
The need for terrain robustness led researchers to develop force control techniques for locomotion: if a user controls a robot leg to produce a specified force, it has a vastly different behavior in response to disturbances than if its position is controlled. If a force-controlled leg steps in a soft patch of earth, the force controller automatically pushes the leg harder into the ground to hold up its weight, instead of stumbling from the unexpected terrain. This allows legged robots to travel on all kinds of terrain without falling, including the Cassie biped (Agility Robotics) and the MIT Cheetah, both of which can walk up slopes and stairs that they can’t even “see.”

In the context of manufacturing, force control is a useful mode for sensitive manipulation using robotic arms. A force-controlled end effector can grip and move an object of unknown geometry or softness, thereby decreasing sensitivity to unknowns in manufacturing.

**Self-Stable and Emergent Control Behaviors**

Roboticists have given a lot of thought to a key question about effective control: What quantities need to be controlled—the position of a robot’s legs, the orientation of its torso, the forces at its feet? All of these options have been useful in different applications of the field of legged robotics. The right choice of control target can lead to self-stable and emergent behaviors that are far more capable than their programming was predicted to accomplish.

The bipedal robot ATRIAS (figure 3) was programmed with a self-stabilizing walking controller that systematically cycles its feet and controls its forward speed without needing elaborate computation to maintain balance. Further, when commanded to speed up using this relatively simple controller, the robot did something unexpected—it started running without being explicitly commanded to do so (Hubicki et al. 2018). Imagine how this emergent behavior might manifest in an automated factory: In a task where one robotic arm must transfer a part to another robotic arm, if commanded to transfer faster, it might toss the part to the other. With emergent control behavior, a factory can be inherently more clever and effective than initially imagined by its engineers.

**Task-Flexible Control Algorithms**

The locomotive robotics field has pushed for not only more stable, faster, and more efficient locomotion but also a variety of walking and running behaviors. How does a robot jump over an obstacle, run around a corner, or walk with a fragile object? Preprogramming each task with its own human-derived controller quickly becomes impractical. Consequently, achieving a task-flexible control framework has become a critical push for practical viability.

The push for task flexibility has led to a proliferation of real-time optimization methods to generate stable controllers on the fly for a given task. One method is model-predictive control (MPC), where easy-to-compute optimizations are solved extremely quickly and the solutions form a plan for the controller to complete its task in a specified timeframe. The key benefit of MPC is the ability to appropriately react to disturbances, which are myriad out in the field. If an obstacle appears or the goal suddenly changes, fast optimization enables responsive replanning.

This task flexibility made MPC and similar optimization-based methods popular approaches for the vaunted DARPA Robotics Challenge in 2015.
Teams at this challenge were tasked with building a robot that would respond to a simulated industrial disaster. They needed to control a robot to drive a car to the site, exit the vehicle, open a building door, walk over rubble, climb a staircase, shut off a valve, and drill a hole in a wall—all with minimal human supervision on site. The teams succeeded in formulating optimizations that could handle the complexity of robots with dozens of degrees of freedom, solved hundreds of times per second.

The emergence of these planning algorithms enabled the next generation of versatile legged robots, including prototypes for package delivery with Agility Robotics’ Digit robot (figure 4). Future manufacturing may need such real-time task flexibility as well: If a robot performing one specialized task malfunctions, another robot not designed explicitly for the role could be adapted to replace it.

**Conclusion**

Legged robots have had to make a number of advances in order to move out in the real world. Many of these approaches have straightforward extensions to the needs of improved manufacturing. At the same time, legged robots would benefit from the reliability of modern manufacturing processes. And there are lessons that human legs can take from factory robots, too. Ideally, manufacturing assembly lines of the future will be as robust and adaptable as human walking, and conversely, the reliability of walking robots will be measured in “sigmas,” like manufactured products.

**References**


A digital twin is intended to simulate a product’s performance using periodically updated knowledge about the state and use of its physical twin.

Pamela A. Kobryn

The digital twin concept involves simulating the future performance of a specific product or system based on current knowledge about the system and how it is operated. Key aspects of the concept include near- and long-term performance predictions individualized to both the particular product/system (e.g., by serial number) and its use; delivery of results in an intuitive, interactive, and affordable manner in a timeframe suitable for use; and timely and automated updating of results.

While the original concept focused on the health management of engineered systems with stringent reliability and safety requirements (e.g., airplanes), the scope of digital twin applications is rapidly expanding across the entire product/system lifecycle. Advanced computing, information system, network, and device technologies are being joined with advanced analytical methods to unlock new digital twin applications that bring value to enterprises, communities, and individuals across a broad spectrum of uses—in transportation and logistics, mining and construction, manufacturing and production, power generation and distribution, communication and computing networks, and medicine.

Motivating Factors and Significance
An early motivation for the digital twin concept was the structural health management of military aircraft, which led to investment in Airframe

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Digital Twin (ADT) technologies by the Air Force Research Laboratory (AFRL) beginning in about 2009 (Tuegel et al. 2011). At the time, the US Air Force’s desire to reduce the impact of maintenance on aircraft availability and operating costs inspired AFRL engineers to devise new concepts for predicting structural maintenance needs. These engineers sought to develop methods to increase the fidelity and timeliness of the analyses used to decide when to perform such maintenance (Tuegel and Babish 2014).

Newer applications have a similar motivation: delivering and sustaining the predictable, safe, reliable, and affordable operational capability of engineered products and systems to achieve the outcome desired or required by the end user. Recent advances—in high-performance computing capability; modeling, simulation, and analysis methods; data analytics and information technology; metrology and sensor technology; the internet of things/industrial internet of things (IoT/IIoT); and mobile and cloud computing—support the integration of these capabilities in a digital twin simulation framework for a variety of applications across the product lifecycle, including design, development, testing, and manufacturing, in addition to the original applications in system sustainment.

Several aspects of US Air Force aviation led the AFRL engineers to use the term “digital twin” for their new concept. The facts that every flight of each Air Force airplane is unique and that the types of missions for which the aircraft are used change periodically led to the idea of using flight simulation to predict airplane performance over time.

While the use of flight simulators is not new, the idea of using flight simulation to predict the engineering performance of an individual aircraft over time is novel. Because the physical configuration of different aircraft of the same make and model is unique and changes periodically, tail-number-specific configuration data are used for the flight simulations.

A digital twin simulates the performance of its physical twin using current, periodically updated knowledge about the state and use of its physical twin. This is in contrast to typical engineering-level analyses that use a nominal physical configuration with average or worst-case initial conditions and boundary conditions and are updated only when major changes in configuration or usage occur.

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**Engineers are developing methods to increase the fidelity and timeliness of analyses used to decide when to perform maintenance.**

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The significance of the digital twin concept is derived from its key elements:

- Digital twins are designed to provide timely and actionable information about an asset to a decision maker.
- The output is tailored for the asset operator(s), based on both the known physical characteristics of the assets and the details of past, current, and planned use.
- The output of digital twin simulations is updated based on new information about the physical characteristics of the system and/or its past, current, and future use.

**An Example: AFRL’s Airframe Digital Twin Program**

For AFRL’s ADT program, the decision maker is the airframe structures engineer and the decision is when to require safety- and maintenance-critical structural inspections for each aircraft in the fleet. Because the engineer is not the owner or operator of the fleet, the decision of when to require inspections must include operational considerations such as an adequate planning horizon and minimized downtime and cost.

**Better Maintenance and Planning**

No operator wants an engineer to call for maintenance on short notice, particularly if that maintenance takes the aircraft out of service and/or is expensive. The operator typically wants to defer or eliminate maintenance actions as much as possible! ADT aims to provide

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1 Configuration changes are due to (i) repairs associated with wear and other damage that can occur during manufacturing, operation, and maintenance; (ii) design updates to address newly identified performance deficiencies; (iii) design updates to add new capability to the aircraft; and (iv) the installation of missionized equipment (e.g., weapons, external fuel tanks, sensor pods).
information about operational and economic risks as a function of flight hours and/or calendar time for each aircraft to help the engineer justify inspection requirements to the operator. Furthermore, ADT enables the engineer to provide these requirements to the operator early enough for the inspections to be incorporated in the operator’s plans.

Because of the pressure to reduce maintenance requirements without compromising safety, engineers are always looking for ways to improve their ability to forecast system degradation. In the case of airframe structures, the primary degradation mechanism is fatigue cracking of metallic parts. Such cracking is very difficult to predict because it is driven by factors that are challenging or impossible to know a priori. Current engineering methods for forecasting fatigue cracking employ various safety factors that are uniformly applied to an entire fleet for the duration of its service life.

ADT aims to reduce or eliminate the use of uniform, fleetwide safety factors in favor of aircraft-specific probabilistic analyses. Individualized analyses can reduce some uncertainties in the factors of safety, making the analysis results more precise and reducing the likelihood of over- or underinspecting. ADT analyses of the physical characteristics of a given plane will account for differences induced by manufacturing, assembly, operation, and maintenance that influence fatigue cracking behavior based on data gathered throughout its life (figure 1).

**Analysis Based on Actual Use**

The other way ADT aims to refine analyses is by accounting for how an individual operator uses its aircraft. An operator at a training site flies differently than an operator at a forward operating site, and ADT accounts for such systematic differences to reduce analysis uncertainty. Hence, to forecast fatigue cracking, one must first forecast operations. For ADT, these forecasts are in the form of simulated future flights based on synthesized data from previous use and assumptions about how the operator intends to fly its aircraft (Asher et al. 2017).

Finally, ADT aims to automatically update when the aircraft configuration is changed and when new flight or maintenance records become available. In this manner, ADT further reduces uncertainty, providing additional opportunity to tailor maintenance requirements.

**Proof of Concept**

While simulating the engineering performance of a physical aircraft and updating it over its lifetime is a simple concept, in practice it involves the synchronization of numerous models, analyses, and data elements. The time and cost of developing and validating a digital twin are not trivial, so proving that the concept is viable and can benefit both engineers and operators is a necessary early step. However, given the time scale of fatigue cracking in operations—typically thousands of flight
hours—proving the concept using operational aircraft would simply take too long.

AFRL engineers therefore focused on developing a laboratory-based method for proof of concept. This effort resulted in a one-of-a-kind full-scale structural experiment in which the external aerodynamic loads from individual flights are applied to full-scale aircraft wings in a laboratory environment at the rate of 200 simulated flights per workweek. This experiment is currently running in AFRL’s Structures Validation Facility at Wright-Patterson AFB.

Exciting Frontiers
Since the early days of AFRL’s ADT program, the digital twin concept has become increasingly common and enabling technology has advanced. One exciting recent example comes from the US Food and Drug Administration’s Office of Science and Engineering Laboratories (FDA 2019), which solicited information on “the capability to perform whole human heart computations with a medically implanted device” and “to create ‘virtual patients’ and a ‘virtual population’ such that the FDA can conduct an in silico clinical trial with data that can be used to support a proposal for a real clinical trial.” While this project doesn’t use the term digital twin, many similarities exist, including decision support, tailoring for the individual, uncertainty quantification, and statistical model updating.

Current Limitations and Challenges
Digital twin simulations have many potential applications, but significant technical, economic, and social limitations and challenges remain, including the need to

- determine what information to present to the decision maker and how often to update it
- determine the proper level of fidelity for the simulations
- develop methods to reduce the order of the underlying models to reduce computation time
- decide how much to tailor simulations to the individual asset/operator
- develop affordable, reliable means of collecting state and usage data
- develop computationally efficient methods of updating probabilistic simulations
- develop methods to validate probabilistic simulations
- develop methods to synthesize usage and state data
- protect personal privacy and intellectual property
- secure data and models
- address liability for operational failures.

Summary
The concept of simulating engineering performance of physical assets and updating the simulations with state and usage data over time is a powerful idea that is becoming increasingly feasible as enabling technologies mature. Though challenges remain, engineers are envisioning new applications and finding ways to bring them to fruition.

References
Engineering approaches are helping to address challenges in genome editing.

Genome Editing with Precision and Accuracy

Krishanu Saha

Editing the genetic code of living organisms with word-processing-like capabilities has been a goal of life scientists and engineers for decades. For biomedical applications, changing as little as a single base in the 3 billion bases of the human genome might cure disorders such as muscular dystrophy and cystic fibrosis. New genome editing tools are now capable of “one in a billion” specificity, leading to the prospect of new classes of gene and cell therapies. To illustrate both the excitement and the risks, I begin with a cautionary tale that made global headlines, before describing opportunities and challenges in efforts to develop genome editors for biomedical applications.

A Cautionary Tale

In November 2018 Chinese biophysics researcher He Jiankui surprised the world by announcing the birth of two genome-edited babies, the so-called “CRISPR1 twins” (Cyranoski 2019). It was a momentous step: the intentional alteration of the human germline to produce changes transferred to the next generation.

But the editing outcomes were not as Dr. He expected (Ryder 2018). The Chinese team had injected CRISPR-Cas9 genome editing RNA and proteins into human embryos to modify the CCR5 gene, which encodes a receptor

1 CRISPR (clustered regularly interspaced short palindromic repeats) is a family of DNA sequences in the genomes of prokaryotic organisms such as bacteria.
on the surface of immune cells for human immunodeficiency virus (HIV). CRISPR-associated protein 9 (Cas9) is a nuclease that can cut DNA, and the location of the cut can be programmed by the sequence of a single guide RNA (sgRNA).

The sgRNAs used by Dr. He targeted two locations in the CCR5 gene to delete 32 amino acids of the translated CCR5 protein. The deletion of the CCR5 gene was meant to destroy the ability of HIV to infect T cells and thus make the treated embryos resistant to HIV. But genomic analysis of the CRISPR twins indicated that the intended mutation was not achieved; instead, different insertions and deletions of DNA bases (termed indels) were generated in the CCR5 gene. These insertions and deletions are anticipated to make the twins more susceptible to influenza, with unknown effects on their susceptibility to HIV.

While there are many lessons to be learned from this experiment (Barrangou 2019; Jasanoff et al. 2019), it is a cautionary tale about using genome editing tools with poor precision. Critiques of the approach indicate suboptimal use of both Cas9 nucleases (there are protein-engineered, higher-fidelity variants) and sgRNAs (other target sequences could have been used) as well as questionable timing of the intervention (the proteins and RNA could have been introduced at a different stage of embryonic development).

The challenges of getting all the parameters right are daunting, and many people, including leaders in the scientific community (Lander et al. 2019), argue that human embryo editing should not even proceed. There is intense activity, however, to attempt to tackle the challenges of editing the human genome after birth, so-called “somatic genome editing,” to mitigate certain diseases. I briefly describe efforts to overcome four types of challenges through improved precision and accuracy in genome editing (figure 1).

**Challenge 1: On-Target Nuclease Activity**

The most common interpretation of “precision” in genome editing is the ability to edit the genome at the intended target genomic locus. The protocadjanent motif in the host genome used by Cas proteins for target recognition are shaded in blue; the DNA sequence in the host genome bound by the genome editor is in green at the intended (on-target) locus and in red at the unintended (off-target) locus. Incorporation of the correct sequence in the edited locus after DNA double-strand break formation or after base editing (not shown). Indels = insertions or deletions of DNA. (3) Precise regulation of integrated transgenes by endogenous promoters and distal elements in comparison to random integration. mRNA = messenger RNA, which represents the expression level of the inserted transgene; perturbed expression levels in cells after genome editing can lead to poor efficacy or adverse events. (4) Delivery to specific cell types by engineered nanomaterials or viral capsids. Reprinted from Mueller et al. (2018) with permission from Elsevier.
ponents, such as ribonucleoproteins (RNPs), and to regulate when and where Cas9 is expressed (Chen et al. 2016; Davis et al. 2015; Hemphill et al. 2015). For example, modified Cas9 nucleases can be selectively activated with small molecules to decrease the gene editing time window (Davis et al. 2015).

HDR can generate perfect incorporation of the desired sequence without modifying any other bases in the genome and so is called “scarless editing.” Researchers have attempted to modify DNA repair pathways (Chu et al. 2015; Yu et al. 2015) to increase both the efficiency of HDR and the ratio of precise edits to imprecise mutations. These methods are most applicable for in vitro cell culture applications where potential toxicity is less limiting.

For short insertions, single-stranded oligodeoxynucleotide (ssODN) templates hold significant promise for treating disease because of their ease of synthesis. However, sequence changes encoded by the ssODN are infrequently incorporated after editing (<10 percent), and desired edits are typically outnumbered by other sequence outcomes (presumably from NHEJ). Strategies to link the ssODN to Cas9 help increase HDR (Carlson-Stevermer et al. 2017; Lee et al. 2017). Other methods avoid the use of HDR and leverage other DNA repair pathways (Suzuki et al. 2016).

Base editors are particularly attractive for clinical translation as they avoid DNA double-strand breaks entirely. They employ a catalytically dead version of Cas9 fused to a DNA deaminase to modify base pairs proximal to the sgRNA target, deaminating cytidine bases to form uridine. The modified bases are recognized by the cell as mismatched and corrected to thymidine (Komor et al. 2016). Current work in this area mostly focuses on cytosine (C) > thymine (T) (or analogous guanine (G) > adenine (A)) base conversions, although future versions will aim to allow modifications of any single base (Gaudelli et al. 2017). Additionally, a new strategy, called prime editing, also avoids DNA double-strand breaks and has been demonstrated in vitro with mammalian cells for scarless incorporation of new sequences (Anzalone et al. 2019).

Challenge 3: Precise Transcriptional Control

Even if challenges 1 and 2 are met with perfect accuracy and precision, expression of edited genes to generate RNA transcripts can vary over time as well as across cell differentiation and behavior patterns. Misregulation of the edited transcript can compromise therapeutic efficacy or lead to adverse events. Therefore, it is critical to consider strategies to maximize transcriptional control, especially when inserting new bases.

A striking discovery about the necessity of precise transgene expression recently emerged in the field of chimeric antigen receptor (CAR) T cell therapy. In

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**Misregulation of an edited transcript can compromise therapeutic efficacy or lead to adverse events, so it is critical to maximize transcriptional control.**

Several groups have engineered nickase Cas9 proteins with only one active nuclease domain. A single nickase cannot create a full DNA double-strand break, but when two nickases are paired, the break can be repaired via nonhomologous end joining (NHEJ) in mammalian cells (Ran et al. 2013). While this method lowers off-target effects, the efficiency of the genome editing is greatly decreased as two nickases and two sgRNAs need to be delivered to the nucleus to perform simultaneous cuts.

Rational protein engineering approaches to modify the nuclease have also generated high-fidelity variants of Cas9: eSpCas9 (Slaymaker et al. 2016), Cas9-HF1 (Kleinstiver et al. 2016), and xCas9 (Hu et al. 2018). Cas9 variants decrease the binding time of the sgRNA to the target sites in the genome, resulting in a decrease in off-target binding and cutting. These high-fidelity Cas9 variants may represent a quick path to clinical relevance as they can greatly reduce off-target events.
the CAR T paradigm, a synthetic CAR transgene targeting a cancer-enriched antigen is inserted ex vivo into a patient’s T cells, which are then expanded and infused, thereby engineering the immune system to recognize and target cells bearing the antigen (Piscopo et al. 2018). CRISPR-Cas9 was recently used to generate CAR T cells featuring a transgene at the T cell receptor alpha (TRAC) locus, which ensured that CAR expression was regulated by the endogenous TRAC promoter (Eyquem et al. 2017). These CAR T cells demonstrated promising results in a leukemic mouse model and also displayed fewer biomarkers of dysfunctional CAR T cells, suggesting that precise transgene control may yield a more potent cell product.

**Challenge 4: Precise Editing in Specific Cells and Tissues**

Precise delivery of editing components to the right cells and tissues remains a challenge as many delivery agents suffer from low efficiency, high toxicity, and immunogenicity, but viral and nonviral delivery agents have been engineered to achieve cell and tissue specificity. Viral constructs can be engineered to harbor cell- and tissue-specific promoters that drive expression of the gene editing system (Ran et al. 2015; Swiech et al. 2014) so that editing machinery is not expressed in nondesired cell types. And several nonviral designs have demonstrated high gene editing efficiencies when used with RNPs, ranging from 30 to 40 percent in cell lines, and up to 90 percent delivery efficiency (Chen et al. 2019; Mout et al. 2017; Sun et al. 2015; Zuris et al. 2015).

Custom biomaterials can also be engineered to direct genetic payloads to specific tissue types to allow gene editing in situ, thereby bypassing many of the biomanufacturing challenges associated with ex vivo cell therapy. Researchers recently developed DNA nanocarriers with the capacity to deliver CAR transgenes to T cells in a leukemic mouse model by coupling anti-CD3 ligands to polyglutamic acid (Smith et al. 2017). These nanocarriers demonstrated specificity to circulating T cells over other blood cell types shortly after delivery, causing tumor regression.

**Outlook**

It is likely that strategies to meet these four challenges will be complementary, ultimately enabling more precise genomic surgery in patients’ cells. For in vitro applications, drug discovery will probably be accelerated by enhanced tools for disease modeling, target validation, and toxicological studies. For ex vivo uses, precision-engineered cell and tissue therapies may incorporate more functionality from synthetic circuits (Weinberg et al. 2017). Finally, for in vivo somatic gene editing applications, injectable viral and nanoparticle strategies could specifically edit stem cells to regenerate tissues and correct disease-causing mutations.

Successful strategies to overcome the challenges described above may pave the way for a new wave of transformative therapeutics.

**References**


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The annual incidence of vector-borne disease exceeds 1 billion globally—roughly half of the world’s population is at risk of infection.1 Mosquito-borne diseases account for the majority of cases (WHO 2014), but there are no vaccines for most of them, so prevention, mainly through inefficient vector control of limited effectiveness, is the primary method to reduce disease burden. Furthermore, treatments for most mosquito-borne pathogens are also limited, and those that are effective are under threat from increasing pathogen drug resistance.

The severity of the problem is best exemplified by the repeated development of antimalarial resistance in Southeast Asia. In the 1990s parasite resistance to first- and second-line malaria drugs necessitated the development of combination therapies for treatment (Nosten et al. 1987, 1994). However, high resistance to these combination drugs and their later derivatives resulted in an increase in malaria-related deaths in this region (Dondorp et al. 2009; Ménard et al. 2016; Phyо et al. 2016). Therefore, in most cases, vector control is the best approach for reducing the burden of vector-borne diseases.


CRISPR technology shows promise as an effective vector control method for mosquito-borne diseases.

Using CRISPR to Combat Human Disease Vectors

Omar S. Akbari
**Vector Control Tools**

Chemical insecticides have historically been an important tool for mosquito control, but they have limitations, most notably their limited efficacy due to increasing vector insecticide resistance and their limited species specificity and duration. While insecticide-driven approaches have been successful in some disease prevention programs (Pluess et al. 2010), for a myriad of reasons they have mixed results overall (Esu et al. 2010; George et al. 2015; Maciel-de-Freitas et al. 2014). Even in areas where sustained vector control has been achieved in the past, insecticide resistance has greatly reduced or eliminated the impact of vector control on disease transmission (Hemingway et al. 2002; Liu 2015; Maciel-de-Freitas et al. 2014).

**Sterile insect technique is an environmentally friendly method but not feasible for large-scale control of mosquito populations.**

Given the widespread use of insecticides and limited number of insecticide families available for vector control programs, insecticide resistance will continue to be a barrier to insecticide-based vector control. New control techniques are therefore being evaluated to complement vector control programs.

**Sterile Insect Technique for Insect Control**

Sterile insect technique (SIT) is the gold standard for genetics-based insect population control. In classic SIT, insects are treated with ionizing radiation to induce male sterility and then released in high frequency to mate with wild females, resulting in nonviable progeny. Over time, repeated mass releases of sterile males suppress and can even eliminate target populations. This approach was used to eradicate the screwworm fly (*Cochliomyia hominivorax;* Krafsur et al. 1986), the Mexican fruit fly (*Anastrepha ludens*), and the Mediterranean fruit fly (*Ceratitis capitata*) from regions of North America (Hendrichs et al. 2002).

But in mosquitoes irradiation-based SIT causes high male mortality and exceedingly high fitness costs. For example, field studies show that the release of irradiated, sterile male *Aedes albopictus* led to very limited population reduction (Bellini et al. 2013) likely for these reasons.

So although irradiation-based SIT presents an environmentally friendly method of local population suppression, it is not feasible or scalable in its current form for large-scale control of mosquito populations.

**Novel Vector Control Methods**

In recent years innovative genetic vector control methods, such as the release of insects carrying a dominant lethal (RIDL) (Thomas et al. 2000), have demonstrated large reductions in wild vector populations (Carvalho et al. 2015; Harris et al. 2012). Other novel disease or vector control methods, such as Dengue and Zika virus transmission-blocking *Wolbachia*-infected *Aedes aegypti* and the *Wolbachia* incompatible insect technique (IIT), respectively, are being evaluated in the field (Schmidt et al. 2017). While effective, these methods require large numbers of mosquitoes to be raised, manually sexed, and released as adults in the field near target sites.

Building mosquito mass rearing factories in local disease endemic areas is costly and labor intensive and current procedures are error prone (Gilles et al. 2014; Papathanos et al. 2009). Female release, even in small numbers, is particularly problematic to the *Wolbachia* IIT technology as the release will immunize the target population to the incompatible *Wolbachia* strain and ultimately lead to the failure of the approach. Some studies even indicate that in some contexts, *Wolbachia* actually enhances pathogen infection (Dodson et al. 2014; Hughes et al. 2014) or can have large vector fitness costs, which can be problematic (Joshi et al. 2014).

Additionally, the antibiotic drugs required during rearing of RIDL mosquitoes have high male fitness costs (about 5 percent that of wild-type male fitness) based on RIDL field trials in the Cayman Islands (Harris et al. 2011) and Brazil (Carvalho et al. 2015), due to the loss or alteration of gut microbiome or symbiotic bacteria as well as toxicity to mitochondrial cell functions (Chatzispyrou et al. 2015; Moullan et al. 2015). Therefore, there is still an urgent need for new vector control technologies for the suppression of wild vector populations.
Using CRISPR

The advent of CRISPR technology has excited the potential to engineer new game-changing technologies and innovative systems that can be used to control wild populations of mosquitoes. Two developments of particular interest are a self-limiting system termed precision-guided sterile insect technique (pgSIT) (Kandul et al. 2019) and a homing-based gene drive (HGD) (Champer et al. 2016; Esvelt et al. 2014). The unique features of these systems can make them valuable in the future to control mosquitoes, as elaborated below.

pgSIT

The novel CRISPR-based pgSIT mechanistically relies on a dominant genetic technology that enables simultaneous sexing and sterilization, facilitating the release of eggs into the environment and ensuring that only sterile adult males emerge. Importantly, for field applications, the release of eggs will eliminate burdens of manually sexing and sterilizing males, reducing the time and effort involved and increasing scalability. Moreover, the release of eggs should reduce the need to build factories near release sites as eggs could be shipped to release locations from a centralized facility and hatched directly in the environment.

This system was recently systematically engineered in an insect fly model system and was shown to be extremely efficient at generating 100 percent sterile males that could suppress populations. The system functions by mass producing two strains, one expressing the CRISPR-associated protein 9 (Cas9) endonuclease and the other expressing two guide RNAs (gRNAs), one targeting a gene important for female viability and the other a gene important for male fertility. When the two separate strains are crossed the only surviving progeny are sterile males, which can be repeatedly released as eggs into the environment, resulting in population suppression as they compete with wild males for females (A). HGDs convert heterozygotes to homozygotes using a cut/repair process (B) resulting in biased inheritance and rapid spread into a population (C; green denotes individuals with the gene drive, grey denotes wild-type mosquitoes).

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2 CRISPR (clustered regularly interspaced short palindromic repeats) is a family of DNA sequences in the genomes of prokaryotic organisms such as bacteria.
ever, transgenes that mediate disease resistance to treatment (refractoriness) may inadvertently compromise the fitness of insects that carry them. Furthermore, wild populations are large, partially reproductively isolated, and dispersed over wide areas.

Population replacement therefore requires a gene drive mechanism to spread linked genes that mediate disease refractoriness through wild populations at greater than Mendelian frequencies. In an effort to achieve this, CRISPR methods have been used to accelerate the development of HGDs in model systems in addition to mosquitoes and even mammals (Champer et al. 2017, 2018; DiCarlo et al. 2015; Gantz and Bier 2015; Gantz et al. 2015; Grunwald et al. 2019; Hammond et al. 2016, 2018; KaramiNejadRanjbar et al. 2018; Kyrou et al. 2018; Li et al. 2019; Windbichler et al. 2011; Yan and Finnigan 2018).

HGDs function by encoding the Cas9 endonuclease and an independently expressed gRNA responsible for mediating DNA base pairing directing Cas9-mediated cleavage at a predetermined site (Champer et al. 2016; Esvelt et al. 2014; Gantz and Bier 2016; Marshall and Akbari 2018). When the HGD is positioned in its target site in a heterozygote, double-stranded DNA breakage of the opposite chromosome can cause the drive allele to be used as a template (i.e., donor chromosome) for DNA repair mediated by homologous recombination. This can result in copying, or “homing,” of the HGD into the broken (receiver) chromosome, thereby converting heterozygotes to homozygotes in the germline, which can bias Mendelian inheritance ratios and lead to an increase in HGD frequency in a population (figure 1B,C).

Given recent progress toward developing HGDs in pest species such as mosquitoes (Gantz et al. 2015; Hammond et al. 2016, 2018; Kyrou et al. 2018; Li et al. 2019), there is significant enthusiasm for their potential use to control wild populations. For example, release of HGDs linked with effector genes that inhibit mosquito pathogen transmission (Buchman et al. 2019a,b; Isaacs et al. 2011; Jupatanakul et al. 2017) may lead to replacement of disease-susceptible mosquitoes with disease-resistant counterparts, thereby reducing pathogen transmission (i.e., population modification drive). Alternatively, HGDs targeting genes that affect the fitness of female mosquitoes could also lead to gradual population declines and potentially even elimination (i.e., population suppression drive) (Kyrou et al. 2018; Windbichler et al. 2008, 2011).

**Conclusion**

Both genetic SIT systems and modification and suppression drives have the potential to transform mosquito population control measures (Burt 2003; Champer et al. 2016; Esvelt et al. 2014), and therefore have excited discussions about their potential use, regulation, safety, ethics, and governance (Adelman et al. 2017; Akbari et al. 2015; NASEM 2016; Oye et al. 2014). Field testing of these systems over the next 5 to 10 years will help illuminate the efficacy and safety concerns of these systems.

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Biology as an engineering substrate is a transformative manufacturing technology.

Microbes and Manufacturing: Moore’s Law Meets Biology

Patrick Boyle

Biology is the most powerful known manufacturing “technology.” Proof of this is all around: at the continental scale, the Earth’s land surface is defined by plant life, much of which has been harnessed with agriculture. At the nanoscale, biological systems routinely self-organize with a precision that can’t be matched by the most advanced silicon chip fabrication methods. Even nonbiological technology like petrochemistry uses building blocks that were once biological: petrochemicals, the defining building block of 20th century manufacturing, are derived from the decomposition of prehistoric biomass.

Background
For over 4 billion years, biology has been evolving solutions that scientists and engineers are only now beginning to understand and adapt. For example,

• Antibiotics, aspirin, and many other drugs were isolated from nature. Today, it is possible to further engineer microbes to produce new drug variants.

• Spider silk has been prized for its high strength-to-weight ratio and its promise as a next-generation material. Multiple companies are producing spider silk via engineered microbes.
Many petrochemicals can now be produced from sustainable carbon sources via engineered microbes.

Traditional petrochemical products are being enhanced with biological components. For example, modern laundry detergent contains enzymes (again from engineered microbes) that function in cold water and save heating energy.

All of these applications are advantaged by the fact that biological systems self-assemble, self-repair, and self-replicate. In effect, a microbrewery can serve as a common manufacturing platform for any number of products, simply by engineering the microbe grown in the fermenter.

These advances are possible because the tools are finally available to read (sequence) and write (synthesize) DNA. Both of these technologies have been improving at a rate faster than Moore’s law for nearly 20 years. This exponential improvement in the ability to program DNA is driving a technological revolution that rivals the computer revolution of the 20th century—and is impacting manufacturing at a scale not seen since the industrial revolution of the 19th century.

**History of Synthetic Biology**

Manufacturing with biology far predates the ability to genetically engineer biology. The domestication and breeding of plants and animals for food, clothing, and other materials is synonymous with the emergence of civilization, as these biotechnologies allowed humans to settle in towns and cities with access to cultivated bio-based products.

The earliest domestication efforts were considerable engineering feats in their own right: modern corn bears little resemblance to the teosinte grass that served as the starting point for domestication (Doebley et al. 2006). Similarly, many distinct vegetables such as mustard, broccoli, cauliflower, and even kohlrabi are human-crafted variants of common ancestor species (Dixon 2017). Dogs, cattle, and other animals were similarly differentiated from their wild ancestors via selective breeding over thousands of years.

In the 20th century, the advent of genetic tools and the ability to read and write DNA allowed biologists to consider directly engineering biological organisms for the first time. Many of the early examples of genetic engineering have been extraordinarily successful: human insulin produced in microbes, developed by Genentech in the 1980s, allowed a transition away from the use of animal insulins isolated from pig and cow pancreases (Fraser 2016). In agriculture, genetically modified crops entered use in the United States in the 1990s, and today more than 90 percent of U.S.-grown soybean, cotton, and corn is genetically modified (USDA 2019).

Simply put, biology appeared to be the only technology capable of coordinating atoms with nanometer precision into complex three-dimensional structures. For example, bacterial flagella (tail-like features that propel many bacteria) are self-assembling rotary motors, with a diameter of approximately 25 nm, that rotate at greater than 100 Hz. A typical *Escherichia coli* cell is about 1 µm in length and has several flagella (van den Heuvel and Dekker 2007).

It is hard to imagine how to design machines at the nanometer scale of comparable complexity without biology. Inspired by this, in the mid-1990s a group of electrical engineers, computer scientists, and biologists began to meet regularly to discuss the application of engineering principles to biology. DARPA worked with this group to convene an Information Science and Technology (ISAT) study in 1996 on “cellular computing” that laid the groundwork for the field: seeking to develop methods to understand and program DNA for the purposes of engineering biological organisms to produce new products (Knight and Matsudaira 2016).

Synthetic biology combines efforts from many fields: computer science and electrical engineering abstractions to describe cellular circuitry, metabolic engineering to engineer the metabolic pathways of cells, genetics to understand the control elements of gene expression, and systems biology to measure and simulate cellular systems, among others. Many of the principles developed in the 1996 ISAT study remain relevant to understanding the approaches and applications of synthetic biology today. In particular, a technology development
A roadmap from that study predicted the development of progressively better tools and modeling capabilities that underlie much of today’s rapidly developing synthetic biology “stack” (figures 1 and 2; Canine 2018).

**Design Principles for Synthetic Biology**

Two founding design principles of synthetic biology remain especially relevant: the concept of reusable parts and the engineering design cycle.

Synthetic biologists seek to identify and take advantage of modular subunits of biology as reusable parts, to allow the design of more complex systems. For example, genetic control switches such as promoters (the DNA elements that control transcription of a gene into messenger RNA), ribosome binding sites (RNA elements that control the translation of messenger RNA into protein), and other genetic parts have been repurposed to construct oscillators, logic gates, and memory circuits in cells (Boyle and Silver 2009).

The engineering design cycle breaks down the process of engineering into three stages: design, build, and test (DBT).

**Design**

In contrast to other engineering disciplines, synthetic biologists engineer organisms shaped by evolution, not design. As such, the DBT process in biology requires many more iteration loops than is typical for more mature fields such as mechanical engineering (Petzold et al. 2015). Many successes in synthetic biology follow hundreds or even thousands of
failed designs, and often function in only a narrow range of conditions, such as a tightly controlled fermentation tank. These challenges have led to a worldwide effort to develop better “foundries,” facilities that leverage automation to enable rapid prototyping of biological designs, often by conducting many experiments in parallel (Hillson et al. 2019). But trends in DBT technologies have accelerated progress in synthetic biology.

Systems biology, modeling of cellular systems, and data science have enabled synthetic biologists to develop better design algorithms. As in many other fields, machine and deep learning methods are being applied to large biological datasets to refine biological designs (Camacho et al. 2018).

**Build**

Build technologies in biology have centered around the ability to read and write DNA, the core programming substrate for biology. Here improvement has been defined by two technologies advancing faster than Moore’s law: DNA sequencing and synthesis.

Over the past 20 years, the cost to sequence a human genome has fallen more than a millionfold, to less than $1,000 per genome (NIH 2019). This revolution in sequencing technology has led to exponential growth in the number of sequenced genomes across the tree of life, yielding novel functional parts for synthetic biologists.

Similarly, the cost of DNA synthesis has steadily decreased to today’s price of pennies per base pair (Carlson 2017). DNA synthesis is impressively cheap considering the chemistry involved, but still represents a key bottleneck to progress: imagine paying $0.07 per bit when writing a software program.

**Test**

Finally, test approaches in biology often make use of cheap DNA sequencing as readouts, and new high-throughput methods for mass spectrometry are allowing researchers to measure the majority of metabolites and proteins in engineered cells (Petzold et al. 2015).

**Security for Biology**

Synthetic biology is the only engineering discipline where the engineers are made of the same substrate that they are engineering. Since the advent of DNA engineering technologies in the 1970s, researchers and the broader community have raised concerns about the potential misuse of engineered biology to cause harm. As early as 1975, researchers convened to consider the hazards of engineering DNA (Berg et al. 1975). In Cambridge, Massachusetts, public hearings were held in 1976 to develop guidelines for using DNA editing technology as a research tool (Lindsay 1976). These hearings and resulting regulations (such as standard biosafety ratings) have been credited for the emergence of Cambridge and Boston as leading biotech hubs, as the regulations allowed universities and companies to perform this research in a sanctioned environment.

The rapid progress of biological research has led to continual reassessments of biosecurity (NASEM 2017, 2018; NRC 2004). Given the lessons learned in other fields of engineering—particularly in computing and constantly evolving challenges to cybersecurity—safety and security standards, methods of forensics and attribution, and design of biological safety mechanisms must be continually anticipated and addressed. Some examples of these approaches include the biosafety level (BSL) standard, screening protocols to prevent the synthesis of known harmful sequences (DHHS 2015), and deep learning research to identify engineered DNA in sequencing experiments.¹

**Applications of Engineered Biology**

Many of the current applications of engineered biology are products of engineered microbes. Microbes have a number of properties that make them useful to engineers: they exhibit fast growth rates, have many genetic tools, and can produce products at commercial scale via

fermentation. Many of the early applications for synthetic biology sought to engineer microbes to produce sustainable drop-in replacements for products typically derived from petrochemicals, such as 1,3-propanediol (used in specialty polymers like DuPont’s Sorona product), 1,4-butanediol (used in compostable plastics), lactic acid (used to produce polyactic acid polymers), and farnesene (both a fuel and bio-rubber monomer) (Gustavsson and Lee 2016). But the commercial viability of commodity petrochemical replacements was challenged by the falling price of oil in the 2000s, leading to a pivot to higher-value products.

Today, most companies in the synthetic biology space are focusing on products such as fragrances, high-value materials, and drugs (Schmidt 2017). Because fragrances typically command a high price but are produced in low volume, they were a natural starting point for companies seeking to develop and commercialize new biomanufactured products.

This focus has parallels with the development of synthetic chemistry as a field, which initially focused on the production of high-price low-volume synthetic dyes before expanding to other products (Yeh and Lim 2007). The approach to transfer the production of volume-limited high-value products to more scalable microbial platforms may be best exemplified by the current competition to produce cannabinoids via fermentation, with hundreds of millions of dollars invested in just the past two years (Costa et al. 2019).

Beyond drop-in chemical replacements, many new applications are emerging that are unique to biology. More energy-efficient laundry detergents are effective in cold water in part because they contain enzymes that improve stain removal (Reed 2018). And several companies, such as Indigo Ag, Pivot Bio, and (Ginkgo-affiliated) Joyn Bio, are developing microbial treatments that enhance plant growth or lower the need for conventional fertilizer (Molteni 2018).

Next-generation materials like fermented spider silk may revolutionize textiles, with both Bolt Threads in California and Spiber in Japan developing clothing made of the product (Feldman 2018). Prized for its high strength-to-weight ratio, spider silk is also being explored as a product for aerospace use via a partnership between the German company AMSilk and Airbus (Hyde 2018). Moving the production of silk to microbes means that the proteins that make up silk fibers can be rapidly customized to fit new applications.

Similarly, there has been a growing interest in the production of animal proteins in microbes, allowing vegan production of meat and other animal products without harm to animals. Products such as the Impossible Burger by Impossible Foods in California use microbiologically produced leghemoglobin protein as a replacement for the hemoglobin proteins that contribute to meat flavor (Wolf 2019). Other companies (including Ginkgo spinout Motif Foodworks) are pursuing the production of a variety of animal proteins to produce vegan dairy foods and other animal-derived products like leather. This approach is also seen as a means to provide high-protein diets more sustainably, given the high-energy requirements for animal-based meat production (Sheikh 2019).

**Conclusion**

It is impossible to predict which of the many applications of synthetic biology will come to define the field as it matures. Unlike all other fields of physical engineering, biology is unique in that it depends on a programmable substrate in the form of DNA. As such, rapid progress has been made on the basis of exponentially improving tools for reading, writing, and debugging biological systems.

It is too soon to know just where and how synthetic biology will evolve, but the stunning diversity of the natural world provides a compelling example of what can be achieved with biology.

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Crucial measurement challenges must be addressed to facilitate the transfer of genome editing technologies into trusted data and products.

A revolution is underway to reengineer the blueprint for life: the genetic code, whose sequence determines identity and function for every living organism. The genome (expressed in DNA base pairs) is the entire complement of an organism’s genetic code and is housed in the basic functional unit of life, the cell.

Genome engineering involves tools and techniques to target a specific sequence in a genome and alter the genetic code (genome editing) or to alter the chemical signatures associated with the genetic code (epigenetic engineering). The technology operates by biochemical principles generally applicable to every kind of cell (Carroll 2014; Kim and Kim 2014).

What Is Genome Editing?

Genome editing aims to generate edited cells that have permanently changed genetic codes and are functional (Doudna and Charpentier 2014; Gaj et al. 2016). The process typically involves the following:

1. Determine a target location in the genome.
2. Design the editing system to bind to the target location, which may be zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), or clustered regularly interspaced short palindromic repeats
The bridge

(CRISPR) with CRISPR-associated proteins (Cas) (Sander and Joung 2014; Urnov 2018).

3. Formulate and deliver the editing system into live cells, where the system finds and binds to the target location in the genome and damages the DNA. This DNA damage gets recognized and repaired by the cell either perfectly, restoring the original genomic sequence, or imperfectly, as one or more bases of sequence are changed, deleted, or inserted (Komor et al. 2017). Genome editing is achieved as a result of imperfect DNA break repair.

4. Confirm whether and where the genome sequence was changed, what sequence change resulted, and the percent of the DNA that was changed.

5. Determine whether the engineered cells are fit for the intended purpose. Most often, genome editing is performed on cells of interest in a controlled laboratory setting (ex vivo editing), which allows the opportunity to thoroughly analyze edited cells before using them. For complex organisms like humans and tissues like the heart or nervous system, editing systems may need to be delivered directly into the body (in vivo editing), in which case the cells edited are already in the organs or tissues, leaving no opportunity to assess whether the cells are fit for the intended purpose before use (Maeder and Gersbach 2016; Yin et al. 2017a).

Applications of Genome Editing

Genome editing is being pursued globally by government, academic, and private sectors to transform medicine and bioscience to enable previously impossible advances in areas such as basic biology research, gene therapy, synthetic biology, novel antimicrobials and antivirals, biomanufacturing, agriculture, and food production (Barrangou and Doudna 2016). In some human diseases, just a handful of incorrect letters in the genetic code or as little as a single incorrect letter at a specific position (e.g., sickle cell disease) of the approximately 6.6 billion-letter human genetic code can cause a serious and/or deadly disease.

Genome editing ushers in the first era of technology where the medical field isn’t limited to solely managing symptoms and treating illness episodes, but where the cells of a patient may be edited to “fix” a disease at the genetic code level. The biomedical field is daring to think and even speak the word “cure” for diseases that once had few or no treatment options (Fellmann et al. 2017; Porteus 2015; Salsman et al. 2017).

The agriculture industry has also begun targeted editing of crop genomes to have more favorable traits, higher yield, and better disease resistance (Mao et al. 2013; Yin et al. 2017b). And there are large efforts in the environmental science community to engineer microbes with new abilities to produce biofuels and act as biosensors (Ng et al. 2017).

The Edit’s in the Details: Challenges and Opportunities for Standards

Concurrent with the global pursuit to leverage existing genome editing systems, there is significant technological innovation taking place to expand capabilities for the high-precision targeting of any genomic sequence to make any intended change in any cell. But crucial measurement challenges must be addressed to facilitate the transfer of these technologies into trusted data and products.

Challenges

An editing process is carried out on many cells at a time—often thousands to millions—but there is little technical control over the efficiency of editing and which sequence changes result. Each cell is a closed system where the resulting edits are independent events.

Technical Limitations

Due to technical limitations on the ability to measure the sequence of individual cells at high throughput, edited sequence confirmation involves a bulk measurement sampling of the genomes from a heterogeneously edited cell pool that may contain both intended and unintended edits even at the target site. In addition, due to biological limitations, particularly for human therapeutics, this heterogeneous pool of cells may be the final product.

The biomedical field is daring to think and even speak the word “cure” for diseases that once had few or no treatment options.
It is also technically challenging to accurately parse sequencing data from bulk analyses because the number of edits detected can range into the tens or even hundreds for a single genomic location. Bioinformatic pipelines to parse these data were benchmarked on what has been observed in nature: only a handful (if that many) of variants are expected to occur at any one location. It is therefore unclear how accurately sequencing analysis pipelines report what is biologically present in a sample.

The type of edit also contributes to detection difficulty. In general, small edits (e.g., one to tens of bases) are less challenging to sequence verify; large edits (e.g., hundreds of bases or more) are technically challenging to reliably detect and sequence verify.

**Off-Target Editing**

A prominent measurement challenge for human therapeutic genome editing is the occurrence of unintended, or off-target, editing, when a sequence change occurs at a site or sites other than the target site (Fu et al. 2013; Tsai et al. 2015). Even if the intended edit was effected at the target site, off-target editing may change the cell in a way that makes the therapy or product unsuitable or unsafe. To assess off-target editing, the entire genome, or at least sites where there is reason to think off-target edits could occur, is sequenced after an editing process.

**Reliability, Accuracy**

There are technical limitations to sequencing the entirety of large genomes like the human genome with sufficient sensitivity to report any off-target edit at any location in the heterogeneous sample. Means of limiting where to sequence for off-target edits are being developed, but there is very limited understanding of their accuracy. Even with reliable sequence data in hand, there’s still the challenge of interpreting the significance of unintended edits and understanding whether edited cells are fit for the intended purpose.

Finally, a genome-edited product must be manufactured. Traditional manufacturing approaches don’t directly translate to this field where the input is live cells, which must be manipulated precisely and still be live and functional at the end of the process (Harrison et al. 2017, 2018). Moreover, the product may be a personalized therapy for a patient, involving a short storage life and requiring small batch manufacturing with rapid distribution and use.

**Opportunities**

Standards play an essential role in the translation and durable adoption of technology (figure 1) (Plant et al. 2014, 2018). Standards for genome editing will support and enhance innovation and technology adoption as well as evidence that new biological understanding is based on sound data and that products generated with these technologies are suitable and safe.

Standards in the form of traceable materials can help increase confidence that a process reliably reports where editing occurred, what edit(s) resulted, and the relative abundance of each edit. For this purpose, traceable material or control samples (a well-qualified series of cells or genomes containing a variety of edits at known relative abundance across the genome) can serve as “ground truth samples” for assessing sequencing methods. These control materials would enable comparability among operators at the same site, operators at different sites or organizations, and sequencing methods.

Standards for datasets and metadata can help enhance the accuracy of sequencing data analysis pipelines, transfer and reproducibility of data, analysis, and data interpretation within and between labs. Shared standard datasets, along with associated metadata detailing the editing and data handling process, will provide a means to benchmark data analysis pipelines, to compare the performance between iterations of both a single pipeline and different pipelines (figure 2). Supporting
these technical standards is the need for standardized definitions of key terms in genome editing to enable clear communication of results both within the field and to regulatory agencies.

The US National Institute of Standards and Technology has launched the NIST Genome Editing Consortium to work across the genome editing community to develop standard and norms toward filling the needs stated above. Standards for the safe and efficient manufacture of engineered cell products will likely require a paradigm shift and disruptive technologies to address the particular challenges of manufacturing living cells or manufacturing genome editing delivery systems for in vivo editing at large scale.

Closing Thoughts

Translating the promise of genome editing into production and medical practice requires robust quantitative assays, accurate data tools, and associated standards and benchmarks to enable high confidence in the characterization of engineered genomes and cells. Steps are being taken to address some of these needs through standards such as physical controls, standard datasets, and a standard lexicon for this field.

Genome engineering technology that is more controlled or not reliant on damaging the genome or changing the sequence at all (e.g., a genome's chemical signature might be changed) is rapidly progressing (Anzalone et al. 2019; Liao et al. 2017; Thakore et al. 2016). Further progress can be made through the development of a suite of tools and technology employing a multidisciplinary approach to address unmet measurement needs such as single cell editing detection and in vivo tracking and monitoring of edited cells once introduced into the environment or a live organism (e.g., in a human for therapeutic treatment).

As genome engineering matures, there will be a need for continuous evaluation of new standards and norms that can support rapid innovation and expansion of this field.

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Should those who program autonomous vehicles pay attention to “trolley cases”?

Why Everyone Has It Wrong about the Ethics of Autonomous Vehicles

John Basl and Jeff Behrends

Autonomous vehicles (AVs) raise a host of ethical challenges, including determining how they should interact with human drivers in mixed-traffic environments, assigning responsibility when an AV crashes or causes a crash, and how to manage the social and economic impacts of AVs that displace human workers, among others. However, public and academic discussion of the ethics of AVs has been dominated by the question of how to program AVs to manage accident scenarios, and in particular whether and how to draw on so-called “trolley cases” to help resolve this issue. Some in the debate are optimistic that trolley cases are especially useful when addressing accident scenarios, while others are pessimistic, insisting that such cases are of little to no value.

We summarize the debate between the optimists and pessimists, articulate why both sides have failed to recognize the appropriate relationship between trolley cases and AV design, and explain how to better draw on the resources of philosophy to resolve issues in the ethics of AV design and development.

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AV Accident Scenarios and Trolley Cases

Autonomous vehicles will inevitably be in accident scenarios in which an accident that causes harm (to pedestrians, passengers, etc.) is unavoidable. Whereas human drivers in these circumstances have very limited ability to navigate them with any sort of control, AVs might be in a position to “decide” how to distribute the harms. It has seemed to many that because with AVs there is some ability to exercise control over how harms are distributed, it is essential to think carefully about how to program AVs for accident scenarios. The question is how to do so?

It has not escaped notice that some accident scenarios bear a resemblance to what are known in philosophy as “trolley cases.” These are imagined scenarios in which a runaway trolley will result in the death of some number of individuals unless a choice is made to divert or otherwise alter the trolley’s course, resulting in some other number of deaths.

In the classic trolley case, the trolley is headed down a track and will kill five people that can’t escape. A bystander has the ability to pull a switch and divert the trolley onto another track. However, on this track there is one person who cannot escape and will die if the trolley is diverted. A similar-seeming scenario involves an AV that is traveling down a street when suddenly a group of pedestrians runs into the street. The only way to avoid hitting them is to take a turn that will result in the death of a pedestrian on the sidewalk.

In another version of the trolley case, a trolley cannot stop and will kill five people unless an object of sufficient weight is pushed in front of it. A bystander has the option of pushing a large person off a bridge and onto the tracks in a way that would stop the train before it kills the five. Again, a case involving an AV might have a similar structure: Perhaps an empty AV has gone out of control and will hit five pedestrians unless another AV with a single passenger drives itself into the first AV.

Trolley Optimism

Trolley Optimism is the view that trolley cases can and should inform how AVs are programmed to behave in these sorts of accident scenarios. The general proposal is that various kinds of trolley cases can be constructed, a verdict is reached about what action or behavior is appropriate in that case, and then that verdict is applied in the case of AVs, programming them to behave in a way that mirrors the correct decision in the analogous trolley case (Hübner and White 2018; Lin 2013; Wallach and Allen 2009).

While trolley cases may be born of philosophy, Trolley Optimism is not confined to philosophy departments (see Achenbach 2015; Doctorow 2015; Hao 2018; Marshall 2018; Worstall 2014). Consider MIT’s Moral Machine project, which has a variety of components. One is a website that presents visitors with different accident scenarios and asks how the visitor thinks the car ought to behave in that scenario. The scenarios involve many variables, testing visitors’ judgments about, for example, how to trade off people and animals, men and women, the elderly and children, and those who obey walk signals and those who don’t.

Discussion of the ethics of AVs has been dominated by the question of how to program them to manage accident scenarios.

While some might see the Moral Machine project as simply a tool for collecting sociological data, others think that the data, in aggregate, should be used to decide how AVs should be programmed to behave in accident scenarios (Noothigattu et al. 2017). Whereas philosophers might endorse a type of Trolley Optimism that aims to determine the correct thing to do in a trolley case and program AV behavior in accident scenarios accordingly, the Moral Machine’s democratic variant leaves it up to the people.

Some Questionable Grounds for Pessimism

Trolley Pessimism is the view that it is a mistake to draw on trolley cases to think about how to program AVs to behave in specific accident scenarios. Different forms of Trolley Pessimism can be distinguished on the basis of what mistake they identify.

Challenges to the Validity of Thought Experiments

One basis for Trolley Pessimism is a distaste for using thought experiments to arrive at conclusions. Sometimes, this is grounded in the idea that thought experiments that philosophers deploy are so idealized and
unrealistic that they are useless for navigating the real world.

We think these sorts of objections rest on a mistaken view of the function and value of thought experiments; we set that aside except to note that a key motivation for Trolley Optimism is that accident scenarios seem to closely resemble trolley cases. If trolley cases are useless for thinking about accident scenarios it isn’t because the cases are too unrealistic to be of any use. At the very least, a plausible basis for pessimism must articulate the differences between trolley cases and AV accident scenarios that prevent reasonable conclusions about what to do in the latter based on judgments about the former.

Disanalogy

Another basis for Trolley Pessimism tries to show that there is indeed some point of difference between trolley cases and the behavior of AVs in accident scenarios that makes verdicts in the former inapplicable to decisions about what to do about the latter. What are the differences between trolley cases and AV accident scenarios that justify this form of pessimism?

Nyholm and Smids (2016) point to several points of disanalogy. For example, trolley cases set aside questions of the moral and legal liability of those who are deciding how to act. The person who will decide whether to divert the trolley, it is assumed, will not be held responsible or liable for whichever choice they make. But these considerations should inform deliberations about how AVs should behave in accident scenarios.

Another point of disanalogy is that, in trolley cases, the outcomes of various decisions are stipulated to be known with certainty, whereas in the case of AV accident scenarios, despite what one may want or intend a vehicle to do, there is some uncertainty about whether the vehicle’s behavior will generate the desired outcome.

Again, we think this is not a plausible basis for Trolley Pessimism, as explained below.

Ways to Address Trolley Pessimism

While it is true that traditional trolley cases do stipulate away issues of legal and moral liability and stipulate outcomes with certainty, there is in principle no reason why thought experiments can’t take these variables into account.

It is possible to develop a case that asks what should be done assuming some particular legal liability regime, enumerating the costs to the agent making the decision. Similarly, a case could be constructed in which pulling a switch has an 80 percent chance of altering the course of a trolley, incorporating deliberations about whether this alters one’s moral obligations. The creators of the Moral Machine might even be invited to build these variables into their cases, collect data about what people think should be done in those circumstances, and then aggregate the data to dictate the behavior of AVs in accident scenarios.

The Technological Basis for Trolley Pessimism: Lessons from Machine Learning

There is a better basis for pessimism, in the very nature of AV enabling technology: machine learning (ML) algorithms.

What Is Machine Learning?

For those unfamiliar with ML algorithms, we contrast them with what we call traditional algorithms. An algorithm is a set of instructions for executing a task or series of tasks to generate some output given some input. In a traditional algorithm the instructions are laid out by hand, each step specified by a programmer or designer. In contrast, ML algorithms themselves generate algorithms, which do not have the steps used to carry out some task specified by a programmer.

A good analogy for some forms of machine learning, namely supervised and reinforcement learning, is dog training. It is not possible to just program a dog to respond to the words “sit,” “stay,” “come,” and “heel” by wiring its brain by hand. Instead, when training a dog, it is common to arrange for situations where the dog will engage in some desired behavior and then reward the dog. For example, a trainer might hold a treat in front of a dog’s nose and then lift the treat into the air, causing the dog naturally to raise its head and drop its back legs. The dog is then rewarded. After many repetitions, the
word “sit” is said right before the treat is lifted. Eventually the dog sits on command, having learned an output for the input “sit.”

For machine learning, a programmer provides an ML algorithm with a training set, a dataset that includes information about which outputs are desirable and which are not. The learner then generates an algorithm that is meant to not only yield appropriate input-output pairs when it is fed inputs that match those in the test set, but to extrapolate beyond the test set, yielding, the programmer hopes, desirable outputs for new input data.

**Machine Learning and Autonomous Vehicles**

Machine learning is a powerful tool. It allows programmers to develop algorithms to solve problems that would otherwise be extremely tedious or impossible.

The AVs likely to be on the road in the foreseeable future will rely on ML technologies; at the very least, machine learning is at the heart of the detection systems used in autonomous vehicles. Those systems take in data from various sensors (radar, lidar, cameras) and translate the data to some output that other AV systems use to drive the car, to maintain its position within driving lanes, to slow when there is a car in front of it but not when there is merely a piece of litter.

The fact that AVs depend so heavily on ML algorithms grounds a case for Trolley Pessimism. To see why, first note that how an AV behaves in any given accident scenario is mediated by how the algorithm that governs its behavior is trained. The ML training set must be organized to achieve the AV’s behavior in a particular accident scenario. For example, to produce an AV that suddenly confronts a scenario where it must swerve and risk harm to its passenger or maintain course and hit a number of pedestrians, such scenarios must be included in the training set and a particular input-output pair marked as desirable.

This is not the only way to achieve the desired behavior; the point is that behavior in particular scenarios is influenced by choices that programmers and designers make about how to train the ML algorithms. These choices involve ethical choices.

**Ethical Choices in Machine Learning**

AV programmers will have to make choices about, for example, what proportion of the training data is dedicated to accident scenarios at all. One programmer might focus on nonaccident or typical driving scenarios, including no data about how a car should behave in accident scenarios. Another might dedicate half the training data to everyday driving scenarios and half to accident scenarios. Let’s imagine these two programmers are on the same team and arguing about what proportion of the training set should be dedicated to scenarios where the car detects itself to be in an accident where harms can’t be avoided. The first programmer argues that the car will very rarely be in those kinds of situations and instead should be trained for the most likely scenarios. The second argues that even if the accident scenarios are rare, it’s extremely important to make sure the car does the right thing! The first programmer counters that if they dedicate enough of the training set to getting certain behaviors in accident scenarios, it could make the car less safe in typical driving scenarios or even put the car into accident scenarios more often!

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**AV behavior in particular scenarios is influenced by choices that programmers and designers make about how to train the ML algorithms.**

Clearly this argument over how to train the algorithm that will help govern AV behavior is an ethical one: it invokes various value judgments and judgments about how those values are implicated in potential outcomes.

It follows from the facts that decisions about how to organize the training regime for AV behavior are ethical decisions and that they mediate questions about how AVs should behave in particular driving situations. Trolley cases do not provide direct guidance about how AVs should behave in accident scenarios, despite any superficial similarities. There are several ways to see why.

Let’s suppose that in the imagined argument between the programmers above, the first programmer is correct, that the algorithms that generate AV behavior should not be based on any data about accident scenarios. That is, after engaging in careful deliberation about relevant values, no accident scenarios or anyone’s verdicts about how an AV should behave in them should inform the
training of ML algorithms used in the AV. The resulting algorithm will still generate behaviors in such scenarios, but the training set won’t have been designed to generate any particular behaviors in those scenarios. In this case, the answer to the question “should programmers try to model the behaviors of AVs on the verdicts of trolley cases?” is clearly “no!” because the programmers have accepted that they shouldn’t be trying to train for accident scenarios at all.

**A Thought Experiment**

Another way to illustrate the point is to recognize the way trolley cases—thought experiments, imagined scenarios used to help test more general principles—typically function in ethical theorizing.

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**Choices about how to design for one scenario are not isolated from design choices for others.**

Let’s imagine we are wondering whether we should accept a principle that we should act in such a way as to maximize the total number of lives saved (holding fixed things like whether the people whose lives are saved are good people, how large their families are, etc.). Someone asks us to consider the standard trolley case. We imagine a train hurtling down the tracks and must decide whether diverting the trolley onto a track that results in fewer deaths is the right thing to do.

Let’s assume we come to see this trolley case as supporting the principle that we should maximize total lives saved. If we think that principle is true, programmers and designers should abide it by when deciding how to train AVs. The Trolley Optimist might think that the above case justifies efforts to ensure that an AV in an accident scenario will not drive into a larger crowd to save a smaller. However, it could very well turn out that abiding by the principle we’ve settled on has the implication that we are not justified in doing so.

To see why, imagine that in the programmers’ debate above both are committed to maximizing lives saved. The first programmer argues that this can be done by avoiding accident scenarios as much as possible and to do that they should not train the algorithm for accident scenarios at all but for how to stay out of them. This might have the result that when an AV is in an accident scenario it does veer into a larger crowd to save a smaller, but given that the programmer’s decision is to program for the whole range of behaviors the car will encounter, they haven’t failed to take into account the lesson of the trolley case; they’ve taken it into account in just the right way. The other programmer might come to agree, seeing that if they were to emphasize a training regime that included more accident scenarios that looked like trolley cases, the AV would end up in those scenarios more often or perform poorly in other driving scenarios, causing additional fatalities. This programmer might see it as regrettable that the best way to maximize lives saved overall, given the decision the design team faces, will produce an AV that veers to kill the five instead of the one in a very narrow range of cases, while still acknowledging that this is the approach that conforms with the principle.

**Conclusion**

To be clear, we are not endorsing any particular view of how AVs should be trained or a particular principle as governing that decision. Our point is that the Trolley Optimist makes a mistake in thinking that the lesson from trolley cases is a lesson for how an AV should behave in a superficially similar case.

The ethical question that designers face is not about the right thing to do in a specific scenario but about how to design for the wide range of scenarios that AVs will find themselves in. Choices about how to design for one scenario are not isolated from design choices for others.

The upshot of this is not pessimism about the need for ethics in AV design, nor that trolley cases are useless for the task. The upshot is that designers and ethicists must be much more careful evaluating the appropriate decision and consider how the technologies at issue relate to the ethical principles and reasoning to be deployed.

We hope this paper motivates a closer working relationship between ethicists and designers of AVs to ensure that the right problems are solved in the right way.

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We use optimization-based and game theoretic techniques to produce robot policies that influence human drivers’ behavior toward safer outcomes in interactions with autonomous cars.

Influencing Interactions between Human Drivers and Autonomous Vehicles

Dorsa Sadigh

Society is rapidly advancing toward autonomous systems that interact and collaborate with humans—semiautonomous vehicles interacting with drivers and pedestrians, medical robots used in collaboration with doctors, or service robots interacting with their users in smart homes.

A key aspect of safe and seamless interaction between autonomous systems and humans is the ways robots such as autonomous cars can influence humans’ actions in one-on-one or group settings. This is usually overlooked by the autonomous driving industry, where the common assumption is that humans act as external disturbances like moving obstacles, or that automation can always help societies without actually considering how humans may be impacted.

Humans are not simply a disturbance to be avoided, and they do not always easily adapt to the proliferation of automation in their lives. Humans are intelligent agents with approximately rational strategies who can be influenced and act in novel ways when interacting with other autonomous and intelligent agents.

In this paper I discuss a unifying framework for influencing interactions in autonomous driving—actions of autonomous vehicles (AVs) that can positively influence human-driven vehicles in large-scale or vehicle-to-vehicle (V2V) interactions. Influencing such interactions can be a significant contributor to the safe and reliable integration of autonomous vehicles.
**Influencing Interactions at Vehicle Level**

We have designed a novel framework for understanding the interaction between autonomous and human-driven vehicles. We model this interaction as a dynamical system, where the state of the environment evolves based on the actions of the two vehicles at each time step:

\[
x^{t+1} = f(x^t, u^t_A, u^t_H)
\]

Here, \(x^t\) denotes the state of the environment computed based on the sensor values at each time step including the coordinates, velocity, and heading of each vehicle in the interaction, and the road and lane boundaries. The set of actions of each vehicle \(u^t_A\) for the autonomous car and \(u^t_H\) for the human-driven car includes steering angle and acceleration.

Our key insight is that the actions of autonomous cars can influence the behavior of human-driven cars on the same road. This can be seen when, for example, a car tries to change lanes: it starts nudging into the destination lane, influencing the cars in that lane to slow down. Similarly, the actions of an autonomous car can result in a human driver changing lanes, slowing down, or speeding up.

Our approach to planning for AV influencing interactions has a few fundamental components. We developed imitation learning techniques\(^1\) to build predictive models of human driving behavior, and designed interaction-aware controllers that model the interaction between a human and a robot as a two-player leader-follower game. Leveraging optimization-based and game theoretic techniques, our work produces robot policies that influence human behavior toward safer outcomes in V2V interaction with autonomous cars (Sadigh et al. 2016a,b, 2017, 2018).

**Human Driver Models**

Imitation learning attempts to learn models of humans by imitating a human expert’s demonstrations to enable robots to act in similar ways. Here, we leverage similar techniques, modeling each human driver as an agent who approximately optimizes her own objective, referred to as a reward function (e.g., a driver’s preferences about avoiding collisions or keeping distance from road boundaries):

\[
u^*_H = \arg \max_{u_H} R_H(x, u_H, u_R).
\]

We assume that \(R_H(x, u_H, u_R) = w \cdot \varphi(x, u_H, u_R)\) represents the human’s underlying reward function and that this reward function is a linear combination of a set of hand-coded features \(\varphi(x, u_H, u_R)\). These features in the setting of driving can include distances between the AV and the edges of the road, lane boundaries, or other cars, including their velocity and direction.

We collect training data in a driving simulator and use them in the form of demonstrations or preferences to learn the parameters \(w\) of the reward function using techniques such as maximum entropy inverse reinforcement learning or active preference-based learning of reward functions (Basu et al. 2019; Bıyık and Sadigh 2018; Palan et al. 2019; Sadigh et al. 2016a,b, 2017, 2018).

**Planning for Interaction-Aware Controllers**

Once we have a predictive human driving model, we can plan for autonomous cars that better interact with humans by being “mindful” of how their actions influence humans. We consider a setting where the autonomous car optimizes for its own reward function:

\[
u^*_R = \arg \max_{u_R} R_R(x, u_R, u^*_H).
\]

Here, the robot’s reward function directly depends on and influences \(u^*_H\), the learned and predicted human behavior (called human policy).

In game theory, this interaction modeling results in a two-player game between a human-driven and an autonomous car. The actions of the autonomous car influence those of the human-driven car, and vice versa. To efficiently solve this interaction game and plan for autonomous vehicles, we approximately solve the game as a Stackelberg (leader-follower) game. Our work results in influencing actions by the autonomous vehicle that are more assertive, more efficient, and in many settings safer. Some of these trajectories are shown in figure 1. Our user studies suggest that autonomous cars that are programmed to be aware of their interactions with humans can achieve tasks such as lane changing or coordinating at intersections safely and efficiently (Sadigh et al. 2016a,b, 2018).

**Influencing Interactions at the Global Level**

Influencing interactions at the vehicle level can be observed in many driving settings—such as changing lanes, merging, or exiting from a highway—and has substantial effects on the larger traffic system (Bıyık et al. 2018, 2019; Fisac et al. 2019; Lazar et al. 2018;
For instance, the presence of a large number of autonomous vehicles on roads can influence the state of traffic—such as congestion, delay, or flow—and hence human drivers’ routing choices.

We now discuss the challenges arising in mixed-autonomy traffic settings where a large number of autonomous and human-driven vehicles interact.

**Equilibria in Mixed-Autonomy Traffic: Altruistic Autonomy**

Traffic congestion has large economic and social costs. The introduction of autonomous vehicles may reduce congestion both by increasing network throughput and by enabling a social planner to incentivize AV users to take longer routes that can alleviate congestion on more direct roads.²

To formalize the effects of altruistic autonomy on roads shared by human drivers and autonomous vehicles we developed a model of road congestion based on a fundamental diagram of traffic (showing the relation between traffic flux [vehicles/hr] and traffic density [vehicles/km]). We considered a network of parallel roads and created algorithms that compute optimal equilibria that are robust to additional unforeseen demand.

² This can be done through pricing schemes or latency management. If, for example, there are two highways to the same destination and one is shorter than the other, drivers will likely select the shorter one, increasing traffic on that route. If a few autonomous cars choose the longer highway, their latency will be lower than that of the congested route—and will also help the latency of the shorter road.

Our results show that even with arbitrarily small altruism, total latency can be unboundedly better than without altruism, and that the best selfish equilibrium can be similarly better than the worst selfish equilibrium. We validate our theoretical results through microscopic traffic simulations and show average latency decrease of a factor of 4 from worst-case selfish equilibrium to the optimal equilibrium when autonomous vehicles are altruistic (Bıyık et al. 2018).

**Humans’ Routing Choice Models**

When users of a road network choose their routes selfishly, the resulting traffic configuration may become very inefficient. Because of this, we consider how to influence human routing decisions so as to decrease congestion on these roads.

We consider a network of parallel roads with two modes of transportation: (i) human drivers who will choose the quickest route available to them, and (ii) a ride hailing service that provides users with an array of AV ride options, each with different prices.

We designed a pricing scheme for the autonomous vehicles such that when autonomous service users choose from their options and human drivers selfishly choose their routes, road use is optimized and transit delay minimized. To do so, we formalized a model of how autonomous service users make choices between routes with different prices versus delay values.

We developed a preference-based algorithm (similar to our work in learning reward functions discussed above) to learn users’ preferences and used a vehicle flow model related to the fundamental diagram of traffic.
traffic. Based on these, we formulated a planning optimization to support the objective of reduced congestion and demonstrate the benefit of the proposed routing and learning scheme (Bıyık et al. 2019).

Dynamic Routing in Mixed-Autonomy Traffic

We are developing a social planner by studying a dynamic routing game in which the route choices of autonomous vehicles can be controlled and the human drivers react selfishly and dynamically to the AV actions. As the problem is prohibitively large, we use deep reinforcement learning to develop a policy for controlling the autonomous vehicles. This policy influences human drivers to route themselves in such a way that minimizes congestion on the network (figure 2).

To gauge the effectiveness of our learned policies, we established theoretical results characterizing equilibria on a network of parallel roads and empirically compared the learned policy results with best possible equilibria. We found that, in the absence of these policies, high demands and network perturbations result in large congestion, whereas using the policy greatly decreases travel times by minimizing congestion.

Summary

We have described our work in planning for influencing interactions in autonomous driving at two levels: (i) vehicle-to-vehicle interaction, in which an autonomous car influences human-driven cars for safer and more efficient driving behavior; and (ii) global-level interaction, in which a large number of autonomous and human-driven vehicles interact in the same traffic network. We design routing decisions for autonomous vehicles that influence humans’ routing choices in order to decrease the total delay of the traffic network for a more desirable societal objective.

Autonomous systems are weaving their way into daily life as robots and the Internet of Things move into homes and smart cities become a reality. Our long-term goal is to develop a theory for modeling and designing the effects of automation and robotics on human decision making, and this work is a first step toward developing efficient robotics algorithms that lead to safe and transparent autonomous systems as they interact with and influence humans and society.

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References


Cryptocurrencies as Marketplaces

Jacob Leshno

Bitcoin was introduced in 2008 as a computer protocol establishing a decentralized system that allows users to hold balances and make transfers to one another (Nakamoto 2008). Computer systems that provided similar services have existed for decades, but required a trusted party to control and operate them. For example, PayPal Holdings Inc. maintains the required computer infrastructure and charges usage fees to fund its activities and make a profit.

Bitcoin Infrastructure and Protocol

Bitcoin is a decentralized system. Instead of having a company that is responsible for maintaining the system’s infrastructure, it is operated by a decentralized network of computers called miners (the term also refers to the people who operate these computers). Much like Uber and Lyft, which allow anyone with a car to provide transportation services in return for compensation, Bitcoin allows anyone with a computer to provide the payment processing infrastructure in return for compensation. It eliminates the need for a centralized infrastructure by creating an open marketplace.

But Bitcoin is unlike Uber and Lyft in that no entity is in control of the marketplace. Uber can change the price paid to drivers, add or remove the option to tip, and charge fees from the participants in its market. In contrast, Bitcoin is governed by its protocol, which no single entity can
change (making changes to Bitcoin is akin to changing communication protocols such as TCP/IP). The computer protocol dictates the rules that govern the system and its implied marketplace, determining how miners are compensated and the fees users pay.

The viability and success of Bitcoin, and other cryptocurrencies that followed (e.g., Litecoin, Ethereum, Dogecoin), require that the protocol establish a functioning marketplace. But cryptocurrencies cannot control the miners who provide the infrastructure, and incentives are required to get miners to follow a desired behavior (Carlsten et al. 2016; Eyal and Sirer 2018). Miners provide their services at will and can withdraw from the system at any time, or try to exploit the system for profit and jeopardize its security (Auer 2019; Budish 2018). Game theory provides tools to understand how miners and users will behave in such an environment and to determine whether the system is secure.

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**Bitcoin’s computer protocol dictates the rules that govern the system and its implied marketplace.**

Since Bitcoin is not integrated with (and does not wish to rely on) other financial services, payments to miners can be made only with the system’s native coin, bitcoin, whose value is determined by financial markets, raising questions from monetary theory (Schilling and Uhlig 2019). These elements and others differentiate cryptocurrencies from traditional computer systems and make them economic objects, akin to marketplaces.

**Monopoly without a Monopolist**

In my work with Gur Huberman and Ciamac Moallemi (Huberman et al. 2019) we study the properties of this marketplace for transaction processing and ask who pays for the costs of operating the platform, how, and how much. We compare the Bitcoin payment system (BPS) with a traditional payment system (e.g., PayPal) and ask whether the decentralized design offers new benefits. (While we focus on Bitcoin’s design, our analysis also applies to other cryptocurrencies with similar design features.)

The system processes transactions in batches called blocks. To ensure that a block is propagated throughout the network before the next one is issued, the protocol limits block size and frequency, limiting the system’s transaction processing capacity. Because of stochastic elements in the system, the system can periodically get congested and transactions can be delayed.

We observe that the blockchain design of the BPS has the following features, which are key elements of its economics:

- Miners can enter or leave the system as they see fit.
- Miners can select the transactions they process and are rewarded with protocol-determined block rewards and transaction fees offered by the users (because Bitcoin’s protocol specifies that block rewards are halved approximately every 4 years, transaction fees will become more important over time, as they will eventually be the only form of payment to miners).
- The system’s transaction processing capacity (that is, average number of transactions that can be processed per unit time) is independent of the number of miners.
- Users choose the transaction fees they pay when their transaction is processed; they may even choose to pay only a minor minimal transaction fee (but when the system is sufficiently congested the delay can be so long that payment is required to get through before a transaction is timed out).

We offer a simplified economic model of the BPS that allows analysis of the implied marketplace based on the following: (i) some users are willing to pay to expedite the processing of their transactions, (ii) miners are profit maximizers, and (iii) miners can freely enter or exit the system.

**Transaction Fees Are Determined in Equilibrium**

We find that the BPS is well described by an equilibrium in which users choose a transaction fee to gain processing priority over other users; miners process the transactions that offer the highest fee, up to capacity. Nobody dictates the equilibrium fee schedule. Transaction fees are set in an implicit auction without any explicit auctioneer.

We offer closed-form expressions for the equilibrium fees and waiting times. We find that total transaction fees
depend on three parameters: maximal block size, congestion or load (transaction arrival rate divided by system’s capacity), and the distribution of user willingness to pay higher fees to reduce transaction processing delay.

When the system is not congested, the fees are low and essentially insensitive to its use—the expected processing delay is similar across transactions. As the system’s use approaches capacity, fees and cross-transaction variation in processing delays rise rapidly. The fee schedule satisfies the Vickrey–Clarke–Groves property: each transaction fee is equal to the externality it imposes by increasing the delay for transactions that offer lower fees.

**Comparison with a Profit-Maximizing Firm**

Pricing under the BPS isstructurally different from the pricing of a profit-maximizing firm. A firm sets a price and denies service to users who are unwilling to pay that price. When the BPS has sufficient capacity, the system can raise revenue without denying service to anybody; users who are willing to bear delays can have their transaction processed even without paying transaction fees.

Because the miners who collectively operate the system compete with each other, they cannot profitably affect the level of fees paid by users. This provides users protection from price increases: even if the system becomes a monopolist (in the sense that users have no alternative payment methods) users will still pay a low competitive transaction fee. In that way, the decentralized nature of the system may provide economic benefits to users.

However, the design has several weaknesses.

- Transaction processing delays are essential to fee generation and therefore to the BPS’s long-run revenue model.
- The amount of infrastructure consumed by the system is determined in equilibrium, and there is no mechanism that ensures an efficient level of infrastructure.
- The amount of energy consumed by Bitcoin has received much media attention. It varies depending on the demand for transactions and the bitcoin-to-USD exchange rate, and the system design does not indicate either a desired level or a way of reaching such a level.

**Design Suggestions**

We provide a design that can partly address these concerns. It modifies a component of the protocol so that instead of maintaining a constant capacity, the protocol scales capacity according to demand (within a feasible region) to maintain congestion at a moderate level. This ensures that total transaction fees and the level of infrastructure are kept at a constant level. Our analysis also indicates that smaller block sizes allow the system to raise revenue more efficiently: a smaller block size allows the system to raise the same amount of revenue with shorter transaction processing delays.

**Governing a Decentralized System**

The limitations of the Bitcoin protocol have motivated much research and the development of other decentralized systems (e.g., Bentov et al. 2016; Chen and Micali 2016; Poon and Buterin 2017). To update such systems, agreement is needed on a new protocol, but without an entity that controls the system such agreement can be difficult to achieve.

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The implied rigidity of the system reduces its ability to react to new circumstances, which is important given the early stage of the technology.

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The implied rigidity of the system can be advantageous to users, who are guaranteed continuation of service at the same terms (with no ratcheting of fees), but it also reduces the system’s ability to react to new circumstances, which is especially important given the early stage of the technology. Game theoretic analysis can shed light on governance issues and help in the design of systems accordingly (Barrera and Hurder 2018).

**Conclusion**

Through a combination of cryptographic tools and economic incentives, Bitcoin and its followers have shown that it is feasible to create a global decentralized system controlled by no one. Services that previously could be provided only by a trusted firm can now be provided by a community coordinated only by a protocol. This allows for new economic models for the operation and funding of such services. The interdisciplinary nature of these systems calls for exciting future collaboration.
References


I propose a “teaching factory,” like a teaching hospital, where engineering students get hands-on professional training and are exposed to needs of the engineering enterprise.

Jyotirmoy Mazumder

Higher education in engineering in the United States has been driven by engineering science since the Second World War, geared toward in-depth understanding of engineering science for long-term benefits. The model proposed by Vannevar Bush, recommending more emphasis on science in education to benefit defense efforts, became the guiding principle for the next 70 years (Bush 1946; Stokes 1997). This emphasis led to extensive scientific and engineering innovation that came out of the American university system, with widespread benefits.

Historical Context

The 20th Century

For the first part of the 20th century, the path from scientific innovation to a commercial product was linear. Scientists were more or less restricted to the pursuit of basic understanding. Engineers would take it from there to search for constitutive relationships to convey the fundamental knowledge to practice. Technologists then developed the technological base needed for industry to manufacture a product.

During World War II, the development—mostly by physicists—of sonar, radar, and the atom bomb changed the paradigm and demonstrated that basic science, when applied toward a given definite goal, can produce and
serve the needs of society in a shorter time compared to what can be achieved through empirical pursuit. During the Cold War, a partnership between the government and higher education institutions led to a research paradigm that encouraged applied science areas, such as engineering, to delve into a more basic understanding of phenomena to accelerate much of the technological development required for national defense.

**Increasing competition in manufacturing from European and Asian countries is challenging the relevance of US higher education in engineering.**

Funding from the US government through various agencies, including the Department of Defense, was the fuel for this engine. But the end of the Cold War, changing security needs, and calls from the general population for a focus on more immediate societal concerns (e.g., the energy crisis) reduced the defense research budget for engineering science. Now increasing competition in the manufacturing arena from European and Asian countries is challenging the relevance of US higher education in engineering.

**More Recently**

One of the downsides of following the physics model was a slow departure of engineering from hands-on experience-based practice. Funding from defense programs accelerated the trend. Other professional degrees such as medicine, law, and architecture require extensive practical experience, whereas engineering education focuses more on scientific theory. As Simon Ostrach (1995, p. 34) put it, “Emphasis on problem solution rather than problem formulation is a deficiency of modern engineering education. Consideration of open-ended problems of importance to industry would enrich the education process.” With the increase in global competition higher education institutions in the United States need to evaluate their role in training the engineer not only to adapt to the changing world (Duderstadt 2008) but also to drive it.

To address the challenge of preparing engineering students for the work world, universities have introduced a rich variety of programs and opportunities.

**Models of Experiential and Hands-on Learning in Engineering Institutions**

The concept of hands-on learning is not new. Aristotle, the founder of empiricism, advocated in *The Nicomachean Ethics* that all knowledge originates in experience and learning by doing: “For the things we have to learn before we can do them, we learn by doing them.” Hands-on (experiential) learning has been integrated in the engineering curriculum in many ways, as illustrated in the following models.

**Cooperative Programs**

Cooperative (co-op) programs, in which industries, research centers, and government “cooperate” with universities to give engineering students practical experience for academic credit, combine classroom learning with practical experience for students in a paid position for 3 to 6 months.

A brief history of co-op programs attributes the vision behind them to Herman Schneider, who “worked his way through school” and “believed that his work experience had given him an advantage upon graduation”; he began the first cooperative engineering program in 1906 “with 12 students in mechanical engineering, 12 in electrical engineering, and 3 in chemical engineering” (Akins 2005, p. 63). The author concludes that “there is no substitute for blending practical application with theory learned in the classroom, and there is no better laboratory than the real world” (Akins 2005, p. 67).

**Global Industrial Internships**

To address the globalized nature of the engineering enterprise, major engineering schools in the United States have international internship programs that give undergraduate students an opportunity to gain invaluable real-world work experience in their field. Such programs include the University of Michigan’s International Minor for Engineers and Engineering Global Leadership Honors Program, University of Rhode Island’s International Engineering Program, and Global Perspective Program at Worcester Polytechnic Institute (WPI) (Mazumder 2008).
Design Projects
Product design degrees are offered at institutions such as Stanford University, Carnegie Mellon, Georgia Institute of Technology, and University of Illinois at Urbana-Champaign. In practicums students conduct projects under the guidance of supervisors from both industry and academia. Senior design projects give students the opportunity to design, invent, build, and use their engineering skills on a product before entering the workplace. Student projects and products may be highlighted in campus fairs and conferences.

NAE Grand Challenges Scholars Program
The NAE Grand Challenges Scholars Program (GCSP) prepares undergraduate students to address 14 important global challenges for engineering. The combined curricular, cocurricular, and extracurricular program calls for each student’s development of “viable business/entrepreneurship competency,” defined as an “understanding, preferably developed through experience, of the necessity of a viable business model for solution implementation.”

Interdisciplinary Spaces
The global classroom formation of multidisciplinary teams and collaborations with companies and agencies is leading to the creation of interdisciplinary spaces. In the University of Delaware’s new Interdisciplinary Science and Engineering Laboratory, classrooms and laboratories are side by side and students easily move from theory to practice.1 And at Drexel University cutting-edge laboratories and research spaces include a 3D printing lab and a Center for Interdisciplinary Clinical Simulation and Practice where faculty and students from multiple disciplines can come together to innovate and work on projects.2

Project-Based Learning
In 2016 the NAE’s Bernard M. Gordon Prize for Innovation in Engineering and Technology Education was awarded to WPI for its project-based engineering curriculum preparing students to tackle global issues through interdisciplinary collaboration, communication, and critical thinking. The program offers a specially designed sequence in which first-year students complete projects on topics such as energy and water; second-year capstones focus on the humanities and arts; junior-year interdisciplinary projects relate technology to society; and senior design projects are done in conjunction with external sponsors, providing relevant experience upon graduation. In 2018 WPI launched its Institute on Project-Based Learning to help other colleges and universities implement project-based learning on their campuses.

Architectural Design Studio
The architecture studio, an American adaptation of the atelier-based training at the École des Beaux-Arts in 19th century Paris (Chafee 1977), offers a teaching model from a design discipline in which the functional and the structural, the social and the technical, must be successfully blended (Kuhn 1998). Such project-based pedagogy is central to the training of architecture students (Kuhn 1998). Design engineers can learn from this model how to incorporate social need with technical need; the former may be anything from waste reduction to a smaller carbon footprint.

Engineering Clinics
In the medical field, “hands-on learning” is an essential part of medical education. By shadowing a physician and through rotations, externships, and the performance of procedures and surgery under supervision, the medical student is prepared for the profession.

With a teaching factory, education can meet industry needs, reduce training costs, and enhance innovation.

Similarly, a few engineering schools are creating “clinics” to familiarize students with real-world engineering problems by seeking problems from industry and working with practicing engineers. Harvey Mudd College’s Clinic Program (Loftus 2013) is a collaboration with industry with sponsorship from industry and funding agencies. These may be steps toward the creation of engineering clinics. But to create professional training comparable to that for medical students, what’s needed is a “teaching factory,” like a teaching hospital.

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1 www1.udel.edu/iselab/
2 http://drexel.edu/virtual-tour/laboratory-tour/
Challenge
Even with this rich variety of hands-on initiatives in the engineering curriculum, a new approach is needed. For engineering education to be more effective for global society and the economy, students need to be trained both to contribute to immediate competitive needs and to develop analytical skills. The information they acquire is not as important as skill in gathering and analyzing it.

Education for professions such as medicine, architecture, and law explicitly entails real-world experience. Medicine has teaching hospitals where students train and practice their skills on real patients. In law school, students intern under judges or participate in university “innocence projects” to free wrongly convicted death row prisoners. In engineering, capstone design courses and other models described above provide similar, but less extensive, experience. Capstone design courses, which are mandated by ABET, often consist of projects that are extensions of faculty research projects.

Teaching factory experience can reduce the need for in-house training provided by companies and thus reduce their costs.

Borrowing from the medical profession, I propose a “teaching factory,” like a teaching hospital, where engineering students can get hands-on professional training and be exposed to various needs of the engineering enterprise. This model will also provide flexibility to design and develop new products to meet global and local challenges.

The challenge for academia is to maintain rigorous academic requirements while serving industry needs and attracting industry partners. With a teaching factory, education can meet industry needs, reduce training costs, and enhance innovation.

The need to explore and develop the practical, real-world preparation of engineering students is well recognized, as evident in studies and workshops of the National Academy of Engineering and others (Bailey et al. 1993; Bement et al. 2016; Duderstadt 2008; NAE 2004), and academics have expressed interest in the concept (e.g., President Vistasp Karbhari of the University of Texas at Arlington; private communication). The question is not whether to do it but how.

The Case for a Teaching Factory
The educational programs and models described above provide students with some exposure to the industrial workplace, but they do not immerse them the way a medical student gets immersed in a teaching hospital. Co-op programs are probably among the best available for making students familiar with real-world problems. But they do not offer students the experience of the process of conceiving an idea and taking the product to market for societal benefit. Industrial internships, real-world projects, and engineering clinic programs also partially expose students to industrial problems and processes.

The timing is right for the NAE to take the lead in this area, which I believe will create a national trend if successful. Factories around the country have closed because of the downturn in US manufacturing industry associated with globalization, and universities may be able to negotiate the inexpensive acquisition of a closed factory to start a pilot project. For example, a closed GM truck plant next to Tinker Air Force Complex (TAC) east of Oklahoma City was acquired by TAC for $1/year with the city’s help (Inhofe 2008).

The benefit to engineering education will be hands-on experience with real quality and time management demands as well as flexibility in addressing societal engineering challenges. I foresee the following benefits of the teaching factory for engineering students:

Teaching factory experience will reestablish engineering education as preparation for a profession. Engineering students, both undergraduate and postgraduate, will have rigorous hands-on professional training, making them ready to take on global competition.

Engineering schools can combine knowledge from other schools and disciplines, such as business and public policy, which are generally needed in any industry. Figure 1 shows that a teaching factory would draw expertise from various schools to provide students with a first-hand view of the total engineering enterprise.

As shown in figure 1, a teaching factory will work with industry to develop, design, and manufacture a product needed by a particular industry. The engineering school will of course provide the technology and manufacturing methodology. An advisory committee
will include industry representatives and faculty members from other relevant disciplines. Students’ products will have to satisfy cost and public safety requirements. Business school faculty can advise on cost marketing. Medical school faculty may provide guidance on public health products and impacts. School of public policy faculty can provide guidance on policy issues. From the school of literature, arts, and sciences students will develop a well-rounded education.

Students will thus be exposed to the entire engineering enterprise of design, development, production, and marketing. In a nutshell they will have experience of the real world before they embark on their career. This can also be the place for an industry to try different concepts of product design and development.

The teaching factory can offer a number of benefits not available through existing programs:

- It will reduce the need for in-house training currently provided by industry and thus reduce their costs and make US industry that much more competitive in the global arena.
- Products created by students in a teaching factory can be marketed at a reduced cost (thanks to lower overhead and “salaries”), thus decreasing some of the need for offshoring.
- Teaching factories can become a source for “in-sourcing” and, again, arrest the growth of outsourcing. With the help of the business school and economics department, students will learn costing of economic analysis and develop in-sourcing skills.

**Concluding Remarks**

A teaching factory will provide engineering students with the professional experience of the entire engineering enterprise, similar to that of medical students during their training.
Acknowledgments
The author thanks Aparajita Mazumder, former director of International Programs in Engineering at the University of Illinois at Urbana-Champaign and University of Michigan, for her valuable input. Important guidance from Diran Apelian of WPI is also greatly appreciated, as is Cameron Fletcher’s editing.

References
I am extremely pleased to see that as of the spring 2019 issue of *The Bridge* a new EES Interface column has been added. This collaboration with the NAE’s Center for Engineering Ethics and Society is an excellent development. It offers thoughtful perspectives, sometimes slightly different from what I have in mind, but certainly worthy of serious consideration.

In the summer 2019 issue Rosalyn W. Berne, addressing the topic of resilience engineering, asks probing questions about the well-being of all citizens in the face of technological challenges. She suggests that “there is a case to be made that social inequality should be considered in engineering design and development,” and she brings to our attention the inequalities that might evolve in such catastrophic situations as hurricanes and electric blackouts. Certainly we are all in favor of engineering efforts to protect the populace from disaster, and I suppose that “needy” people might require extra attention. But the definition of need may vary. Recently I was in a widespread electric blackout in New York City and discovered that, with elevators not working, tenants on the upper floors—the most expensive apartments—suffered more deprivations than those on the lower. Sometimes luxury neighborhoods require more protection in floods or fires than others, or the reverse. There are many interesting ethical/technological problems to consider.

At this particular moment, however, I find myself, along with many citizens—and many engineers—absorbed by a most insidious, widespread source of calamity: our electronic world of communication. From our old friend the telephone to the most dazzling features of the internet, troubles are manifold. As a basic challenge to everyday life, many of the telephone calls that come into my home, and the homes of my neighbors, are criminal acts—attempts to mislead, cheat, or steal. And at our offices, that part of life we call the business world, the situation is even worse.

I’m a civil engineer, retired after a relatively wholesome career in the construction industry, and I cannot believe what I encounter and what I am told by others about the challenges. There have always been hazards in our industry—economic and even, on rare occasion, physical. But nothing as threatening as the world described in an article in *Engineering News-Record* titled “A Match Made in Cyber Hell” (May 8, 2019). “Cyber-criminals,” I learn, “find the construction world a rich phishing ground with fat prey and soft targets.” And from ENR’s annual conference this past June I learn that “Malicious hacking and ransomware are growing threats to the industry.”

Beyond thievery in industry, on the front page of the *New York Times* (August 23, 2019) I find a featured article: “Hackers Cripple Dozens of Cities, Hunting Ransom.” Incredible: municipalities find that their records have been attacked and they are forced to pay ransom to criminals in order to maintain order.

Well, I’m an engineer. How ought I react? An answer comes in a recent issue of *The Bent*: an article titled “Digital Resilience: What You Can Do—Now.” The author assumes a world full of villains and cheerfully advises me to stand up to them, outthink them, “choose not to be socially engineered.” The tricksters are here to stay, and don’t assume you can make them more moral or find others to protect you. Be clever, be alert. “Good luck in your digital pursuits. And change your password—often!”

Oh no, I was born too long ago to outmanipulate today’s clever digital crooks. And I don’t want to be bothered changing my passwords over and over again. In desperation, what inevitably comes to mind? Legal action, of course. Protective legislation. Surprisingly, I haven’t found this concept widely recommended.
Robert W. Lucky, whose “Reflections” column has graced the pages of IEEE Spectrum for close to 40 splendid years, tells the story (November 2019): “No one can argue in favor of unethical engineering, but I do have some concern about who decides what is ethical and how those decisions will be used to control technological evolution.” Mr. Lucky assures us that “having tough problems is good for engineers.” But he gives no assurances about government and the future. I am certainly no wizard; but I am inclined to bring government into the picture sooner rather than later.

There is an ever-increasing need for engineers and scientists to participate in conferences, debates, and activities at the highest levels.

For The Bridge issue of fall 2002, I contributed an article entitled “Engineering Ethics: The Conversation without End.” I pointed out the obvious, that the laws had been changing, and that the very definition of ethical engineering was undergoing change. In the not too distant past, codes of engineering ethics resembled ancient guild rules: Don’t compete for commissions on the basis of price. Don’t advertise. Don’t review a fellow engineer’s work without first getting clearance, etc. Such admonitions might forever be considered professional protocol or professional decorum. But in the 1970s, society, acting through the US Department of Justice and the courts, declared such restrictions to be violations of antitrust laws. This was quite a change, for engineers especially. But change had always been in the air.

In the earliest days of the American republic—the “good old days”—the rule of the land was caveat emptor, buyer beware. Robber barons single-mindedly pursued profit, and a swarm of rascals, exemplified by snake-oil salesmen, plied their wares with little or no restraint. However, as time passed, public will decreed change, and revised interpretations of the Constitution followed. Steamboat ferries had been exploding with terrible casualties, and in 1852, despite objections by powerful senators, Congress enacted a law requiring inspection of the perilous boilers. Railroads had been spreading across the nation, ghastly accidents occurred, then multiplied, and in the 1880s railroad safety regulations were introduced. Objections were raised to illness caused by food and medications; between 1880 and 1906, 103 bills were introduced proposing control of interstate traffic in food and drugs, until finally the Pure Food and Drugs Act was passed and signed by Theodore Roosevelt. The Federal Trade Commission Act was passed in 1914, the Federal Power Commission founded in 1920, the Federal Communications Commission established in 1934, and the Civil Aeronautics Board in 1938. In the 1960s the courts commenced imposing “strict liability” for injuries caused by dangerous products whether or not negligence was involved. As for industrial pollution, its problems have not been resolved, but it has become a subject of legal controversy rather than mainly a matter of ethical integrity as it once was. Finally, starting in 1970, after the first celebration of Earth Day, the floodgates were opened. A proliferation of laws, and the agencies to administer them, was a manifestation of the public will.

“The problems of the Information Age—who should control the Internet and how—are still too new for us to predict their resolution.” That is what I wrote 17 years ago, pronouncing the obvious.

As I write today, Mark Zuckerberg, cofounder and leader of Facebook, has vigorously defended his company’s decision not to fact-check the political ads it accepts and displays, even though the ads are placed on the social network by politicians. At the same time I read in the New York Times that the two sides, Facebook and the publishing industry, “have formed an uneasy truce.” In clarification, Mr. Zuckerberg explains: “If a publisher posts misinformation it will no longer appear in the product.” Oh? I am certainly not the only innocent who doesn’t understand.

As of November 2019 I have no idea if legislation is being considered, although Mr. Zuckerberg has held meetings with people in Washington. And I have no idea who will be active in this arena in the years ahead—financially, politically, technologically, legally. There are the four giant big tech organizations—and many business groups opposed to them. There are political groups, labor groups, lawyers, academics, religious and philosophical groups. And should I add military groups? In many parts of the world they are political giants. Happily, not here, except for technical contributions.
Well, how about engineers? Of course. Clearly there is an ever-increasing need for engineers and scientists to participate in conferences, debates, and activities at the highest levels.

Margaret O’Mara, professor of history, is the author of *The Code: Silicon Valley and the Remaking of America*; an essay adapted from the book appeared in the *New York Times* (July 6, 2019). “Silicon Valley’s story,” she writes, “isn’t just one of freewheeling entrepreneurs and far-sighted technologists. It’s about laws and regulations that gave the men and women of the tech world remarkable freedom to define what the future might look like…. The tech world likes to look forward, not backward. But reckoning with its past is essential in mapping out where it goes.”

Just as I reach the end of my meandering speculations, I come across, of all things, the “Tech and Design Issue” of the *New York Times Magazine* (November 17, 2019). On the cover is the statement: “So the internet didn’t turn out the way we hoped.”

Looking through this wide-reaching compendium I am particularly attracted to the message contributed by Nicole Wong, US deputy chief technology officer during the Obama administration. “Technology regulation is coming,” she states. “Indeed, regulation is here already, and we should expect more of it…. One thing we will need to see is training people to be bilingual in policymaking and technology—placing smart, talented, technically sophisticated people into government.”

What the future holds is far from clear. The entrepreneurs and the politicians are making themselves heard. We engineers don’t want to remain silent. In the spirit of Mark Twain’s *Life on the Mississippi*: “To business now, and sharp’s the word.”
An Interview with . . .

Gary Taubes, Investigative Journalist and Author

RON LATANISION (RML): Hello, Gary, we’re really happy to have this opportunity to talk with you today. I see that you are an aerospace engineer, is that right?

GARY TAUBES: I have a master’s in science and engineering from Stanford.

CAMERON FLETCHER (CHF): Why did you choose a degree in engineering?

MR. TAUBES: I had a physics degree from Harvard with an interest in astrophysics. This was the late ’70s. It sounds naïve 40 years later and I suppose it was, but I wanted to be an astronaut. I thought getting an aerospace degree and then maybe going into the Air Force and becoming a pilot would be a reasonable approach.

CHF: And what happened to that trajectory, those thoughts?

MR. TAUBES: I wasn’t very good at engineering. I was 6’2”, 220 pounds, and played football in college. (That’s something I can’t undo; I worry about all the concussions.) Anyway there didn’t seem to be any real demand for a 220-pound astronaut when you could put up a 150-pound astronaut who was just as smart and talented or smarter. And I lived with some Navy pilots while I was at Stanford and realized that I wouldn’t last very long in that kind of authoritative hierarchy. I had trouble with authority figures, a common theme in my journalism career.

When I finished my degree at Stanford, I looked for a few engineering-related jobs in the airline industry, but nothing panned out. Meanwhile, I’d always had this urge to be a journalist, and particularly an investigative journalist. I applied to Columbia Journalism School and they accepted me.

CHF: I’d say that’s worked out pretty well for you.

MR. TAUBES: Yes, it did. Although when you consider that my schoolmates at Harvard included Bill Gates and Steve Ballmer, success is relative. Steve Ballmer was the manager on my football team. I occasionally try to track him down to see if I can induce him to fund nutrition clinical trials.

CHF: That brings me to another question. What got you started on diet and nutrition? It looks like that was about 15 years ago?

MR. TAUBES: Twenty now. After journalism school, the best jobs I could get were in science journalism because I had physics and engineering degrees from the best universities in the country. I took a job at Discover magazine in New York. I still wanted to be an investigative journalist, but nobody was hiring me to do that. As it turned out, there’s a demand for critical investigative work in science journalism just as there is in any other endeavor. My first two books covered scientific fiascos,

controversies, researchers who did their work poorly and got the wrong answer.

I became fascinated by how hard it is to do good science and how easy it is to screw up, for lack of a more technical term. After I did my second book, on cold fusion, I was still getting guidance from physicists and chemists, superb experimentalists. They suggested that if I was interested in bad science, I should look at some areas of public health because it would live down to my expectations. In particular, they were interested in the question of whether electromagnetic fields from power lines could cause brain cancers and leukemia. The concern was based on the science of epidemiology.

I did a piece for The Atlantic on electromagnetic fields and the science. And much of what I had learned from my first two books, about what it takes to do science right and establish reliable knowledge, was considered a luxury that didn’t have to be done in public health research because it was simply too difficult. The thinking was (is) that they don’t have to do well-controlled experiments or maybe do experiments at all. It’s hypothesis without the test. They can make observations and then conclude from those, because the experimental tests are too challenging, that the hypotheses are likely to be correct because, well, they seem plausible. Then they can give public health guidance because it’s important that they do so. After all, people are dying out there. That sounds extreme but that’s been the reality. I did my first article on this problem for Science in ’94, “Epidemiology Faces Its Limits,” and this has been a primary focus of my career and interests ever since.

In the late 1990s, I stumbled into the nutrition field purely serendipitously. I was working as a correspondent for Science, a glorified freelancer, and asked my editor for a story so I could pay my rent. A new study was coming out in the New England Journal of Medicine, on dietary approaches to stop hypertension, the DASH diet. It had been leaked to Science before publication by a researcher, and I didn’t know that it had been leaked or why.

Typically, the way a reporter will do these stories, particularly as the article isn’t out yet and there’s an embargo, is you get the article in advance, you call the principal investigator, you interview him or her about what they did, then you ask for the names of two or three people who could comment on the study, even though it hasn’t been published yet. You do three interviews, write up the article, get your paycheck, pay your rent, and move on to the next story.

In this case, the article had been leaked to Science along with a list of people to interview, although I didn’t know that. I interviewed the principal investigator at Johns Hopkins, who told me about the research, which shows that you can reduce blood pressure with this dietary approach as much as or more than some blood pressure medications. Then I contacted one of the people on that list, a former president of the American Heart Association. And she refused to talk to me because she said she’d lose her funding if she did. I said that’s crazy, people don’t lose their funding for talking about a diet study in the New England Journal of Medicine! I said, “Can we go off the record, not for attribution? Tell me what it is that bothers you about this study.” But I couldn’t get her to tell me anything.

My next interview was with a fellow who was one of the grand old men of the field. The PI at Johns Hopkins had given me his name. He started yelling at me that there’s no controversy over salt and blood pressure, when I didn’t think I was calling about salt and blood pressure but about this DASH diet trial in the New England Journal of Medicine.
It turns out that the DASH diet lowered blood pressure without reducing salt consumption, so it spoke to the question of whether salt was the cause of hypertension, as we’d all been told. I got off the phone and called my editor at Science and said, “I’m going to write up the story and turn it in because I need my paycheck. But I had a former AHA president refuse to talk to me, and a fellow yelling at me that there’s no controversy over salt and high blood pressure, when I wasn’t calling about that. There must be a controversy over salt and high blood pressure that I know nothing about.”

The question of salt and high blood pressure is one of the most vitriolic controversies in medicine.

I spent the next 9 months investigating the salt–blood pressure research, and it turns out to be one of the most vitriolic controversies in medicine. I interviewed 85 people for this one article for Science—researchers, administrators, basically anyone who ever played a role in influencing how people thought about salt in the diet, from the researchers who did the clinical trials to the laboratory researchers to administrators with the FDA or NIH or USDA or around the world. I’m a little relentless as a journalist because I’m obsessed with what I don’t know and if somebody can tell me something I don’t know I want to talk to them.

RML: What is the current thinking about salt and blood pressure? I’ve always thought they were mortal enemies. Is there some disagreement?

MR. TAUBES: There’s actually little evidence to support that hypothesis. Clinical trials, and there have been many, simply failed to confirm it. But the proponents of the hypothesis convinced themselves it’s true anyway; they still select out the results that support their preconceptions and ignore all those that don’t. So this salt–blood pressure connection has become dogma, nonetheless.

In 2013 the Institute of Medicine did a review on sodium and blood pressure in which they managed to balance the review committee so it wasn’t stacked with the usual biased suspects, and the review concluded that there was precious little evidence to tell people or to insist that industry reduce the salt content in their food. And now they’ve just come out with a new review in which they put together a typically biased panel and it returned to the conclusion they’d been espousing all along. And, of course, the reason for the new review is because the folks who had been fighting this battle for the past 40 years, the ones who believe dogmatically that salt leads to high blood pressure, found the unbiased perspective unacceptable. They believe there’s little more important they could do for the public health than to get people to avoid salt.

CHF: What was the genesis of that contention that salt was associated with hypertension?

MR. TAUBES: If you eat more sodium in the short term your body works to maintain a sodium balance in the circulation. That’s why you get thirsty: your body works to increase the water content to keep the sodium concentration stable; that increases blood pressure in the short term. That much is clear: you can definitely increase your blood pressure in the short term by having a large dose of salt. Then you make observations in populations: those that ate higher-salt diets maybe had higher blood pressure than populations that didn’t. So the hypothesis, based on this observation, is that sodium raises blood pressure in a chronic sense. But in longer-term trials the hypothesis fails the test. You read the papers, it bordered on misconduct how these researchers interpreted their results: negative trials interpreted as positive because they believe what they believe.

I actually printed out a stack of the key studies—about a foot high—and sent them for review to three epidemiologists I’d met over the years who I thought were good scientists and critical thinkers. Importantly, they’d never been involved in the salt debate so they had no bias on this. My interpretation was based on their reviews—very critical—as much as anything.

As I was doing this, one of the people I interviewed at length was that fellow who yelled at me that there was no controversy over salt and blood pressure. This guy was one of the worst scientists I’d ever interviewed—and remember I had done an entire book on cold fusion that was called Bad Science. This guy was clearly in the

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2 Now the National Academy of Medicine.


bottom five. He took credit not just for getting Americans to eat the low-salt diet we’d been eating but the low-fat diet we’d all been following.

After I got off the phone with him I called my editor at *Science* and said, “One of the worst scientists I’ve ever interviewed just took credit for getting us to eat low-fat diets. Everything I know about science tells me that bad scientists never get the right answer. Nature just isn’t that kind. So if this guy, as he claims, was involved in any substantial way in the low-fat diet movement, there’s probably a good story in that, too.”

When I finished the salt piece, which won a major science journalism award, I turned to dietary fat. I interviewed about 140 people for that article, spent an entire year on it. Won that same major science journalism award. The science behind the dietary fat dogma was as bad as the salt science. Again, it was an interesting hypothesis that was tested at length and simply didn’t survive the test. But the tests are very expensive and if you convince the NIH to let you spend $150 million on a test and you get a negative result, that’s considered a waste of money. So the NIH administrators also didn’t like to admit these trials had failed to confirm their hypotheses and assumed instead that they did the trials incorrectly.

RML: What made it bad science, Gary? Was it because the analysis of the data collected was not straightforward or not properly handled?

MR. TAUBES: This is the book I want to write. To define bad science, you have to establish what good science is. Richard Feynman put it as well as anyone: “The first principle [of science] is that you must not fool yourself—and you are the easiest person to fool.” Another way it’s described is science as institutionalized skepticism.

Let’s say you do a clinical trial or an observation and you get a result: there’s almost an infinite number of ways you could misinterpret that result or screw up the measurements. So the first thing you do is discuss the results tentatively. Good scientists will always discuss their conclusions tentatively because they know, as Feynman said, that there’s a high likelihood that they’re wrong. Even when they can’t imagine how they could possibly be wrong, there are likely to be people who can and one of them is probably right, because there’s always an infinite number of wrong answers for every right answer.

CHF: Isn’t this part of the argument for replicability?

MR. TAUBES: Absolutely. But when you’ve spent $150 million on an experiment, as I said, it’s hard to convince Congress to give you another $150 million to replicate it. And it needs to be replicated by an independent group of people who are not invested in the hypothesis. And remember, a negative result in this field is considered a waste of money. So if you find that your hypothesis of prevention is wrong—‘Hey, it turns out low-fat diets don’t make us live longer’—that’s considered money poorly spent. In a drug trial a randomized placebo-controlled trial is necessary to be able to correctly interpret any effect you think you see. But in nutrition studies, you can’t do placebo controls: a low-fat diet doesn’t look or taste like a high-fat diet. The participants know if they’re on the low- or high-fat diet. The nutrition field responds to these challenges not by being even more tentative in their interpretation of the data, but by lowering their standards of what they think is necessary to establish reliable knowledge. They don’t care anymore that they can’t do blinded trials or trials with a placebo control.

Good scientists always discuss their conclusions tentatively because there’s a high likelihood that they’re wrong.

One reason for doing the experiments is to get the public to change its behavior, right? If you think salt causes high blood pressure, you want the public to eat less salt, you want the industry to put less salt in food. You can’t be tentative; you can’t say, “We kind of think that salt raises blood pressure. And we kind of think that you should spend the rest of your life eating a bland low-salt diet and if you do you might live a little longer than you would otherwise.”

The numbers, for instance, suggest that if you cut your saturated fat content in half, the probability is that you’ll live a few weeks to a few months longer than otherwise. One of the letters I got in the course of my research was from a researcher who did this assessment at the behest of the Surgeon General’s Office. When he got the results and wrote them up, the Surgeon Gen-
The BRIDGE

General’s Office tried to prevent JAMA from publishing his study because his conclusion was that cutting back on saturated fat would only extend your life by this trivial amount. And probabilistically, as he pointed out in this letter to the surgeon general (which he shared with me), it’s not an extra month on your honeymoon, it’s a month at the very end of your life.

RML: In the work that I’ve done and as a practicing engineer, I always take the position that nature is consistent. I’m a materials engineer, and when I put materials into an engineering system and that system is placed in service, sometimes there’s a failure, and it’s usually because the service environment is aggressive to the materials of construction. That’s where nature is consistent. If I expose stainless steel to high-temperature chloride, things that are not good will occur.

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**People are still being told to eat low-fat, low-salt diets and yet we have obesity and diabetes epidemics that coincide with that dietary advice.**

That phenomenology is inviolate. Nature will always provide the same result. Understanding it mechanistically or from the point of view of causative factors, that’s where the debate comes in—you may have 100 researchers with 100 different ideas trying to interpret a simple phenomenon.

But in the case of nutritional issues like salt, is nature consistent? And if it is, is it just a matter of interpretation? Why is there a controversy?

**MR. TAUBES:** Among other things, people are still being told to eat low-fat, low-salt diets and yet we have obesity and diabetes epidemics that actually coincide with that dietary advice.

The dogma has been accepted, but I think it’s based on bad science. The term that physicists use is “pathological science,” coined by the Nobel Laureate chemist Irving Langmuir, who gave a famous lecture at IBM in 1953 on what he called “the science of things that aren’t so.” It’s not fraud or misconduct; it’s where people have a lack of understanding about how easy it is to get the wrong answer, to be misled by threshold interactions or subjective phenomena. That’s how Langmuir phrased it.

The same thing happens in nutrition and public health. On one level, science is a very slow process, and it’s supposed to be a critical exchange of information in which you want your colleagues to explain to you, when you present a new result, all the possible ways you could have misinterpreted it or screwed up (because assuredly you did). You want them to help you realize that before you go public and embarrass yourself. But in nutrition and public health the argument is that people are dying and we have a moral obligation to act as quickly as we can to save lives.

So if you believe your hypothesis is correct, and you get any confirmation from observations and experiments, then you must tell people such that they can act on it. And then if the science should change—and this is what public health administrators told me—“we’ll just change what we tell people.”

But what these public health authorities don’t realize is that this process won’t allow the science to change. When studies then suggest that the public health guidelines are wrong, the proponents of the hypothesis refuse to accept it. They see what they want to see in the data to convince themselves that they were right all along. This is a paraphrase of what Francis Bacon wrote 400 years ago, when he argued for the experimental method in science. It was true then. It’s true now.

RML: But wouldn’t it be a straightforward thing to conduct a clinical trial in which a certain number of people eat a high-salt diet and another group eats a low-salt diet? Then you collect, over a period of years, some indications of whether that’s beneficial or not. What am I missing?

**MR. TAUBES:** Clinical trials were done. They’re relatively easy with high salt versus low salt. But people still know if they’re eating a high-salt diet or not, and you’re going to get the biases that come with that. And you can’t do these trials for decades, although chronic diseases take years to decades to manifest themselves.

What you want to know is not just whether salt raises blood pressure but whether that salt-stimulated

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6 In the Novum Organum, 1620 (https://oll.libertyfund.org/titles/bacon-novum-organum).
elevation in blood pressure causes chronic disease. The clinical trials that were done ran from months to a year or 2. They showed a slight elevation in blood pressure on the high-salt diet; depending on who is doing the meta-analysis, it might be 3 or 4 millimeters of mercury (with hypertension, blood pressure is significantly higher than that). But you can’t run the study long enough to see whether the low-salt diet prevents heart attacks or strokes because that takes far more than a couple of years.

The meta-analyses of these studies show that, on average, a high-salt versus a low-salt diet leads to a difference in blood pressure of 3 or 4 mm of mercury. If you believe that salt causes high blood pressure, you say, “Look, it elevated blood pressure. That means we should all eat low-salt diets.” If you don’t believe it or you’re skeptical, you say, “Look, the elevation in blood pressure is trivial for a significant reduction in salt that we’re never going to achieve in public health anyway. So let’s spend our limited public health currency on something more important because this clearly isn’t.” The result is a polarized environment in which the skeptics, who are the minority, are seen as irresponsible.

Moreover, the skeptics tend to leave the field. After I did my article for Science, the NIH had a symposium to discuss the science prompted by my work. The three epidemiologists to whom I had sent that stack of papers for review attended the symposium and gave their critical assessment of the data. But then they left and went back to what they were doing before. They didn’t want to spend their precious time kvetching about bad science on salt. (That was my job.) But the people who, 20 years ago, believed that salt is a killer never stop believing it. They stay in the field and continue proselytizing.

I left the field, too; I didn’t want to write about salt and blood pressure my whole life. Now there’s virtually nobody left to fight the “pro science” argument. And when young reporters come along and write about salt, they don’t see any reason not to trust the “experts,” who are the ones who have been telling us to avoid salt for so long.

RML: Much of your writing today is focused on other aspects of nutrition and dietary issues.

MR. TAUBES: Yes. After I did the dietary fat story for Science I started talking to the New York Times Magazine and we decided I would write an article on the likely causes of the obesity epidemic. This was back in 2000 and awareness of the epidemic was relatively new.

What was clear was that the prevalence of obesity in America jumped in the 1980s. I wanted to know why. The result of my research was a relatively infamous cover story for the New York Times Magazine, headlined “What If It’s All Been a Big Fat Lie?,” the “it” being the idea that eating fat makes us fat. The cover was a Porterhouse steak with a pat of butter. The article led with the idea that if the medical community had some kind of “find yourself standing naked in Times Square” nightmare, it was that the low-fat dogma was wrong and Robert Atkins, of Atkins diet fame, was right.

That article got me a large advance to write the book I wanted to write—although I had no idea what I was getting into. I spent the next 5 years working on it. The internet had come along and made it possible to do what would have been a lifetime’s worth of research in 5 years. You didn’t have to spend 30 years buried in the stacks at some Harvard library. Among other things, I eventually amassed probably one of the largest private libraries in the world on obesity.

The gist of this book was that in the post–World War II era, obesity and nutrition researchers settled on a couple of hypotheses of nutrition and health that seemed obvious—and were wrong. One is that we get fat merely because we eat too much, that it’s a behavioral problem, not a hormonal regulatory issue. The other is that dietary fat is the evil in our diet.

Obesity and nutrition researchers settled on a couple of hypotheses of nutrition and health that seemed obvious—and were wrong.

While they were coming to these conclusions, researchers ignored copious evidence that obesity is the result of a hormonal regulatory defect in fat storage and metabolism, and that the hormone that dominates fat accumulation in the human body is insulin, which we secrete in response to the carbohydrate content of our diet. And there was a conventional wisdom until the 1960s that carbohydrates—bread, pasta, potatoes,
sweets, beer—were fattening. One of my favorite quotes is from a 1963 British Journal of Nutrition article by one of the two leading British dietitians; the article begins, “Every woman knows carbohydrates are fattening.”

Between the 1950s and 1980s, though, our public health authorities transformed the “fattening carbohydrate” into the “heart-healthy carbohydrate as diet food.” Hormonal regulatory thinking about fat accumulation was replaced with the idea that people get fat just because they eat too much and it’s a behavioral issue. The research became dominated by psychologists and psychiatrists, trying to figure out how to get fat people to eat less, rather than endocrinologists studying the hormones involved in fattening. We ended up with a full-scale national fiasco, and we’re still mired in it.

The implications are profound. We’re told salt causes high blood pressure, but hypertension is associated with obesity, diabetes, heart disease, and stroke, and not just in individual patients but in populations. When populations go from eating their traditional diets to the Western diet, they get obese and diabetic and they develop heart disease, cancer, hypertension, all simultaneously. It’s a well-documented phenomenon around the world.

So, while American researchers were trying to answer the question “Why do we have so much heart disease in America and how do we stop all these fat people from eating so much?,” British researchers had developed an alternative hypothesis that all these chronic diseases of Western diets and lifestyles—obesity, diabetes, heart disease, stroke, hypertension, and a dozen others—are driven by the carbohydrate content—the quality, not the quantity—and the sugar content particularly.

**RML:** Well, here’s another question. When I travel in Japan, I’m always amazed at how much thinner they appear. They have a diet that’s quite different from a Western diet. How does that factor into all this? They do consume a lot of fish.

**MR. TAUBES:** The Japanese actually have an interesting role in this. Death rates from diabetes, from about the Civil War to the 1920s, increased in some American cities 15-fold. Diabetes was virtually nonexistent before the Civil War. But by the 1920s public health authorities were saying, “Look, this explosion of diabetes coincides with the creation of the sugar-sweetened food and beverage industry.” The chocolate, candy, and ice cream industry from the 1840s, soft drinks in the 1870s, 1880s—by the early 1900s Coke and Pepsi were everywhere, and Dr. Pepper. By the 1920s diabetes experts and public health experts were saying that the prime suspect for this epidemic is sugar.
But Elliott Joslin, the leading authority on diabetes in the country, didn’t believe sugar was the cause because the Japanese ate a high-carb diet and had very low rates of diabetes. Joslin didn’t understand that sugar is metabolized differently than rice. Rice breaks down into glucose; sugar breaks down into glucose and fructose; fructose is metabolized in the small intestine and liver; glucose in virtually every cell in the body.

**RML:** The Japanese have a low-fat diet compared to Western diets?

**Mr. Taubes:** They do.

**RML:** And do they have the same incidence of coronary and other problems?

**Mr. Taubes:** In the 1930s the Japanese were used as a reason to say that sugar doesn’t cause diabetes. Then in the 1950s and 1960s, driven by University of Minnesota nutritionist Ancel Keys, they were cited as a reason to argue that fat was the cause of all these diseases of civilization because they eat a low-fat diet high in carbs and they don’t get fat or diabetic and their heart disease rates were very low. But the obvious suspect, to me anyway, is that the Japanese were also eating a very low-sugar diet.

The Japanese are one of the many populations that, when they transitioned to a Western diet, as in all of Southeast Asia, see a rise in obesity and diabetes. You see the same nutrition transitions in populations like the Maasai, who lived on milk and meat. They didn’t have obesity and diabetes until they transitioned to a Western diet. It’s the same thing with the Inuit, who lived on walrus and caribou and seal and fish and didn’t eat carbs at all. And with Native Americans, whether they’re Plains Indians living on buffalo or Southwestern agriculturalists. Until these populations eat a Western diet you don’t see obesity, diabetes, heart disease, or anything else. (And, yes, you often don’t have Western doctors around to diagnose them, but it was a common observation nonetheless.)

When you look at the regulation of fatty acid metabolism and storage in the human body, it turns out that insulin is the primary driver of fat accumulation. The fructose in sugar and the glucose from these easily digested carbohydrates raise insulin levels, albeit by different mechanisms. This is textbook medicine, but it’s rarely if ever considered relevant to obesity. I discuss why in my books, although I still can’t believe it.

**RML:** One of the things I imagine our readers will wonder is, What would Gary Taubes say a healthy person should eat?

**Mr. Taubes:** I’m working on a new book that tries to put all this in context. Part of the problem is the idea that we get fat because we eat too much, which is the way lean people think about obesity. Lean people think, ‘I’m lean. I don’t eat a lot of food.’ And then the natural conclusion is ‘I’m lean because I don’t eat too much, and if fat people just ate in moderation they’d be fine, too.’ But for those of us who are predisposed to put on fat, we get fat even when we eat in moderation. We can’t eat what lean people eat. That’s where the idea that carbohydrates and sugars drive fat accumulation comes in. We have to keep our insulin low, and the way to do that is to avoid carbohydrates and replace those foods with fat—i.e., Atkins, or keto, as it’s now called. That’s why this is a controversy, because these low-carb diets tend to be high in fat. You have to replace the carb calories and you do it with fat because that keeps insulin low. So we end up with a diet with which people have ethical issues. It tends to include animal products, which are nutritionally ideal combinations of protein and fat. And for 50 years we’ve been hearing that this way of eating will kill us. But if you want an insulin-lowering diet, you replace the carbohydrates not with lean protein, like skinless chicken breast, but with fatty foods and then you get the calories from fat, which is the one macro nutrient that does not stimulate insulin secretion.

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**For the past 50 years physicians and dietitians have been told to prescribe diets to their patients by hypothesis.**

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In Michael Pollan’s *In Defense of Food*, he gives his famous mantra, “Eat food, mostly plants, not too much.” The problem is that for those of us who tend toward obesity and diabetes, “not too much” is meaningless, because we get fatter even when we’re consciously trying to restrict how much we eat, and mostly plants is probably wrong, because plant foods tend to be carbohydrate rich.
There’s one thing I mention in my new book, which I wish I could take credit for but can’t. For the past 50 years physicians have been confronted with this conflict: They’ve been told and dietitians have been told to prescribe diets to their patients by hypothesis: eat a low-fat, low-salt diet, which will keep your LDL cholesterol and blood pressure low, and you should live longer than if you eat otherwise. That’s the hypothesis. But they have no way to know if it’s true, and particularly not for a specific patient, even if they think they have reason to believe it’s probabilistically true. Even if the patient lives to be 100, they don’t know if the diet did that or not. We’re not privy to that information. And the flip side is that patients on the low-carb, high-fat (keto) diet get healthier: their blood pressure comes down, their blood sugar gets under control, they lose weight relatively effortlessly without hunger. So we’re dealing with diet by hypothesis vs. diet by clinical observation and that observation is a powerful one. Moreover, clinical trials are now demonstrating that patients with type 2 diabetes who eat this way can get off all their diabetes medications.

I took one engineering course as an undergraduate at Harvard, systems operations or some such. I can’t remember who taught it, but he would end every few lectures with the comment, “You pays your money and you takes your chances.” On some level, that’s what I’m arguing with diet: you eat the diet that makes you healthier, and you takes your chances on the long run. People will lose dozens or 100 pounds eating low-carb, high-fat foods and their doctors and friends will try to deter them by saying, “You’re going to kill yourself eating all that fat, all that bacon!” But while they eat that way, it’s clear they’re healthier. Are they going to live longer? Well, you pays your money, you takes your chances. Everything is a risk. If you do the low-fat diet, that’s a risk too. Your doctor just isn’t properly communicating all the possible risks.

Studying what happens when researchers get the wrong answer tells you a lot about what it takes to establish the right one.

Iq took one engineering course as an undergraduate at Harvard, systems operations or some such. I can’t remember who taught it, but he would end every few lectures with the comment, “You pays your money and you takes your chances.” On some level, that’s what I’m arguing with diet: you eat the diet that makes you healthier, and you takes your chances on the long run. People will lose dozens or 100 pounds eating low-carb, high-fat foods and their doctors and friends will try to deter them by saying, “You’re going to kill yourself eating all that fat, all that bacon!” But while they eat that way, it’s clear they’re healthier. Are they going to live longer? Well, you pays your money, you takes your chances. Everything is a risk. If you do the low-fat diet, that’s a risk too. Your doctor just isn’t properly communicating all the possible risks.

RML: This is certainly a familiar concept in an engineering mindset.

MR. TAUBES: Isn’t that one thing engineers effectively do? Manage risk?

In a clinical trial or observational study to assess the benefits of, say, lowering cholesterol through diet, like the famous Framingham Heart Study, they looked at people’s cholesterol at, say, 180 and 150 and then at how long they lived, and then concluded that we should all reduce our cholesterol dramatically. But assuming the numbers are causal—which of course we have no idea—what I want to know is how much longer can I expect to live if I lower my cholesterol by this amount? Isn’t that a reasonable question?

There are two ways to look at it. Maybe everybody shares the benefit and lives 2 weeks to a month longer, or maybe one person hoards the benefit and doesn’t have a heart attack—that’s a bridge that doesn’t collapse when it could. So then everyone else is going on the diet for nothing.

As I was trying to understand what this meant, I ended up talking to people like engineers at JPL studying risk assessment. How do we make sense of this because the data don’t contain the information to tell us what we want to know, which is how much longer am I going to live, or if somebody’s not going to have a heart attack, what are the odds that it’s me?

CHF: That actually dovetails with a question I want to ask you, Gary, which is how your engineering background informs your work.

MR. TAUBES: I think it’s a combination of the engineering and science. These are disciplines that provide immediate (and occasionally tragic) feedback if you’re wrong. What engineering on some level tells you is that failure is probabilistic and we need to do everything we can to understand that.

RML: I’m going to have to sign off, I’ve got to get to a meeting. Gary, thank you so much for joining us today.

MR. TAUBES: It’s my pleasure. Thanks, Ron.

Back to your question, Cameron, it’s hard for me to say because so much of what happened in graduate school led me into science journalism. Then I had the opportunity in my first book to talk and work with exquisite experimental scientists. They have a way of thinking about the world and the universe that is very different from most of us, other than maybe very good
homicide detectives. They want to establish cause and effect beyond reasonable doubt.

CHF: With the areas that you’re researching now, diet and nutrition and the human body, it’s much “squishier.”

MR. TAUBES: I’ve had nutritionists say to me, this isn’t particle physics, every human is different. So it’s incredibly hard to do this research. But you can’t lower your standards of what it takes to establish reliable knowledge because it’s too hard to rigorously and correctly test your hypothesis.

In my first two books I documented people who got the wrong answer and lived to regret it. In the case of cold fusion, they ruined their careers and their reputations. Studying what happens when researchers get the wrong answer tells you a lot about what it takes to establish the right one, how rigorous you have to be and how easy it is to fool yourself. When I moved into public health I found that nobody seems to care, on a profound level.

CHF: That is certainly vividly illustrated in your book The Case Against Sugar.

MR. TAUBES: Yes, and now you read in the paper about this reproducibility crisis. I would call it a sort of systemic pathology in the science. Some enormous amount of what’s published every day in the medical literature is wrong, misinterpreted, irreproducible. Anyone who bases work on those results is going to build their edifice of science on a foundation of cards. And we have no idea how systemic that problem is. One estimate from my youth is that 90 percent of the results published in the physics journals are wrong or meaningless. The process of science is to sift out the 10 percent of the wheat from the 90 percent of the chaff. (That’s quoting the physicist-turned-philosopher-of-science John Ziman.) But it’s probably worse in other fields, because they’re harder to do.

Researchers are supposed to promote their work, to make it look like it’s worth funding, like it has public health or medical implications, because they’re trying to keep the money flowing and get tenure. All of these are completely contrary to the idea that what you’ve just done is very likely wrong and that you’re fooling yourself. Presenting your data as tentatively as possible is actually the best idea because you don’t want to be locked into believing it’s true. Once you are, all the human biases will kick in to make you confirm over and over again something that isn’t true.

CHF: What polemic is next for you?

MR. TAUBES: Well, all my books so far have been about good science and bad science because that’s what I’m interested in. Eventually I would like to write a book called How (Bad) Scientists Think and what to do about it. But we can’t talk about bad science without talking about what science should be.

CHF: How you would characterize effective public health studies?

MR. TAUBES: An effective public health study is a study that is done rigorously enough that we can trust the result and the interpretation of the result to be reliable.

We can’t talk about bad science without talking about what science should be.

Public health tends to work when associated with infectious diseases: Ebola, for instance, or cholera. One of the things we want to do is develop effective Ebola vaccines or treatments, and we know what kind of clinical trials you have to do to establish whether a vaccine works or not. And we can test them in the field and see if they work. With chronic diseases, the argument is the trials take too long and cost too much. But that’s an effort problem.

Think about what’s happened in high-energy physics. A few years ago the Higgs boson was discovered. This is the last remaining predicted particle in the standard model, and the Large Hadron Collider that was used to discover it cost almost $5 billion. It was an international collaboration—money came in from all over the world to build it at CERN, straddling the French-Swiss border. The device included four separate experiments, so results could be replicated in real time. The physics community said, “This question is really important to us at the moment and we’re willing to raise the money and make the effort to answer it.”

If the same effort were put into these nutrition questions, if you spent a billion dollars on the right clinical trials, you could do a pretty good job of it. It might not be good enough, but it would be better than what

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The catch is that you wouldn’t know until after the experiment how you screwed up. This is the unknown unknowns problem. Still, we could do a pretty good job if we’re willing to make that kind of unilateral investment. But that’s not how NIH funds this research. Instead it disseminates a lot of money among thousands of researchers, all working on projects that are completely inadequate to answer any meaningful question.

And, of course, the community shakes off critics, regardless of how credentialed (or not) they might happen to be.

CHF: Being a critic is an important role to play.

MR. TAUBES: Yes. We always need to hear from the people who can point out how we most likely screwed up.

CHF: Presumably, someone plays that role for you.

MR. TAUBES: Yes. A fellow who I thought was the best scientist in the field when I did the research for my book *Good Calories, Bad Calories*—and I interviewed effectively everyone who was still alive who ever did meaningful research in obesity and chronic disease—does it and he has no compunction about being sensitive to my feelings when he reads my work. Francis Crick once said that you have to be able to tell your colleagues exactly what you think about their ideas without worrying about hurting their feelings. If you can’t do that the collaboration will fail. This fellow has no problem with that.

A few years ago, I attended a seminar on childhood obesity and after every talk somebody in the audience raised their hand and said, “That was a brilliant talk, thank you.” There was no criticism at all. No attempt to challenge the speaker on what they had presented. One of the speakers actually suggested that there’s a gene that makes fat people want to eat at fast food restaurants. And nobody raised their hand to say, “Professor, are you out of your mind?” It was clear to me that whatever this was—and I’m still not sure—it wasn’t science. It wasn’t about forwarding our understanding of childhood obesity.

CHF: That argument about the fast food restaurant gene is in the same category as the meteorological “finding” that—and I’m putting this in quotation marks—tornadoes are more likely to strike trailer parks.

MR. TAUBES: Yes, imagine if the field of climate science became based on the trailer park–tornado assumption and 30 years later there are thousands of papers based on this idea that trailer parks somehow attract tornadoes. Tornado movement would be plotted in computer models based on trailer park locations. It sounds crazy, but that’s effectively what happened in nutrition and obesity research.

CHF: That gives me an idea for another polemic for you: climate change.

MR. TAUBES: I’m staying out of the climate change field.

CHF: That sounds like a fruitful topic for you to help people understand.

MR. TAUBES: Maybe so, but when you’re fighting to remain a credible source in a very contentious field, it helps to remain fixed on the problem at hand. For me that’s obesity and the chronic diseases that associate with it.

CHF: What’s the title of your new book?

MR. TAUBES: It’s *The Case for Keto: Rethinking Weight Control, the Science and Practice of Low-Carb, High-Fat Eating*. I’m not wild about putting the faddish word “keto” in the title, but I figure I’ve been making the case for this way of eating since 2002, I should live up to it. The book argues that those of us who put on fat easily simply cannot eat like lean people, so we have to eat and think about it differently. And among other things, we have to stop taking lean people’s advice. It’s not true that what works for them works for us.

CHF: When is your book coming out?

MR. TAUBES: In April.

CHF: Thank you so much, Gary, what a blast. I’m so glad you were able to stay on the phone a little longer. I really enjoyed our conversation.

MR. TAUBES: Okay, terrific. Take care.
NAE Newsmakers

Kevin G. Bowcutt, senior technical fellow and chief scientist of hypersonics, Boeing Research & Technology, the Boeing Company, has been awarded the 2019 Spirit of St. Louis Medal by ASME. It is awarded for meritorious service in the advancement of aeronautics and astronautics.

James J. Collins, Termeer Professor of Medical Engineering and Science, Institute of Medical Engineering and Science and Department of Biological Engineering, Massachusetts Institute of Technology, has won the 2020 Delbruck Prize awarded annually by the American Physical Society. The award recognizes and encourages outstanding achievement in biological physics research. Dr. Collins' citation reads “For pioneering contributions at the interface of physics and biology, in particular the establishment of the field of synthetic biology and applications of statistical physics and nonlinear dynamics in biology and medicine.”

The Nobel Prize in Chemistry 2019 has been awarded jointly to John B. Goodenough, Virginia H. Cockrell Centennial Chair in Engineering, University of Texas at Austin; M. Stanley Whittingham, Distinguished Professor, Chemistry and Materials Science & Engineering, Binghamton University; and Akira Yoshino, Asahi Kasei Corporation and Meijo University, “for the development of lithium-ion batteries.”

Geoffrey E. Hinton, Distinguished Researcher, Google Inc., and Yann A. LeCun, chief AI scientist, Facebook AI Research, and Silver Professor of Computer Science, Courant Institute of Mathematical Sciences and NYU Center for Data Science, will share the 2018 ACM Turing Award with Yoshua Bengio, professor at the University of Montreal and scientific director of both MILA (Quebec’s Artificial Intelligence Institute) and IVADO (the Institute for Data Valorization). They are honored for conceptual and engineering breakthroughs that have made deep neural networks a critical component of computing. Working independently and together, they developed conceptual foundations for the field, identified surprising phenomena through experiments, and contributed engineering advances that demonstrated the practical advantages of deep neural networks.

On November 15 M. Cynthia Hipwell, TEES Distinguished Research Professor, Mechanical Engineering, Texas A&M University–College Station, was recognized with the 2019 Eminent Scholar Award, which is presented jointly by the Aggie Women Network and the Texas A&M Office of the President and honors the outstanding contributions of faculty based on research, scholarship, and service. Dr. Hipwell is well known for her contributions to innovation.

Jay D. Keasling, Hubbard Howe, Jr. Distinguished Professor of Biochemical Engineering, University of California, Berkeley, was selected by the American Institute of Chemical Engineers (AIChE) as its 2019 Doing a World of Good Medalist. The award was presented during the 2019 AIChE Gala December 3 in New York. AIChE honored Dr. Keasling for his groundbreaking and high-impact contributions to resource sustainability and human
welfare, which include an innovative biotechnology-based method for the inexpensive production of the antimalarial drug artemisinin. The award also recognizes his commitment to fostering secure and inclusive educational and working environments for people of all backgrounds.

Robert M. Koerner, director of the Geosynthetic Institute and Harry L. Bowman Professor of Civil Engineering Emeritus, Drexel University, has received the A.J. Drexel Paul Award for Service to Alma Mater, the highest honor for a graduate of Drexel University.

Raymond J. Krizek, Stanley F. Pepper Professor of Civil Engineering, Northwestern University, has been selected for the 2020 OPAL Award in Education for demonstrated excellence in furthering civil engineering education. ASCE's OPAL (Outstanding Projects And Leaders) awards honor civil engineers for career achievements in five categories: construction, design, education, government, and management. Dr. Krizek will receive the award March 13 at the 2020 OPAL gala in Washington.

J. David Lowell, owner, Lowell Mineral Exploration, has endowed the J. David Lowell Field Camp Scholarship Program Endowment. The Geological Society of America Foundation announced the creation of the scholarship, which allows more students access to the unique and critical learning opportunities of first-hand observation in a field setting.

Asad Madni, independent consultant and retired president, chief operating officer, and CTO, BEI Technologies Inc., and Nicholas A. Peppas, Cockrell Family Regents Chair in Engineering #6, have been selected for the 2020 OPAL Award in Education. ASCE's OPAL (Outstanding Projects And Leaders) awards honor civil engineers for career achievements in five categories: construction, design, education, government, and management. Dr. Krizek will receive the award March 13 at the 2020 OPAL gala in Washington.

Nicholas A. Peppas, Cockrell Family Regents Chair in Engineering #6, professor in the Departments of Biomedical and Chemical & Biomedical Engineering, Pediatrics Surgery, Pharmacy, Dell Medical School, University of Texas at Austin, was the 2019 recipient of the Sigma Xi Monie A. Ferst Award sponsored by the Georgia Institute of Technology Sigma Xi chapter. Dr. Peppas was honored for his contributions to research through his efforts to mentor and support several generations of graduate students.

George P. Peterson, independent consultant and former director of materials and manufacturing, Air Force Research Laboratory, was inducted into the Engineering and Science Hall of Fame in Dayton at a ceremony on November 6.

H. Vincent Poor, Michael Henry Strater University Professor, Department of Electrical Engineering, Princeton University, will receive the 2019 ASEE Benjamin Garver Lamme Award. He is recognized for landmark contributions to signal processing, wireless communications, and related fields, and their underlying scientific bases of information theory and stochastic analysis, including fundamental new theories and algorithms that significantly expand the applicability of signal processing technology. He is also being honored as one of the leading engineering educators of our time, whose gifted and creative teaching and mentoring, and inspired academic leadership at Princeton, greatly increased the size, scope, and influence of engineering in liberal arts institutions in the country.

Norman R. Scott, professor emeritus, Department of Biological and Environmental Engineering, Cornell University, was presented the Magnolia Silver Award by the Shanghai government on September 12 at a ceremony in Shanghai. The award, named after the city flower, was established to recognize the contributions of foreigners who have injected a strong vitality to the city and facilitated its economic and social development as well as international cooperation and exchanges.

At its annual meeting in October, four NAE members were inducted into the National Academy of Medicine: Sangeeta N. Bhatia, John J. and Dorothy Wilson Professor, Institute for Medical Engineering and Science and Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology; Deborah S. Estrin, Tishman Professor of Computer Science, Associate Dean for Impact, Cornell Tech; John A. Rogers, Louis Simpson and Kimberly Querrey Professor of Materials Science and Engineer-
The 2019 NAE annual meeting was held October 6–7 at the National Academy of Sciences Building in Washington, DC. This year’s meeting had a record high attendance of more than 900 members, family, and guests.

NAE Chair Gordon England opened the public session on Sunday, reminding members that their election to the NAE carries with it a responsibility of service to the nation, bringing to bear their expertise in addressing critical issues that face the country.

The Hagler Institute of Texas A&M University has announced its 2019–2020 Faculty Fellows, selected from among top scholars who have distinguished themselves through outstanding professional accomplishments or significant recognition. Kathleen C. Howell, Hsu Lo Distinguished Professor of Aeronautics and Astronautics, Purdue University, and Edwin L. Thomas, E.D. Butcher Chair of Engineering and professor of materials science and nanoengineering, Rice University, will be among those inducted at the Institute’s annual gala in February 2020.

The MIT School of Engineering announced the following awards received by faculty members. Sangeeta N. Bhatia, John J. (1929) and Dorothy Wilson Professor, Institute for Medical Engineering and Science, Electrical Engineering and Computer Science, was awarded the Othmer Gold Medal from the Science History Institute on March 8. Arup K. Chakraborty, Robert T. Haslam Professor of Chemical Engineering and director, Institute for Medical Engineering and Science, won a Guggenheim Fellowship on March 4, 2018. Anantha P. Chandrakasan, dean, MIT School of Engineering, was elected to the American Academy of Arts and Sciences on April 18. Elazer R. Edelman, Edward J. Poitras Professor in Medical Engineering and Science, MIT/Harvard Medical School, won the Excellence in Mentoring Award from the Corrigan Minehan Heart Center at the Massachusetts General Hospital on June 18. Karen K. Gleason, associate provost and Alexander and I. Michael Kasser Professor of Chemical Engineering, was honored with the John M. Prausnitz Institute AIChE Lecturer Award on April 3. Paula T. Hammond, David H. Koch (1962) Professor of Engineering and head, Department of Chemical Engineering, was honored with the AIChE Margaret H. Rousseau Pioneer Award for Lifetime Achievement by a Woman Chemical Engineer on June 1; she also received the American Chemical Society Award in Applied Polymer Science on January 8, 2018. Klavs F. Jensen, Warren K. Lewis Professor, was honored with the 2018 John M. Prausnitz Institute AIChE Lecturer Award and, on May 1, 2018, the Corning International Prize for Outstanding Work in Continuous Flow Reactors. Robert S. Langer, David H. Koch Institute Professor, won the Dreyfus Prize for Chemistry in Support of Human Health from the Camille and Henry Dreyfus Foundation on May 14. In 2018, Dr. Langer was named on the 2018 Medicine Maker’s Power List and was also named US Science Envoy on June 18, 2018. Nancy A. Lynch, NEC Professor of Software Science and Engineering, won TDCP Outstanding Technical Achievement Award from the IEEE on April 18. Michael S. Strano, Carbon P. Dubbs Professor of Chemical Engineering, received the AIChE Andreas Acrivos Award for Professional Progress in Chemical Engineering on July 1. Gregory Stephanopoulos, Willard Henry Dow Professor of Biotechnology and Chemical Engineering, was honored with the Gaden Award for Biotechnology and Bioengineering on March 31.
President John L. Anderson delivered his first annual address and articulated his priorities, including the importance of expanding the visibility of NAE programs such as the Grand Challenges Scholars Program, Frontiers of Engineering, EngineerGirl, and the Center for Engineering Ethics and Society. He also laid the foundation for prioritizing membership engagement, through what he called the 4 I’s:

- Identify and inform the frontiers of engineering theory, practice, and policy.
- Increase engineering talent through a strong commitment to diversity and inclusion.
- Instill a culture of ethical and environmental responsibility in engineering.
- Improve capabilities and competencies for complex systems engineering.

He concluded with a reminder of the importance of the NAE’s need for adequate funding to ensure that the Academy can effectively achieve its mission.

This was followed by the induction of the class of 2019. Introductions were made by NAE Executive Officer Alton D. Romig, Jr. The program continued with the presentation of the 2019 Simon Ramo Founders and Arthur M. Bueche Awards. The Simon Ramo Founders Award was presented to Cato T. Laurencin, University Professor; Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering; professor of materials science and engineering; professor of biomedical engineering; director, Raymond and Beverly Sackler Center for Biomedical, Biological, Physical and Engineering Sciences; chief executive officer, Connecticut Convergence Institute for Translation in Regenerative Engineering; University of Connecticut, “for fundamental, critical, and groundbreaking scientific advances in the engineering of tissues, guiding technology and science policy, and promoting diversity and excellence in science.” Roderic Ivan Pettigrew, CEO of EnHealth; Health Science Center and College of Engineering; Robert A. Welch Professor and executive dean, EnMed; Colleges of Medicine and Engineering; Houston Methodist Hospital;
Texas A&M University, received the **Arthur M. Bueche Award** “for leadership at the NIH and for academic and industrial convergence research and education, resulting in innovations that have improved global health care.”

The **Bernard M. Gordon Prize for Innovation in Engineering and Technology Education** recognized Georgia Institute of Technology and Emory University educators Paul J. Benkeser, Joseph M. Le Doux (NAS), and Wendy C. Newstetter “for fusing problem-driven engineering education with learning science principles to create a pioneering program that develops leaders in biomedical engineering.”

Immediately following the awards program, Dr. Romig introduced the two plenary speakers. General **Thomas P. Stafford**, former US Air Force deputy chief of staff, Research, Development, and Acquisition, and astronaut, spoke about “The Apollo Experience.” “Humans Go to Mars” was the topic addressed by the Honorable Charles F. Bolden Jr., former NASA administrator and astronaut.

Monday began with the annual business session for members, followed by the forum on “Human Space Flight: Apollo 50 Years On.” The topics and panelists were “The Apollo Experience”: General Thomas P. Stafford, “Space Shuttle Development and Early Flights”: Captain **Robert L. Crippen**, US Navy (retired), former president, Thiokol Propulsion; “Commercial Space Exploration”: Captain Christopher J. Ferguson, Boeing test pilot astronaut and CST-100 Starliner director of crew and mission systems, Commercial Crew Program, Boeing; “Commercial Space Exploration”: Hans Koenigsmann, vice president, Build and Flight Reliability, SpaceX; “The Space Station Experience”: Sandra H. Magnus, deputy director, engineering, Office of the Secretary of Defense, Research and Engineering; and “The Diplomacy of Space Exploration”: the Honorable Charles F. Bolden Jr. Deanne Bell, TV host and founder/CEO of Future Engineers, moderated the panel discussion and handled many questions from the audience about human space exploration today.

On Monday afternoon members and foreign members participated in NAE section meetings at the NAS Building and Keck Center. The meeting concluded with a reception and dinner dance at the JW Marriott.

The next annual meeting will take place October 4–5, 2020, in Washington. Mark your calendars!
Welcome to the 2019 National Academy of Engineering annual meeting, and a special warm welcome to our newly elected members and their families. For each of our new members, this is a memorable day.

Election to the NAE is emblematic of a highly successful engineering career and you should feel a great deal of satisfaction and pride in your election. However, as you heard in your orientation, election carries with it your personal commitment of service to the nation. You can be instrumental in promoting a vibrant engineering profession and by adding your expertise to address critical engineering issues facing the nation.

In my first address to the membership, shortly after my election as chair in 2016, I said, “My goal as chairman is to provide sustainable funding for the Academy as the means to continuously improve the engineering profession and the standing of the profession in the world. Engineering is changing society and this organization needs to be leading that change.”

The next year, in 2017, I announced that the NAE Council approved a major fundraising campaign with the kickoff scheduled for the following year. My heartfelt thanks to all of the members who provide financial support, especially to all of our Einstein, Golden Bridge, Heritage, and Loyalty Society members.

Nonetheless, the Academy continues to fall far short from achieving its potential—at a time when engineering leadership is critically needed.

As many of you know, the Academy does not receive a federal allocation. The NAE relies on philanthropic contributions to fund our yearly operations and programs. The problem is that fluctuations in requests for advice are not predictable and contributions vary each year. It is therefore very difficult for the Academy to plan for, initiate, and execute any new requests.

To address these issues, I announced at last year’s annual meeting that Academy leadership approved the next phase of a fundraising campaign. Today, thanks to Dan Mote, John Anderson, the council, and staff, the NAE is active in the advanced gift phase of the most ambitious fundraising campaign in its history: the Campaign for the NAE, Leadership in a World of Accelerating Change.

The goal is to raise $100 million to promote a more vibrant engineering profession by strengthening and expanding our signature programs and by providing additional funding to better address pressing engineering issues facing the nation.

For example, how can the Academy help rid the oceans of trash, provide clean water for the world’s populations, provide inexpensive and persistent energy, and guard against rising water levels? The NAE cannot directly solve problems like this but with adequate unrestricted funding it can convene the world’s engineering experts and provide unbiased, fact-based advice for the way ahead.

My expectation for this coming year is that all the continuing hard work of the past three years by the
Welcome to the National Academy of Engineering 2019 annual meeting. It is my honor to address this very distinguished gathering for the first time as president of the NAE. I look forward to serving this extraordinary institution, and I thank the membership for entrusting me with this important responsibility.

I thank Dan Mote for his excellent leadership as president for the past six years, and I look forward to continuing to work with chair Gordon England and the members of the NAE Council and NAE staff. We have many significant initiatives underway, and we will continue to explore ways to meet the NAE’s mission to advance the wellbeing of our nation by promoting a vibrant engineering profession and engaging the expertise and insights of accomplished engineers like those of you being inducted today.

I’ll begin with some background about the NAE and its sister academies. President Lincoln signed a congressional charter that created the National Academy of Sciences in 1863 because he saw an urgent need for the government to have a source of independent scientific advice. The National Academy of Engineering expanded that role in 1964 with its creation as a sister organization to the NAS, and in 1970 the Institute of Medicine—which recently became the National Academy of Medicine—was established.

The National Research Council (NRC) was formed in 1916 “to bring into cooperation government, educational, industrial, and other research organizations” to advance science, aid development of American industries, strengthen national defense, and promote national security and welfare. We call our overall organization the National Academies of Sciences, Engineering, and Medicine (NASEM).

Along with that background, I should point out that the Academies are not part of the government, and this is by design. Our work is independent—there is no federal line item for us, or any Congressional appropriation, as many may think. We are dependent on sponsors, donors, and volunteers to do the vital work of the NAE.

Election to the three Academies is a high honor but, like a university commencement (which today’s induction will resemble), it is just the beginning. Your participation in NAE and NRC activities is crucial. We need your expertise as well as your bold and creative ideas.

Let me highlight just a few of the things we’re now doing.

I recently returned from a remarkable event in London, the Global Grand Challenges Summit. It was the 4th in a series that’s collaboratively organized by the NAE and similar academies in the UK and China. The series was inspired by the NAE’s Grand Challenges for Engineering, 14 goals spanning sustainability, health, security, and joy of living, outlined in a highly influential 2008 NAE report.

These summits, which take place every two years, are aimed at sparking progress in addressing
the challenges by inspiring future engineering leaders and promoting international cooperation on our shared visions. At this year’s event,

- There were more than 30 speakers and almost 1,000 attendees—nearly half of which were students, from numerous countries—and lots of networking opportunities.
- There was a student business plan competition and a collaboration lab in which mixed-country student teams brainstormed solutions to important problems; 300 students participated—100 each from the US, UK, and China.

We hope many of the connections made there will continue beyond the summit and we will work to facilitate that. The next Grand Challenges Summit will be held in Beijing in 2021.

Another initiative inspired by the NAE Grand Challenges is the NAE Grand Challenges Scholars Program, aimed at equipping future engineers to tackle the biggest issues of our time. It focuses on five competencies: talent through research, working across multiple disciplines, multicultural experiences, entrepreneurship, and social consciousness.

Launched in 2010 at just 3 schools, now there are almost 80 active programs and a similar number in development. A dozen of those are outside the United States, with more on the way.

It’s worth noting that more than half the students in the Grand Challenges Scholars Program are women, and many more come from underrepresented groups. In addition to building change makers, the program is helping to meet the important goal of making our profession more diverse and inclusive.

**EngineerGirl**, aimed mainly at middle schoolers, was launched as a resource website in 2001. It has grown to include a number of interactive programs with opportunities for girls. For example, a Gallery of Women Engineers features profiles of more than 300 women in different fields of engineering who volunteer their time to answer questions for students. And this year we started a feature with multiple perspectives on engineering-related questions of particular interest to young girls.

Since 2003, EngineerGirl has had a yearly writing contest asking students for their ideas on various topics. Last year we received over 14,000 submissions. And the new Ambassadors Program encourages high school girls to reach back and introduce younger girls to engineering through ambitious projects that include afterschool tutoring, summer camps, workshops…and a Girl Scouts Expo that resulted in 16 new girls’ robotics clubs!

I wish to highlight one very impressive student from this pool, Gitanjali Rao, who is a two-time writing contest prize winner and was the keynote speaker at the GGCS in London. Gitanjali is only 13 years old but very mature for her age, with charisma, intellect, and great communication skills. I was supposed to follow her on the stage, but after I met her I decided this would not be a wise idea for me. She’s too good! As president of the NAE I didn’t want to be upstaged by a 13-year-old. So I made a plan to have another person speak before me and postponed my remarks until later. It worked—and the NAE’s image is still intact!

The Frontier of Engineering program is supported by The Grainger Foundation as well as several government agencies and companies. In-kind support is provided by companies, universities, and federal labs that host individual meetings. We also receive support from NAE members and FOE alumni.

At this year’s US Frontiers of Engineering meeting the percentage of male and female attendees was just about even—51 percent and 49 percent, respectively. And the breakdown by employment sector was 44 percent each from industry and academia, and 12 percent from government and other organizations.

We are always delighted when FOE alumni are elected to the NAE. Since the program started, 110 FOE alumni have been elected, including 17 percent of this year’s class.

The NAE’s quarterly *The Bridge* is about to celebrate its 50th anniversary. It is among the most popular pages on the NAE website; like all our publications, *The Bridge* is available free of charge online. Issues this year focused on Technologies for Aging that facilitate both independence and quality of life; Engineering for Disaster Resilience, on infrastructure innovations; and Cybersecurity.

Each issue also includes interviews with engineers who are doing interesting things, especially outside of the engineering profession. The fall issue
features an interview with mechanical engineer and TV host Deanne Bell, who will moderate our forum tomorrow on human space flight. I am very much looking forward to it.

I am proud to report that NAE members are active across the National Academies divisions that conduct studies and issue consensus reports. In this past year, for example, we have been fortunate to have NAE member involvement in three very different studies.

The first one I’ll mention is a report on Strategic Long-Term Participation by DoD in Its Manufacturing USA Institutes, which are considered crucial and game-changing catalysts that are bringing together innovative ecosystems in various technology and market sectors critical to DoD and the nation. This report, in partnership with the Academies’ Division on Engineering and Physical Sciences, reviews the role of DoD’s investment to date in establishing its eight institutes as public-private partnerships and its engagement with each institute after it has matured beyond the start-up period.

Next is a report on transportation, Renewing the National Commitment to the Interstate Highway System. This congressionally requested report, chaired by Norm Augustine and issued by the Academies’ Transportation Research Board, makes recommendations on the “features, standards, capacity needs, application of technologies, and intergovernmental roles to upgrade the Interstate System.” It also suggests a path forward to meet the growing and shifting demands of the 21st century.

And from the Academies’ Health and Medicine Division comes the report Guiding Cancer Control. As we know, cancer is in effect a system of diseases that afflict individuals in myriad ways. Its burdens are equally broad and diverse, from the physical, financial, and psychological tolls it imposes on individuals to the costs it inflicts on the nation’s clinical care and public health systems. Using a complex systems engineering approach, this report breaks new ground in advancing our thinking about how to shape and significantly improve our approaches to advance cancer control.

These and other studies are possible because the NAE, and the broader National Academies, have tremendous convening power. We can bring together the very best minds in the country—even the world—to advise policymakers and others about ways to address some of the greatest national and global problems. In 2018, 361 NAE members participated in studies of the NAE and National Academies.

As the new NAE president, I have thought about four ways the NAE can contribute further to the national good:

- Identify and inform the frontiers of engineering theory, practice, and policy.
- Increase engineering talent through a strong commitment to diversity and inclusion.
- Instill a culture of ethical and environmental responsibility in engineering.
- Improve capabilities and competencies for complex systems engineering.

For all these priorities, member engagement is important, and I look forward to working with all of you, including the members of the class of 2019. There were 506 nominations for members, of which only 86 were elected, and 17 foreign members were elected from 79 nominations. The process is very selective because all the nominations were strong. It’s not easy being elected to NAE membership, so we are inducting very special people today.

In celebrating your election, we are also celebrating your families, friends, and colleagues. I would now like to acknowledge the families of the class of 2019—would you please stand so we can thank you for your support?

Before we begin the induction ceremony, I want to briefly address the difference between a scientist and an engineer. I thought of a story told to me by a friend that illustrates the difference.

A scientist and an engineer went hiking in the wilderness. At the end of the day, they pitched their tent, enjoyed dinner, and went to sleep. After a few hours the engineer wakes the scientist and says, “Look toward the sky. What do you see?”

The scientist replies, “I see millions of stars.”

The engineer says, “What does that tell you?”

The scientist says, “Astronomically speaking, it tells me there are millions of galaxies and potentially billions of planets. Astrologically, it tells me that Saturn is in Leo. Time-wise, it appears to be approximately 3:30 in the morning. Meteorologically, it seems we will have a beautiful day tomorrow.”

Then the scientist turns to the engineer and says, “What does it tell you?”

The engineer replies, “Somebody stole our tent.”

With that, congratulations again on your election to the NAE. I look forward to working with all of you in the coming months and years.
The 2019 Simon Ramo Founders Award was presented to Cato T. Laurencin, University Professor, Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery, professor of chemical and biomolecular engineering, of materials science and engineering, and of biomedical engineering; director, Raymond and Beverly Sackler Center for Biomedical, Biological, Physical and Engineering Sciences; chief executive officer, Connecticut Convergence Institute for Translation in Regenerative Engineering; University of Connecticut; “for fundamental, critical, and groundbreaking scientific advances in the engineering of tissues, guiding technology and science policy, and promoting diversity and excellence in science.”

Thank you, National Academy of Engineering, for awarding me this singular honor.

Regenerative Engineering is the Convergence of technologies that a generation ago might not be thought to be connected. I am humbled that the work I’ve accomplished in creating a fundamentally new field has been acknowledged by the National Academy of Engineering. The work continues to provide new knowledge, new science, and ultimately provides new solutions for those I consider the ultimate heroes, our patients. I am the first engineer-physician to receive the Founder’s Award and I believe that engineering, which is the bridge between Science and Society, has as its future revolutionizing medical care in the coming decades. It is my belief that the improvement in outcomes of patients in this century will largely hinge on the Convergence of engineering principles with the life sciences.

I am also the first Black person to receive the Founders Award of the National Academy of Engineering. I want to make sure that the importance of the struggle Black people have had collectively for me to be here today is not lost. In the words of the Negro National Anthem, “Stoney the road we trod, bitter the chastening rod, felt in the days when hope, unborn, had died… We have come over a way that with tears has been watered. We have come treading our path through the blood of the slaughtered.”

And in the words of Maya Angelou. “I am a Black Ocean, leaping and wide. Welling and swelling I bear in the tide. Bringing the gifts that my ancestors gave. I am the dream and the hope of the slave. I rise, I rise, I rise.”

I am appreciative. And, as my friend Richard Farr believes, being appreciative is a cornerstone of one’s being.

I would like to first provide my appreciation to Professor Robert Langer, my mentor, who taught me how to be a scientist and is responsible for so much good in my career and in my life. Bob, thank you.

I want to thank those who have helped provide guidance and inspiration to me scientifically including Professor Nicholas Peppas who is here today, Professor Shu Chien and Professor Y.C. Fung (who with Nich are Founder’s Award winners). I want to thank my science family, Professor Lakshmi Nair, Professor
Yusuf Khan, and Professor Kevin Lo—all former students—who each have moved multiple times to stay with me. I am appreciative.

I want to acknowledge and thank the Academy presidents I have worked with over the years including Dan Mote, Victor Dzau, Harvey Fineberg, and dear, dear Charles Vest, who first befriended me when I was a faculty member at MIT.

This life would not have been possible but for my parents, Helen I. Moorehead Laurencin, M.D. and Mr. Cyril Laurencin. My mom was a family doctor who delivered compassionate care, performed surgical procedures, and had a lab on the first floor of our house, and my dad was a master carpenter and inventor. My life is a tribute to them. For both my parents, mens et manus was the theme, i.e., mind and hand were equally important to cultivate. Thus I am an engineer and an orthopaedic surgeon, both fields bringing mens et manus to bear. There is a Chewa African Proverb that states that a child brought up where there is dancing cannot fail to dance. I can attest to the veracity of this. My siblings and I grew up in an intellectual environment that could be likened to a discotheque meeting a ballet studio. To my late parents, I am appreciative.

Finally, my greatest discovery, scientific or otherwise, has been my wife and life partner, Cynthia Laurencin. We have spent over 70 percent of our adult lives together, and to paraphrase the artist Ne-Yo, we are a true force when we’re together. We are blessed with three wonderful children, Cato, Michaela, and Victoria. They are truly the joy of our lives. To my wife and children, I love you. Thank you. I am appreciative.

I want to close by again thanking the National Academy of Engineering for bestowing upon me the Simon Ramo Founders Award. Since I am provided a short time for my remarks I will not be able to have an extended discussion on my philosophy of life. So I leave you all just one piece of philosophical advice from what I’ve gleaned from my life to date.

Love More, Worry Less, and above all, Be Appreciative. Thank you.

2019 Arthur M. Bueche Award Acceptance Remarks by Roderic Ivan Pettigrew

The 2019 Arthur M. Bueche Award was presented to Roderic Ivan Pettigrew, CEO of EnHealth Health Science Center and College of Engineering, Robert A. Welch Professor and Executive Dean, EnMed Colleges of Medicine and Engineering, and Houston Methodist Hospital, Texas A&M University, “for leadership at the NIH and for academic and industrial convergence research and education, resulting in innovations that have improved global health care.”

Good afternoon, everyone, and to President John Anderson, Chairman Gordon England, Awards Committee Chair Maxine Savitz, and Past President Dan Mote, who called to inform me of this committee decision.

I am so deeply appreciative of this wonderful and historic award. To the committee, Dr. Savitz, and all those involved in the committee’s deliberative process, I thank you. To the nominators and supporters—no doubt some in this audience—I thank you. To my 35 years of colleagues along the way across industry and three institutions—I thank you all. In particular, I thank

• AV Lakshminaraynin, an industry mentor from whom I really learned MR physics;
• Bill Casarella, Bob Nerem, and Don Giddens, Emory—Georgia Tech, who gave support at the start of my career;
• Doug Maynard and Shu Chien, who were critical to the creation of the National Institute of Biomedical Imaging and Bioengineering (NIBIB) and have been career-long mentors; and
• dear friends Larry Tabak and Francis Collins, who provided strong support for me at NIH.

Though I did not personally know Arthur Bueche, I have marveled at his history and his professional life. An international statesman for engineering, a steadfast advocate for science and technology, an advisor to the government and academia, a top-level industrial executive, and an innovator relentlessly focused on the application of research to societal needs.... He was truly a man for all seasons.

What a humbling experience to receive an award named in recogni-
The BRIDGE

tion of such a person, and what a great honor for one’s life work to be recognized by colleagues and peers. All of us are privileged to work in a field that contributes so profoundly to the betterment and quality of life on this planet. In fact, engineering has indeed been transformative for the global society—we know this. Modern medicine, for example, simply would not be possible without engineering, and the same can be said for all sectors of society.

Moreover, what the future holds is staggering to consider. There is realistic hope to meet currently daunting challenges, such as

- the ready availability of modern precision medicine across the planet, including the world’s vast underserved populations;
- Alzheimer’s treatments commensurate with recent advances in detection;
- immunoengineering to control the immune system, which is central to many of the most devastating diseases; and
- engineered molecular therapies for an array of illnesses that have no current effective treatments.

These challenges can be addressed through converged approaches with engineering playing the role of catalyzing discovery and translating discoveries into practical advances that improve well-being. This is our imperative and our responsibility—we embrace this.

In sum, for health care, engineering medicine can help achieve the overarching goal of good health for the entirety of our lives.

I would like to acknowledge my family in the audience and at home. Critical family commitments prevented the attendance of Robin and Rory Pettigrew, my immediate and dedicated support system. But with me are my dear cousin Denisha Willis, adopted sister Lillian Ashley, and NIH colleagues Drs. Peter Basser, Shadi Mamaghani, Bruce Tromberg, and Michael Cheetham (formerly of the State Department and now at NIH), and my new TAMU colleague Dr. Cynthia Hipwell. I also must recognize my deceased parents, Edwina and CW Pettigrew. If they were here today, I can assure you that they would be among the proudest of persons in this galaxy. But more than proud, they would be most pleased to know that the profession I have entered is so meaningful and has brought so much good to so many.

I do thank you all.


Highlights from the 2019 Golden Bridge Society Dinner

On October 6, new NAE president John Anderson and his wife Pat hosted a dinner in the historic Presidential Suite at Union Station to celebrate the NAE’s most generous members and friends. The historic venue was built in 1901 after the assassination of President James A. Garfield to give US presidents a safe place to await their travel. Several presidents have welcomed world leaders and dignitaries to the
Inaugural Norman R. Augustine Senior Scholar

The National Academy of Engineering has named Guru Madhavan as the inaugural Norman R. Augustine Senior Scholar. This endowment, which supports Dr. Madhavan's work, was made possible through a generous donation from Norman R. Augustine and Lockheed Corporation. The Norman R. Augustine Senior Scholar is awarded to an outstanding individual who will act as an advisor and assistant to the NAE president and will aid in the management and execution of the NAE's programmatic activities.

Dr. Madhavan’s leadership and expertise are evident in his work as the NAE director of programs and, before that, with the National Academy of Medicine. He is a biomedical engineer and senior policy advisor, vice president of IEEE-USA, and the author of *Applied Minds: How Engineers Think*.

Norman Augustine was elected to the NAE in 1983 and has received the US National Medal of Technology, Joint Chiefs of Staff Distinguished Public Service Award, Distinguished Service Medal, NAS Public Welfare Medal, and the Department of Defense’s highest civilian decoration five times. He has served as a trustee of Princeton University, Massachusetts Institute of Technology, and Johns Hopkins University, and a regent of the University System of Maryland. He has aided the President’s Council of Advisors on Science and Technology (PCAST) for 16 years, and has received 35 honorary degrees.

New Einstein Society member Nadine Aubry with her husband John Batton, flanked by Gordon England and John Anderson.

Norman R. Augustine, Guru Madhavan, and John L. Anderson.
MIT Hosts Introductory Event

On November 7, MIT dean of engineering Anantha P. Chandrakasan hosted an event at the school to introduce NAE president John L. Anderson to NAE members in the area. After brief remarks by Dr. Anderson, MIT Charles Stark Draper Professor of Aeronautics and Astronautics Professor Wesley L. Harris joined him at the podium for a lively discussion with about 40 members in attendance. Topics ranged from what the NAE should be doing in terms of addressing climate change to industry's perception of the Academy.

Angela Belcher, head of MIT’s Biological Engineering Department, said that young people are looking for role models in the area of climate change and that if they see the NAE getting involved it will have a huge ripple effect for involving the next generation—those who, she said, are going to make the biggest impact—in solving challenges related to this issue. Others, such as Harvard Medical School's Rakesh Jain and MIT Institute Professor Ronald Rivest, made similar comments about the NAE's involvement in the climate change issue.

David Spencer, chair of the board at wTe Corporation, said he hopes the NAE becomes better known in the business community and that members need to become more involved to differentiate the NAE from similar organizations and create value.

The lively discussion spanned other issues, such as how proactive the NAE should be in its role of advising the government, what the NAE can do to diversify the engineering profession, and the status of engineers in society.

Dr. Anderson gave additional remarks at a reception afterward, where members were joined by a number of alumni of the NAE’s Frontiers of Engineering program.

2019 US Frontiers of Engineering Hosted by Boeing South Carolina

This year’s US Frontiers of Engineering Symposium took place September 25–27 at Boeing South Carolina in N. Charleston. NAE member Jennifer L. West, Fitzpatrick Family University Professor of Biomedical Engineering at Duke University, chaired the organizing committee and the symposium. The sessions were Advanced Manufacturing in the Age of Digital Transformation, Engineering the Genome, Self-Driving Cars: Technology and Ethics, and Blockchain Technology. Mr. Perry Morrissette, senior manager of the Boeing SC Design Center, welcomed the group to the meeting.

The session on Advanced Manufacturing in the Age of Digital Transformation explored impacts of the fourth industrial revolution, in which industrial and information advances have merged to create systems that are smart, agile, resilient, and customizable. The first speaker focused on manufacturing applications of data analytics, autonomy, model-based engineering, and machine learning. This was followed by a presentation on computational modeling used in the sequencing of digital manufacturing in the domain of additive manufacturing. The next speaker discussed new directions for legged robots and their future applications in the manufacturing sector. The session concluded with a talk on the concept of the digital twin to boost efficiency, reduce costs, and manage maintenance for individual aircraft.

The next session, Engineering the Genome, described how genome engineering tools have the potential to alter any DNA or RNA sequence, leading to an almost limitless range of applications in treating human genetic diseases, developing industrial biotech products, improving crop and livestock productivity, and addressing conservation and invasive species challenges. Talks detailed methods and uses of CRISPR-Cas9, impacts of genome engineering on ecosystems such as mosquito transmission of diseases, industrial scale-up for manufacturing molecules for various applications, and the need for standards and data sharing in this rapidly evolving field.

Although self-driving cars are now on the roads, the ramifications of this trend are complex given potential effects on infrastructure, the economy, and society and the ways transportation factors into daily life. The first presentation provided an overview of the challenges and opportunities provided by self-driving vehicles. The next
speaker described how self-driving cars are being developed at scale. This was followed by an exploration of the philosophy and ethics surrounding the programming of self-driving cars. The session closed with a talk about humans’ interactions with autonomous and intelligent systems, including research on design and learning algorithms that influence humans’ actions for better safety and coordination.

Blockchain—the underlying technology for Bitcoin and other applications—was the topic of the final session. The presentations introduced the history and key concepts of blockchain and provided an overview of the major platforms and applications including Bitcoin, Ethereum, and Hyperledger; discussed the domain of private and permissioned blockchain platforms designed as building blocks of networks between groups of enterprises; and delved into the economic and social research that leverages blockchain technologies.

On the first afternoon of the meeting, Meet and Connect breakout sessions provided an opportunity for attendees to share their research and technical work so they could get to know more about each other relatively early in the program. On the second afternoon, Boeing arranged tours of its plant where the Boeing 787 Dreamliner is manufactured. This was followed by a reception overlooking Final Assembly and dinner with a view of the Boeing South Carolina (BSC) complex.

On the first evening, Ms. Joan Robinson-Berry, vice president of engineering, modifications, and maintenance for Boeing Global Services, spoke about the breadth of research and engineering—“from freezer to flight”—at BSC. She also issued a call to action for increased diversity in the engineering workforce, encouraging the attendees to be drivers of change and to bring people from outside their communities to the table.

Participants at this year’s meeting will be eligible to apply for The Grainger Foundation Frontiers of Engineering Grants, which provide seed funding for US FOE participants who are at US-based institutions. These grants enable further pursuit of important new interdisciplinary research and projects stimulated by the US FOE symposia.

Jennifer West will continue as chair for the 2020 US FOE, which will be hosted by the National Renewable Energy Laboratory in Golden, Colorado, September 14–16. The 2020 topics are bioengineering for women’s health, new approaches to food production, cleaning up ocean waste, and next-generation energy systems integration.

The NAE has been hosting an annual US Frontiers of Engineering meeting since 1995, and also has bilateral programs with Germany, Japan, China, and the European Union. The meetings bring together highly accomplished engineers from industry, academia, and government at a relatively early point in their careers, providing an opportunity for them to learn about developments, techniques, and approaches at the forefront of fields other than their own, which is increasingly important as engineering has become more interdisciplinary. The meeting also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the symposium series, visit www.naefrontiers.org or contact Janet Hunziker in the NAE Program Office at JHunziker@nae.edu.

EngineerGirl Announces 2019 Class of Student Ambassadors

For the 2019 class of the EngineerGirl Ambassadors program, 16 high school girls have been selected to participate in a year-long program designed to build their leadership skills by helping them promote engineering to younger students in their community. Each ambassador will design, develop, and implement a project that will encourage younger girls—particularly those with little access to engineering role models—to think about engineering careers and give them practical experience in engineering design. They will work with local sponsors and receive guidance and support from EngineerGirl staff.

Following are the 2019–20 EngineerGirl ambassadors and their proposed projects:

Kelly Cha (12th grade, Clifton, NJ) is running an engineering workshop for young, underprivileged girls in her community and hopes this exposure will help them discover their STEM-related interests and help diversify the engineering field.

Rachel Chae (10th grade, Centreville, VA) is developing an after-school program for students to become involved with their community’s environmental protection organizations.

Anastasia Cook (11th grade, Saint Charles, MO) will create a Junior FIRST LEGO League team and “EngineerGirl Junior” club for girls ages 6–9 in her community.

Sarah Eckert (9th grade, Davenport, IA) will organize a summer engineering day camp for underserved and underrepresented girls and their siblings in her community.

Lauren Eppinger (12th grade, Saxtons River, VT) will offer a week-long summer “design camp” for middle school girls in rural Vermont; the camp sessions will be collaborative and focus on how engineering helps solve real-world problems.

Maggie Haber (10th grade, Carmel, NY) plans to run both an after-school program and hands-on programs in summer camps.

Madelyn Heaston (10th grade, Issaquah, WA) plans to host STEAM workshops for young girls experiencing homelessness in the Seattle area.

Sara Huelskamp (10th grade, Grantsville, MD) is planning a hands-on after-school program to introduce girls in her community to new skills while showing them how STEM concepts relate to their everyday life.

Bridget Li (12th grade, Austin, TX) is putting together an after-school engineering club to allow girls at her local middle school to complete independent projects using the engineering design process, then present their research at science fairs.

Ashley Lin (10th grade, Vancouver, WA) is creating a 10-week digital exchange program on themes of engineering and community engagement.

Parvati Menon (11th grade, Suwanee, GA) is creating an after-school program to spark interest in engineering among girls at an underresourced local middle school.

Adun Oladeji (11th grade, Alpharetta, GA) is planning to hold engineering workshops every few months for girls and underrepresented minorities.

Sophie Poole (11th grade, Pasadena, CA) will create an after-school program to give 5th and 6th grade girls the opportunity to explore the many career paths in engineering.
Saraswati Sridhar (10th grade, Mayaguez, Puerto Rico) is building an online learning platform—with videos, quizzes, and simulations—about biomedical engineering.

Lucille Steffes (12th grade, Milwaukee, WI) is creating a club for middle school girls, focusing on environmentally friendly engineering projects that will improve their local community and get the girls interested in all that engineering has to offer.

Lillian Williams (11th grade, Connelly Springs, NC) will host a one-week summer camp at a local elementary school, focusing on chemical engineering and designed to empower and build character among young Hispanic girls while encouraging them to pursue a career in a STEM field.

Profiles of the student ambassadors and videos are available at the EngineerGirl website (www.engineergirl.org/2019-ambassadors.aspx).

The EngineerGirl ambassadors received an all-expenses-paid trip to the Society of Women Engineers (SWE) Annual Conference, project funding of up to $250, leadership development, a free one-year SWE membership, and a certificate and letter of recognition from the NAE that may be sent with college applications.

EngineerGirl is part of the NAE’s ongoing effort to increase the diversity of the engineering workforce. The EngineerGirl Ambassadors program is made possible by a generous grant from John F. McDonnell.

Human Rights and Digital Technologies: A Symposium

The Committee on Human Rights (CHR) of the National Academies held a symposium to increase awareness of how human rights and digital technologies intersect. The public event, which was also webcast live, took place at the NAS Building September 18 and brought together internationally recognized human rights scholars and practitioners to discuss the human rights challenges and opportunities posed by digital technologies. Recordings of session panels and background information about the meeting are on the CHR website at http://nas.edu/humanrights-digitaltech.

The symposium was opened by NAS/NAM member and CHR chair Martin Chalfie (Columbia University), who noted the importance of recognizing and addressing social media’s influence on human rights. Dr. Chalfie was followed by David Kaye, the UN’s Special Rapporteur on the Promotion and Protection of the Right to Freedom of Opinion and Expression, who, in his keynote speech, noted that “human rights” is not part of the American vernacular. The focus in the United States tends to be only on constitutional rights, although international human rights law (which includes some treaties that the United States has ratified) has a broader reach and a network of institutions designed to ensure its implementation. Mr. Kaye stressed that international human rights law can provide an important framework for global regulation of digital technologies.

Jos Berens, of the UN Office for the Coordination of Humanitarian Affairs, noted that the human rights challenges created by digital technologies also create an opportunity for scientists and engineers to develop value-sensitive and rights-based technologies. Ron Deibert, director of the Citizen Lab at the Munk School of Global Affairs and Public Policy at the University of Toronto, expressed his concern that civil society has been ignored by platform developers for whom data security is an afterthought. He noted that websites collect personal and professional data and that tools for mining these data, previously available only to state agents, can now be purchased as off-the-shelf technology. A danger is that spyware can be used by governments with bad human rights records to target individuals or groups (e.g., journalists).

There was a consensus among the speakers that human rights principles such as privacy and freedom of expression should be incorporated in the design and use of technologies. The challenge is that this goal requires greater collaboration between human rights experts and the scientific and engineering communities, and these groups often speak different languages. Recognizing this argues for educational action, perhaps incorporating human rights in STEM curricula, and surely making human rights more prominent in professional education. One significant step in this direction was taken by the Institute of Electrical and Electronics Engineers (IEEE) when it listed human rights first on a list of ethical considerations for AI.

Tanya Karanasios, deputy program director at WITNESS,
underscored the fact that, while digital technologies can help foster human rights, they can also pose a threat. Since she began working at WITNESS in 2011, there has been a worldwide proliferation of smartphones with cameras. The resulting vast archive of visual data, both photos and videos, could be a powerful resource for documenting human rights violations. However, such data are at risk of manipulation through digital techniques, making validation of this visual documentation difficult. One effective means of acquiring reliable visual evidence is crowd sourcing—the documentation of an event by many.

At a workshop following the symposium, Peter Micek, general counsel and business and human rights lead at Access Now, agreed that digital platforms have been a valuable asset to human rights activists, but recently their use has seen increased risk. Some countries are passing laws requiring data to be stored locally and retained for a long time, in violation of platform privacy laws. Some governments are also increasingly seeking “backdoor” access to encrypted messaging services. Adding to these privacy threats, certain governments frequently shut down and disrupt networks, applications, and services, especially during elections and protests. These restrictions produce a chilling effect on the willingness of human rights defenders to use social media, for fear of reprisal.

A further challenge to the use of social media for illuminating human rights abuses was articulated by Michael Elsanadi and Gisela Perez de Acha Chavez, of the University of California, Berkeley School of Law’s Human Rights Center. Social media companies can take down or reduce the visibility of content that is considered by them to fall into certain categories (e.g., violent content). This makes it difficult to access documentation of some human rights violations, such as potential war crimes in Syria. The fact that filtering is often done algorithmically complicates efforts to differentiate useful human rights–related content from that showing gratuitous violence.

Martin Chalfie and CHR director Rebecca Everly closed the symposium and workshop by emphasizing the importance of continuing to create and act on opportunities to explore areas of collaboration between scientists, technologists, and human rights experts as we seek to respond to the significant human rights challenges that accompany digital technologies.

New Staff Join the Development Office

ELANA LIPPA joined the National Academies’ development staff as director of planned giving on September 3. She brings relationship-building skills and more than 17 years of experience managing and closing a broad range of planned gifts at four previous organizations, and is president of the National Capital Gift Planning Council, which is the local chapter of the National Association of Charitable Gift Planners. Elana is a graduate of Virginia Commonwealth University and American University, where she majored in music and nonprofit management, respectively. In her free time, she enjoys singing and baking. Elana is in NAS 037 and can be reached at 202.334.1817 or ELippa@nas.edu.

CASEY ZIA joined the Office of Development as associate director of donor relations and communications on September 3. She has over 12 years of experience in the field and most recently comes from George Washington University, where she worked with a portfolio of schools handling all their donor relations needs. She has experience in planning and executing donor events and will work closely with our events manager. She is a graduate of West Virginia University and a licensed massage therapist. In her free time, Casey enjoys working out, reading, and playing with her German Shepherd rescue dog. Casey is in NAS 047 and can be reached at 202.334.1833 or CZia@nas.edu.
In Memoriam

DONALD C. BERKEY, 99, retired vice president and general manager, Energy Systems and Technology Division, General Electric Company, died August 17, 2019. Mr. Berkey was elected in 1979 for contributions in design, development, and program direction of advanced gas turbines and energy systems, including the first successful high-bypass engine.

ROGER H. BÉTEILLE, 97, retired general manager, Airbus Industrie (retired), died June 14, 2019. Mr. Béteille was elected as a foreign member in 1992 for the technical leadership of a cooperative, multinational program developing and producing a family of advanced-technology transport aircraft.

DANNY COHEN, 81, Distinguished Engineer, Oracle, died August 12, 2019. Dr. Cohen was elected in 2006 for contributions to the advanced design, graphics, and real-time network protocols of computer systems.

HARRY E. COOK, 80, professor emeritus, Department of Industrial and Enterprise Systems Engineering, University of Illinois at Urbana-Champaign, died September 12, 2019. Dr. Cook was elected in 1990 for seminal contributions to phase transition theory and for leadership in the introduction of advanced materials for automotive applications.

ROBERT W. DEUTSCH, 94, chair and director, RWD Technologies, Inc., died March 19, 2019. Dr. Deutsch was elected in 1995 for founding companies to improve human performance in high-technology industries.

THOMAS V. FALKIE, 85, retired chair and CEO, Berwind Natural Resources Corporation, died November 1, 2019. Dr. Falkie was elected in 1989 for contributions to mining technology and management through mineral engineering.

Calendar of Meetings and Events 12/1/19 through 3/30/20

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<td>December 5–6</td>
<td>NAE Committee on Membership Meeting</td>
<td>Irvine, California</td>
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<td>Roundtable on Linking Defense Basic Research to Leading Academia Research and Engineering Communities</td>
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<td>December 13</td>
<td>Committee on Sharing Exemplary Admissions Practices That Promote Diversity in Engineering</td>
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<td>January 1–31</td>
<td>2020 election of new NAE members and foreign members</td>
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<td>January 1–April 1</td>
<td>NAE Awards call for nominations</td>
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<td>January 15</td>
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<td>January 16</td>
<td>Workshop for chairs of 2021 Election Peer Committees, Search Committees, and Special Nominating Committees for Member and Foreign Member Diversity</td>
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<td>2020 Charles Stark Draper Prize for Engineering dinner and ceremony (by invitation only)</td>
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<td>NAE Membership Policy Committee Meeting</td>
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<td>February 19</td>
<td>Call for new nominations for 2021 election cycle (from current members/foreign members only)</td>
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<td>Late February–April 27</td>
<td>Election of NAE officers and councillors</td>
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<td>March 1–31</td>
<td>NAE Regional Meeting: Engineering Therapies for the Future</td>
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<td>March 10</td>
<td>NAE Regional Meeting: Engineering Therapies for the Future</td>
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All meetings are held in National Academies facilities in Washington, DC, unless otherwise noted.
education, industry operations, and government service.

WOODIE C. FLOWERS, 75, Pappalardo Professor Emeritus of Mechanical Engineering, Massachusetts Institute of Technology, died October 12, 2019. Dr. Flowers was elected in 1994 for contributions to the teaching of mechanical engineering design.

MARIA FLYTZANI-STEPHANOPOULOS, 69, Distinguished Professor, Robert and Marcy Haber Endowed Professor in Energy Sustainability, Tufts University, died October 28, 2019. Professor Flynatzani-Stephanopoulos was elected in 2014 for contributions to atomically dispersed heterogeneous metal catalysts for efficient production of fuels and chemicals.

MARY L. GOOD, 88, dean emerita, special advisor to the chancellor for economic development (retired), University of Arkansas at Little Rock, died November 20, 2019. Dr. Good was elected in 1987 for outstanding contributions as educator, researcher, and manager of research and development, and as distinguished spokesperson for R&D policy.

ROBERT C. HAWKINS, 91, retired vice president, Advanced Programs, GE Aircraft Engines, died December 28, 2018. Mr. Hawkins was elected in 1985 for sustained outstanding contributions to engine design and inspired leadership in the development of advanced gas turbine technology.

STEPHEN A. HOLDITCH, 72, professor emeritus, Petroleum Engineering Department, Texas A&M University, died August 9, 2019. Dr. Holditch was elected in 1995 for contributions in hydraulic fracturing and developing low-permeability gas reservoirs, and for technology transfer in both of these fields.

JOHN W. LEONARD, 93, consultant, Washington Group International, died January 2, 2019. Mr. Leonard was elected in 1984 for innovative application of engineering to major construction projects, especially in the areas of mechanized tunneling, coastal, and harbor construction.

CARROLL N. LETELLIER, 90, retired vice president, Jacobs Engineering/Sverdrup, died March 27, 2019. Mr. LeTellier was elected in 2003 for leadership in the planning, design, and construction of major civil infrastructure and military facilities that meet and serve the highest societal values.

GEORGE A. MANEATIS, 92, retired president, Pacific Gas and Electric Company, died December 17, 2018. Mr. Maneatis was elected in 1988 for outstanding engineering leadership in planning, designing, and constructing large complex facilities, resulting in systems combining high performance with improved safety and reliability.

JAMES E. MONSEES, 82, senior vice president, technical director, and principal professional associate, Parsons Brinckerhoff Inc., died August 5, 2019. Dr. Monsees was elected in 1991 for development and application of innovative design procedures for underground structures in gassy and seismic environments and of methods for utilizing rock-structure interaction.

NORMAN A. NADEL, 92, chair, Nadel Associates, Inc., died June 14, 2019. Mr. Nadel was elected in 1983 for engineering improvements in underground construction, including tunneling equipment, excavation supports, and economy of performance.

HILLIARD W. PAIGE, 99, retired senior vice president, General Electric Company, died June 4, 2019. Mr. Paige was elected in 1968 for contributions to jet engines, ballistic missiles, and space technology.

DAVID S. POTTER, 86, retired vice president and group executive, General Motors Corporation, died September 18, 2011. Dr. Potter was elected in 1973 for contributions in underwater acoustic instrumentation, ocean engineering, and manned exploration of the moon.

JENS RASMUSSEN, 91, retired research professor, Risø National Laboratory, died February 5, 2018. Dr. Rasmussen was elected as a foreign member in 2013 for contributions to the science and engineering of human error and reliability, and for the modeling of human behavior.

LAWRENCE G. ROBERTS, 80, CEO, Roberts Consulting, died December 26, 2018. Dr. Roberts was elected in 1978 for contributions to telecommunications and computer systems.

EPHRAIM M. SPARROW, 91, professor of mechanical engineering, University of Minnesota, died August 1, 2019. Dr. Sparrow was elected in 1986 for outstanding, prodigious contributions to heat
transfer through analysis and experimentation, and for superlative teaching.

JAMES J. SPILKER JR., 86, consulting professor in aeronautics and astronautics, Stanford University, died September 24, 2019. Dr. Spilker was elected in 1998 for spread spectrum technology, communications theory, and the global positioning systems.

HENRY E. STONE, 96, retired vice president and chief engineer, nuclear energy, General Electric Company, and consultant, died December 1, 2018. Mr. Stone was elected in 1981 for major pioneering contributions to nuclear power technology development, especially for naval reactors.

SPENCER R. TITLEY, 90, professor of geosciences, University of Arizona, died August 18, 2019. Dr. Titley was elected in 2005 for contributions to our understanding of the genesis of porphyry copper deposits.

MARSHALL P. TULIN, 93, director (retired), Ocean Engineering Laboratory, University of California, Santa Barbara, died August 31, 2019. Mr. Tulin was elected in 1979 for research in hydrodynamics, especially supercavitating flows.

WALTER G. VINCENTI, 102, professor emeritus of aeronautics and astronautics, Stanford University, died October 11, 2019. Mr. Vincenti was elected in 1987 for pioneering contributions to supersonic aircraft aerodynamics and to fundamental understanding of the physical gas dynamics of hypersonic flow.

HANS-JÜRGEN WARNECKE, 84, professor emeritus, Fraunhofer Institute for Manufacturing Engineering and Automation (IPA), died March 20, 2019. Dr. Warnecke was elected as a foreign member in 1993 for leadership and contributions to the theory and practice of the engineering and management of flexible automation.

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In architecture, fundamental concepts such as aspect ratios—how the width of a structure relates to the height—matter a great deal. But Sir Ove Nyquist Arup interpreted them broadly. For him, such elements were only a component of “total design.” He believed that structures were the product of not just sensible engineering but a sensitive engagement with the world. “What we decide to do is much more important than how to do it,” Arup wrote in 1984, “and that opens the sluice valve for a whole flood of questions, social, political, ethical, which threaten us all with confusion, or worse, because we are not able to agree on what to do.”

The design of the team building the structure, he asserted, was as important as the design of the structure itself.

Before Arup became an engineer, he studied philosophy. The British-born, German-Danish-educated polymath, who founded his now global firm in 1946, was an admirer not only of modernists like Le Corbusier but also of ancients like Marcus Aurelius—it is fruitful for the mind not just to look at olives but be attentive to how they ripened. Biographer Peter Jones portrayed Arup as an “endlessly doodling, whimsically rhyming, cigar-waving, beret-wearing, accordion squeezing, ceaselessly smiling, foreign sounding, irresistibly charming, mumbling giant.”

Arup assiduously disrupted professional boundaries through his work, most famously with the groundbreaking design and construction methods that turned an architect’s rough sketches into the engineered reality of the Sydney Opera House. He and his firm (after his death in 1988) brought his sensibilities to such projects as Copenhagen’s modern metro stations, the “Bird’s Nest” in Beijing, the Grand Egyptian Museum, Heathrow Terminal 5, and the Channel Tunnel. The firm’s creative approach led to the insight that off-site construction of custom prestressed stone masonry panels could speed the construction of the technically challenging central towers of Gaudí’s Sagrada Familia.

Crossing disciplines in building projects, however, entails costs, just as it does in other realms. A real dichotomy exists in meeting a client’s needs and generating profits versus achieving the moral aims of a work, as Arup reminded. Perhaps that’s why the current relentless calls for “interdisciplinary,” “multidisciplinary,” “transdisciplinary,” or whatever-buzzword-is-in-vogue engineering feel simultaneously vital and vapid. Hardly a professional meeting now exists where the “silo mentality” is not criticized, even as it persists in practice. The divisions so industriously created are now the ones we struggle to remove. We have to expend effort to gain even a basic perspective on the consequences of our creations.

How then can engineers deepen their reflections on the connections between problems, their solutions, and their contexts, connections that Arup thought were “so ruthlessly severed”? In 1962 he observed that “the chances of achieving harmonious integration decline with the proliferation of experts and available techniques. The moral is the often stated one—all the facts and possibilities bearing on a design must be thoroughly

Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

1 Ove Arup, Foreword to Understanding Structural Analysis by David Brohn (New Paradigm Solutions, 2005), p x.

2 Peter Jones, Ove Arup: Masterbuilder of the Twentieth Century (Yale University Press, 2006), p 1.

understood and digested before the design is frozen, and the whole must take precedence over any of its parts.”

Arup went further in his 1970 Key Speech:

I can’t see the point in having such a large firm with offices all over the world unless there is something which binds us together... Unless we have a “mission”—although I don’t like the word—but something “higher” to strive for—and I don’t particularly like that expression either—but unless we feel that we have a special contribution to make which our very size and diversity and our whole outlook can help to achieve, I for one am not interested.

In Arup’s material conception of total design, tracking and accounting for the effects of an engineer’s work were as much a duty as delivering on the tasks or satisfying a sponsor. That is, design was not merely a contract to be fulfilled but a rigorous reflection on responsibility. He despaired, though, whether this vision could be fulfilled but a rigorous reflection on responsibility. He despaired, though, whether this vision could be realized in practice. “We cannot avoid the splitting up of the business of building among dozens or hundreds of collaborators. Specialization is the way civilization moves forward—and perhaps it is the way it will destroy itself,” Arup wrote in 1968 for The Times of London. “Faced with a complex entity we split it up, catalogue the parts, study and develop them separately and then fail to put them together again.”

British scholars Andrew Chilvers and Sarah Bell, who have studied the moral elements in Arup’s engineering practice, offer a valuable perspective on this. The constraints and trade-offs inherent in engineering often create a professional “lock-in.” In some order, this is the tendency to jot down the requirements, finalize the paperwork, control the costs, start the operations, and be very process-oriented—that is, the logistics of engineering. Open negotiations with the full set of stakeholders in a project are treated as optional, and the synthesis of specialty knowledge, values, and languages is not pursued seriously (if at all). These so-called “nonengineering” issues, which deeply concerned Arup, thus remain fluid.

An argument can be made, though, that the technical and normative goals of engineering should ideally derive from the negotiations among a wide range of parties, and there could be manifold benefits in delaying the “lock-in.” In this mindset, even the basic numerical parameters for a project and its efficient execution become diffuse, and uncomfortably so for many engineers. The parameters develop different utilities, even identities, when subjected to different perspectives. These kinds of abstractions are not a hindrance but part and parcel of engineering rigor and responsibility.

One of Arup’s signature projects provides a cautionary example of the costs of locking in. His and architect Berthold Lubetkin’s 1934 penguin pool for the London Zoo is considered a triumph of both art and engineering for its dramatic spiraling reinforced concrete ramps that seem suspended without support. The project was done in consultation with renowned biologist Julian Huxley (the brother of writer and futurist Aldous Huxley) and represented the best in 1930s scholarship. But the zoo later decided to replace the Antarctic penguins with a South American burrowing species ill-suited for a concrete home, and the surface (layered with quartz crystals) ended up so abrading the penguins’ feet that it caused dangerous infections. With its parameters all cast in stone, as it were, there was no practical way to update the structure. One might even wonder why the original paving with rubber pads was turned into concrete. The pool was abandoned in 2004 and stands today as a lovely but empty monument. Frustrated with the disuse of this Grade I listed pool, Lubetkin’s daughter recently said: “Perhaps it’s time to blow it to smithereens.”

So, can the thinking and practice that produce lock-in be changed? “Just like when dieters appear to command a sufficient market share to make a difference, salad bars start appearing in McDonalds,” Chilvers and Bell write, “if enough engineers, engineering firms and engineering educators challenge prevailing conventions and standards, issues of professional lock-in might, in time, be broken.” If prevailing constraints and conventions are posed in defense, Chilvers and Bell argue that we need to have a more honest and scrupulous discussion on why certain constraints and conventions exist. This is when the conversations about buildings (and engineering) cease being primarily technical and become more culturally—and morally—germane. To get to this maturity and gain the capacity to reflect and

5 Arup, speech delivered to his firm, July 9, 1970, Winchester.
better synthesize, we may all need to unspecialize a bit. But is this too much to ask?

In a world where structural design is defined and circumscribed by a narrow focus on engineering costs, schedule, and requirements, Arup may have sounded unnatural, even unreasonable. Indeed, at the time, his intent was better appreciated outside the spheres of engineering. Among his admirers was Walter Gropius, the founder of Bauhaus, the Weimar movement now celebrating its centenary. Bauhaus too aimed at a concept of a complete building. At its core, that building would be requisitely unfinished and intended for “people’s needs instead of luxury needs” as the Bauhaus architect Hannes Meyer put it. That’s a design beyond individual preferences and also beyond chic and cost-effectiveness. This is not some modernist bravery; this is open-minded engineering.

In an August 1966 letter, Gropius wrote to Arup expressing appreciation of the “total unity [of] form, structure, and economy being inseparable within it.” Gropius explained that: “Education of architects, engineers and artists alike must…, first of all, be directed towards understanding and accepting the collaborative process, the ‘composite mind,’ which by itself will make for more humility and mutual respect.” In doing so, the individuals with the broadest scope are best equipped for total design. “You have shown evidence in your work that this can be done either by an ‘architect,’ or an ‘engineer,’” Gropius wrote. “Good reason to be happy!”