Winter 2020

COMPLEX UNIFIABLE SYSTEMS

The BRIDGE

LINKING ENGINEERING AND SOCIETY

NATIONAL ACADEMY OF ENGINEERING

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.

The
BRIDGE

NATIONAL ACADEMY OF ENGINEERING

Editor in Chief: Ronald M. Latanision
Managing Editor: Cameron H. Fletcher
Production Associate: Penelope Gibbs

The Bridge (ISSN 0737-6278) is published quarterly by the National Academy of Engineering, 2101 Constitution Avenue NW, Washington, DC 20418. Periodicals postage paid at Washington, DC.

Vol. 50, No. 4, Winter 2020

Postmaster: Send address changes to *The Bridge*, 2101 Constitution Avenue NW, Washington, DC 20418.

Changes of address or requests to unsubscribe should be sent to PGibbs@nae.edu.

Papers are presented in *The Bridge* on the basis of general interest and timeliness. They reflect the views of the authors and not necessarily the position of the National Academy of Engineering.

The Bridge is printed on recycled paper. ♻

Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7000, including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

A complete copy of *The Bridge* is available in PDF format at *www.nae.edu/TheBridge*. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

The BRIDGE

Volume 50, Number 4 • Winter 2020

LINKING ENGINEERING AND SOCIETY

Editors' Note

Features

(continued on next page)

News and Notes

Editors' Note

Systemic Vistas

Guru Madhavan

George Poste

William Rouse

Guru Madhavan is the Norman R. Augustine Senior Scholar and senior director of programs at the National Academy of Engineering. George Poste is Regents Professor and Del E. Webb Professor of Health Innovation and chief scientist with the Complex Adaptive Systems Initiative at Arizona State University. William Rouse (NAE) is research professor and senior fellow at McCourt School of Public Policy at Georgetown University.

We live in fragmented worlds. Unbridged, tattered seams abound.

The collision of four calamities—viral, racial, economic, and environmental—infected by human habits, hubris, and behavior as well as big tech, big media, and political acrimony are living examples. Calls for freedoms are posed against lockdowns. Scrolling timelines on social media stir the public distrust of information and institutions.

The result is a "cosmology episode." Meanings and capabilities quickly vanish. Confusions reign. But "there's no disaster that can't become a blessing," novelist Richard Bach (1988) wrote, "and no blessing that can't become a disaster." In the porous borders between disasters and blessings lies the story of engineering and human capacity.

Complex Disaster Scenarios

The following complex disaster scenarios are each far beyond a technofix.

Rising sea levels are threatening Route 1 through the Florida Keys. The costs of raising the roads will amount to $500,000 per resident, an amount the State of Florida cannot afford.

Prospective owners of coastal homes in the United States will no longer be able to get 30-year mortgages as financiers can no longer predict long-term risks. Current owners will no longer be able to afford increasingly expensive flood insurance.

Extreme heat has started to melt roads in states experiencing record high temperatures. Applying an additional rubberized layer to roads helps, but the higher road levels result in trucks not being able to go under many bridges.

Temperature rise has caused warmwater fish to migrate to Northeast waters in the United States, and coldwater fish to move farther north. New England fishers are catching foreign fish and no one in their markets has ordered them.

Recent analyses of temperature trends suggest that Americans under age 35 will live through a time when large parts of the Southeast and Southwest United States may be uninhabitable. Absent any mitigation, large migrations north will include more than fish. It'll be millions of climate refugees.

These are just some ignored indicators of creeping impacts of climate complexities. There will never be a vaccine for sea level rise. Moreover, the titanic US medical system is accelerating toward the illness-icebergs of cancers, Alzheimer's, mental disease, and substance use disorders.

The overarching issue on these matters is not whether the science is right. What's more compelling is how to responsibly engineer countermeasures for these foreseeable complex system dynamics and their impacts now and into the future. It's wise to follow science, perhaps more important to lead with engineering.

A Cultural Engineering Mindset

Engineering as traditionally practiced, in isolation, is limited and limiting. Engineers are touted as "problem solvers" while the opposite is also true: we are problem creators. This is not a simple identity crisis; it's an *identification* crisis. Engineers need to be able to identify what qualifies as a solution, and what's acceptable in what contexts.

What needs to be done? This issue of *The Bridge* aims to prompt that conversation.

Humans have studied complex systems for a century. But we have engineered complex societies for tens of thousands of years. Yet much needs to be done to drive the culturewide appreciation and application of engineering.

> *In the porous borders between disasters and blessings lies the story of engineering and human capacity.*

In some ways engineering has led to safer complex systems, and such accomplishments have been multiplied across industry sectors. But engineering has also shied away from—and even exacerbated—issues connecting culture, environment, and justice. What then constitutes engineering design to promote the collective good? Such questions of complex systems are generally overlooked in engineering practice, scholarship, and education, as well as national priorities. Such questions are also bound to define the kinds of competencies, capabilities, and character needed to cultivate a cultural engineering mindset.

Explorations of Complexity and Unifiability

The articles in this issue are a first step toward exploring the notion of unifiability, not merely as an engineering ethos but also as a broader cultural responsibility. We consider unifiability as the leveraging of approaches and capabilities from different practices and paths of inquiry to foster functional systems engineering for complex problems. Unifiability involves crossing boundaries, as well as leadership, strategy, communications, and accountability.

Engineering to foster unifiability in a fragmented world will necessarily depart from standard technical comforts and technocratic conveniences. Such a practice will lead to reflective conversations on and responsible explorations of approaches to better understand and engage with complex systems. Not all of the ideas in these articles explicitly discuss unifiability, but they imply it, inspire it, or even practice it. Each essay honors and is humbled by complexity.

The essays fall into four clusters: the many approaches or *modes* to consider complexity, and the implications of approaches on *culture*, *health*, and *organizations*. Each short take on complexity is a reminder of the need for certain practices to promote unifiability. Call them the "seven habits of highly effective systems thinkers."

1. *Specialize less, systematize more.* Working across divisions and abstractions can inform and guide better concepts, principles, models, methods, and tools. On matters of complexity, engineers need to confront the true value of various specializations, how far they can take us, and how they are rewarded.
2. *Get over physics envy, try ecology envy.* Less Newton, more Darwin. Engineering achievements and ruins both hinge on reductionism fueled largely by physics. It's time to refocus on deep lessons from nature and culture and all their evolutions.
3. *Evolve logic and psychologic.* Engineering training and algorithms encourage context blindness. Being sensitive to environments will require exercising intellectual senses as well as prudent forms of engineering.
4. *Foster discipline over disciplines.* Complex systems can change faster than the mind can conceive them, and "solutions" can trigger undesirable outcomes. Staying attentive to failure modes requires discipline.
5. *Relate first, rationalize next.* Complexity builds from relationships. Relating to one another is a civic act and engineering should be too. Rationality works only part time—and it's often hard to tell which part.
6. *Progress comes from participation.* Engineers often feel conflicted about being "hired guns" or "order takers." Active reflection becomes a challenge. Broadening participation across populations may alleviate this discomfort. If there are no sacrifices, one might say, there's no engineering. Similarly, if there's no public participation, there's no progress.
7. *Focus more on care than creation.* Capitalism is fueled by newness and novelty, or so the belief goes. But maintenance and care are sources of essential wisdom

and traditions. Vital systems that support people need more care than reckless new creations.

First Steps

In the aftermath of the Civil War, Walt Whitman reflected on the needs for an American character and spirit. In *Democratic Vistas*, he wrote that while there are accomplishments "established and complete, really the grandest things always remain; and discover that the work of the New World is not ended, but only fairly begun."

On matters of complex unifiable systems, engineering has only fairly begun. The ideas in this issue represent a first step and a first draft.

Reference

Bach R. 1988. One. New York: Dell.

Thinking Reflexively

Richard Foster is an emeritus senior partner of McKinsey & Company.

Richard N. Foster

The essence of the word *reflexive* is to act on one's self. Reflexive systems act on themselves. For example, if one instinctively scratches one's arm, this is a reflexive action.

Reflexive is closely related to a similar word, *reflective*. Looking at one's reflection in a mirror may trigger reflective thought. In both cases, the concept involves acting on one's self.

Reflexive acts can introduce unpredictability (it is not possible to forecast whether or when one is going to scratch one's arm), instability, and uncertainty in a system's future performance.

Reflexive systems are ubiquitous. They occur in almost all engineering fields—from the design of computers and artificial intelligence to electric power grid design, cancer therapy, astronomy, military action, economics, and transportation system design and operation.

But they are also complex to understand, difficult to model, and impossible to predict with accuracy. Accordingly, actions based on reflexive models can be misdirected, dangerous, and even treacherous.

Reflexivity through the Ages

The word *reflexive* was first used in 1615, according to Webster's dictionary, but it was in people's imagination well before that. For example, the ouroboros—a mythical serpent that lived (for a while) by devouring its own tail—first appeared in Egyptian tomb scenes in the 14th century BCE.

Epimenides, a (perhaps mythological) 6th BCE Cretan, has been reported to have said, "All Cretans are liars," thus immersing the listener in an endless loop of dilemma. Shakespeare, Diderot, and Pirandello each used reflexivity as a literary device. In the 19th century Droste packaged its cocoa in a tin with a picture of a young woman holding a tin of Droste cocoa with a picture of a woman holding.... You get the picture.

More recently, the artist MC Escher (1898–1972) was famous for drawing pictures of hands drawing pictures of hands. Werner Heisenberg (1901–76), the founder of quantum mechanics, was the first to point out that there is a fundamental limit to the precision with which the values for certain pairs of physical variables can be predicted from initial conditions. Kurt Gödel (1906–78), the Princeton logician, believed reflexivity was ubiquitous. He proved that any system that was consistently described had not been completely described, and any system that had been completely described could not be internally consistent. Sixty years later financier George Soros reframed Heisenberg's and Gödel's messages for financial systems (Davis and Hands 2017).

There are nefarious uses of reflexivity. Double agents who spy against their own country are an example. Uncertainty about whether someone is a double agent provides a further example.

Lack of Predictability

The common feature of all reflexive systems is feedback between the "observer" and the "observed." In financial equities trading, for example, predicting securities price behavior requires understanding not only the fundamentals of the securities but also the precise relationships between the securities and traders' motivations in order to understand market behavior. Attempts to simplify the analysis run the risk of introducing errors into models.

As Soros pointed out (Davis and Hands 2017), the market is not precisely predictable in either the short or long term. Consider the VIX, the index of market volatility. If the market moves up or down with constant volatility the VIX will be constant. If, however, the volatility of prices of individual securities changes, then the VIX will change. The VIX is anything but constant or predictable.

The inability to predict reflexive system behavior creates substantial problems for decision makers in politics and finance as well as in physics. One needs to be skeptical of models that do appear to work, since the past will be an unreliable guide to the future. Heisenberg would have been comfortable in this environment.

Illustration: The 2008 Market Crash

The challenge for managers of reflexive systems comes when the systems are performing in a way that appears to be driven by cause and effect, but in fact is driven by hidden feedback. For example, in the middle of 2008, the financial markets were beginning to "jitter." Half the market participants read the signs as a not unusual increase in daily variance. Others saw a quake coming and got out.

In July and August of 2008 all views were being reported hourly, as they always are in the capital markets. Volatility had increased significantly. Questions swirled: Was the increase in volatility "just noise" or a sign of an underlying instability—a coming quake—in the market? No one knew the answer, but everyone had a view.

Reflexive systems may perform in a way that appears to be driven by cause and effect, but in fact is driven by hidden feedback.

Then it happened. On September 29, 2008, the market broke, and over the next 9 months it fell just over 50 percent. Half of America's wealth—wealth that had taken decades to build—was destroyed. The market took 4 years to fully recover. In total the US economy lost 7 years of productive effort. It was a high cost to pay for failing to understand and manage recursive systems.

Reflexive Questions

As the speed and ubiquity of communication increase—with 24-hour news coverage, fake news (sometimes from state actors), and news about the news—reflexivity will play an increasingly important role. And, of course, now the dark web exists, with news that is hidden from the news.

The increasing ubiquity of reflexivity raises questions that must be answered:

- Who gets to write history?
- Who decides whether history as written should be rewritten?
- Did the writer have hidden sponsors? We need to know as much about the writer as we do about the history.
- What constitutes “well” or “poorly” written history?
- When does it make sense to “revise” history?

These are all reflexive questions. In the reflexive future the challenge will be to be less wrong rather than precisely right.

Reference

Davis JB, Hands DW, eds. 2017. Reflexivity and Economics: George Soros’s Theory of Reflexivity and the Methodology of Economic Science. Oxon UK: Routledge.

Embracing Behavioral Science

Leidy Klotz

John Pickering

Leidy Klotz and
John Pickering

A defining feature of complex systems is that fully predicting the effects of changing them is impossible. Thankfully, engineers have never been deterred by the specter of impossibility.

When it comes to designing in complex systems, however, there remains an obstacle to unleashing the full force of engineering. The problem is that an essential science for understanding and influencing complex systems is deemed by engineering to be either out of scope, or—at best—an optional consideration for niche disciplines. This needs to change. Because, whether the goal is to quickly introduce a new vaccine or to stabilize climate change, a unifying characteristic of complex systems is that they are driven by human behavior.

Role of Behavioral Science in Engineering

Asking engineering to embrace behavioral science is not unreasonable. In fact, behavioral science provides the overlooked foundation of modern engineering. Sure, engineering often involves creatively applying science and math. But *how* this science and math are creatively applied rests on assumptions about logic and reason.

Leidy Klotz is the Copenhaver Associate Professor at the University of Virginia. John Pickering is cofounder and CEO of Evidn.

It is assumed, for example, that engineering will derive and then select optimal solutions given a set of constraints and goals. It is assumed that engineering will be consistent in how these goals are set and in how resources are valued. Such basic assumptions about engineering design do not garner much attention. They are, after all, "common sense."

But behavioral science has shown that some of these foundational assumptions are wrong. People satisfice, settling for good enough solutions and leaving optimal ones unexplored. People value the exact same thing differently depending on whether they have this thing or not. Such systematic deviations from old models of logic and reason better explain the behavior of complex systems—and can better inform design within these systems.

Mental Traps in Engineering

To take full advantage of opportunities for behavioral design in complex systems, engineering needs to overcome a couple of mental traps that have held back its fields, and therefore society.

To overcome the first mental trap, engineering should stop thinking of behavioral science as "soft," which too often connotes a lack of rigor. Certainly, human behavior varies with context. The degree to which people satisfice, for example, is not absolute. It depends on how much people care about the problem at hand.

But the behavior of molecules and materials also varies with context. Newton's apple falls at a different rate through water, or with a parachute attached. The need to adjust scientific generalizability to practical context is why there are so many variables and coefficients in engineering equations. Precious little behavioral science has been formalized into variables and coefficients, and that is all the more reason for engineering to engage.

To overcome the second trap, engineering should stop concerning itself with the hierarchy and prestige of science. Complex systems trample past the made-up boundaries between disciplines, fields, and types of science.

Contrast the reality of complex systems with how engineering programs are accredited, with students required to learn "sciences appropriate to the discipline" and sciences narrowly defined as "biological, chemical, and physical." Simply eliminating this latter distinction and allowing that engineers can benefit from all sciences would go a long way toward producing engineers who more fully understand the logic and reason that underpin their disciplines—not to mention complex systems.

Engineering researchers must overcome these mental traps in order to engage in research that needs the perspective of engineers. For example, to rationally consider the prospects of climate engineering, we need to understand how engineering behavior aligns with and deviates from findings observed across human populations.

If we are serious about engineering in complex systems of any sort, we need to acknowledge how these multifaceted and unpredictable systems change the cognitive load on designers. In other words, what mental shortcuts do we bring to engineering complex systems? Which are harmful? Which are helpful? And we need to consider engineering-specific social norms to find ways to dismantle systemic sexism and racism in the field.

Engineering practitioners who overcome these mental traps will be rewarded with an expanded role in creatively applying science. Because behavioral science is already being applied, with or without the aid of engineering. Listen to the Nobel-winning behavioral scientist Daniel Kahneman: "There is a technology emerging from behavioral [science]. It's not only an abstract thing. You can do things with it."[1]

Listen to the market: hundreds of organizations and companies have scrambled to build capabilities in behavioral design. The question is not whether behavioral science will be applied. The question is whether engineering will play a leading role.

Closing Thoughts

Engineering will sacrifice impact and market share, and complex systems will remain more vexing than necessary, until engineering embraces behavioral science. There is no time to wait. Minimizing pandemic deaths depends on the behavior of those least at risk; removing carbon from the atmosphere requires different attitudes from those that put it there; and maintaining social growth within planetary boundaries requires simultaneous consideration of environmental impact and human wellbeing.

Our common future depends on our ability to understand and influence complex systems, which depends on our success in creatively applying behavioral science.

---

[1] Edge Master Class 2008: Richard Thaler, Sendhil Mullainathan, Daniel Kahneman – A Short Course in Behavioral Economics, Jul 25.

Managing Failure Risks

Elisabeth Paté-Cornell

Elisabeth Paté-Cornell (NAE) is the Burt and Deedee McMurtry Professor in the School of Engineering and professor and founding chair of the Department of Management Science and Engineering at Stanford University.

The complexity of engineered systems can be baffling, scary, and paralyzing. From fear of flying to fear of nuclear power plants, people have expressed their reluctance about technologies that are useful but, to some variable degree, risky.

Failure risks generally have to be managed under uncertainties, budget constraints, and other social complexities. Herein lies a paradox. It is sometimes stated that system complexity increases failure risk. That is not necessarily true: fly-by-wire aircraft are more complex and safer than classic turbojets. Redundancies generally increase both the complexity and the safety of a system, although their benefits can be limited if their failures are dependent.

Other questionable statements are that more information means less uncertainty, and its corollary, that more uncertainty implies less knowledge. Neither of these is necessarily true. One may have not yet discovered a scenario under which the system has a higher probability of failure than previously believed.

Many types of rare failures can be anticipated while acknowledging uncertainties. Invoking "black swans" after the fact is often a poor excuse for not doing so. Pandemics, earthquakes, and plane crashes will continue to occur, and safety measures need to be taken proactively instead of waiting for a disaster.

Bayesian probability allows combining uncertainties, both epistemic (lack of fundamental knowledge) and aleatory (randomness), and machine learning allows updating automatically the failure risk with new information. Model-based systems engineering has been an accepted tool for decades, generally involving deterministic models. Uncertainties, however, need to be considered, such as those related to loads on a system and its capacity in order to assess the chances that the former exceed the latter over the system's lifetime.

Management negligence, inappropriate incentives, and poor information are main causes of operator errors. This was the case in the accidents that destroyed the *Piper Alpha* (1988) and *Deepwater Horizon* (2010) offshore oil platforms. Risk management thus starts at the top of the organization—and in hiring, training and rewarding people.

Complete risk management involves linking management decisions (M) (e.g., setting incentives), operator actions (A) (e.g., response to signals of potential problems), and system safety (S) based on the performance of critical subsystems (a model called SAM).

Moreover, risk analysis need not be more complex than the situation requires. Some risk management measures, such as maintaining the brakes of a car, do not require a formal analysis. Beyond common sense, one can observe, in practice, several levels of complexity in implicit or explicit risk assessment, from a simple identification of the worst case to central values of the loss distribution and, finally, a full analysis based on scenario probabilities and outcomes. In all cases, the aim is to ensure that extreme values, if they are significant, are properly accounted for.

But risks may change over time. Modeling the dynamics of failure risk may be essential when systems, procedures, risk attitudes, or information are changing. Analyses relying solely on past experience may then be simply wrong. In that case, although statistical information may have become irrelevant, it is often tempting to stick with it because it looks more "objective." But it is not relevant if elements of the system or its environment have changed, or if one has received new information.

If one is considering long-term risk management, the analysis must include the dynamics of a decision sequence and the possible outcomes of the various options.

With risk communications, warning systems can serve as powerful tools, including to better understand both false positives and false negatives. Near misses and important information are sometimes dismissed at the operational level because, though precursors occurred, the accident did not actually happen.

At the management level, the structure and procedures of the organization must ensure that warnings reach the right decision maker. Obviously, all signals should not be transmitted to the top, but the filters in place should be designed to recognize the importance of messages even if they include uncertainties. For instance, in 2001 the FBI in Phoenix had received signals that individuals were taking unusual flying lessons, but the information was not acted upon.[1]

In flat organizations, information may circulate easily and decisions may be widely understood, thus facilitating risk management, but managing a program that requires a number of systems and organizations can be particularly complex. Space programs such as Apollo or Artemis have involved a large number of contractors, interfaces, techniques, assumptions, and risk tolerance levels. It is the role of management to ensure that these programs interact effectively to gather and share information and warnings in order to ensure consistency, compatibility, and safety.

Compatibility and consistency are key to managing the failure risk of complex systems and programs. Risk analysis does not yield predictions but rather the chances that a failure may occur and the effectiveness of various safety measures.

When assessing a complex system, a key issue is the model formulation. This may require simplifying the system's representation to make the analysis manageable. For example, the heat shield of space shuttle orbiters involved about 25,000 different tiles, and the formulation of the risk analysis model required grouping them in zones with similar values of key parameters.

A challenge for unifying systems is to find better ways to communicate the risk assessment results and the uncertainties, rather than presenting the most likely hypothesis as if one could be sure of it. For the risk message to be effective, one should avoid large numbers of complex scenarios.

In the end, one needs to check that the results fit common sense and if not, determine whether it is the model or the intuition that needs to be reassessed.

---

[1] Findings of the Final Report of the Senate Select Committee on Intelligence and the House Permanent Select Committee on Intelligence Joint Inquiry into the Terrorist Attacks of September 11, 2001: Final Report, Part 1, section 5e, Dec 10, 2002, pp. 325–35 (https://www.intelligence.senate.gov/sites/default/files/documents/CRPT-107srpt351-5.pdf).

Complexity Blind Spots

Susan Fitzpatrick is president of the James S. McDonnell Foundation.

Susan M. Fitzpatrick

Although scientists and engineers know that many of the hardest problems daunting society and in dire need of solutions are complex, the tendency in the academic research community is to pursue its work as though problems are simple.

Seeing Holes—and Their Absence

Complex systems researchers David Krakauer and Geoffrey West (2020) have offered a compelling insight into why the traditional practices of science and engineering struggle to seek meaningful solutions that address complex problems: Humans have a cognitive blind spot that causes us to ignore what is not seen. Krakauer and West illustrate this point with a World War II story about the analysis of the location of bullet holes in planes returning from missions.

Faced with the dilemma of balancing the need to armor planes from enemy bullets without making the planes too heavy, the military called in experts to study the pattern of bullet holes in returning planes and make recommendations about armoring future planes. The experts at first suggested the obvious: the military should add armor to the areas most frequently damaged. Makes sense, yes? Well, maybe not.

One of the experts consulted, the statistician Abraham Wald, pointed out that since the planes analyzed *had all made it back*, the parts of the planes with bullet holes were those that could sustain damage and still fly. What if, Wald asked, the parts of the returning planes that showed no damage were those essential for continued functionality? What if the planes that did *not* return were those that sustained damage in these essential areas?

Persuaded by Wald's thinking, the military armored the parts of the planes that typically returned with no damage. It worked. Protecting the essential components of the planes (e.g., engines) allowed aviators to adhere to weight limitations while decreasing losses and saving lives.

What the Pandemic Has Revealed

Krakauer and West use this powerful World War II example to direct attention to the damage *not* attended to during the covid-19 global pandemic, what they describe as "the deeper nature of the crisis—the collapse of multiple coupled complex systems."

> *Pervasive system failures result from willingness to ignore the* damages we do not see.

From my perspective, the covid-19 global pandemic has revealed the fragility and brittleness of any number of the engineered systems that we rely on, as individuals and as a society. Be it transportation or health care, education, or the food supply chain, it can all fall apart quickly when shocked.

Most importantly, although the virus is where our attention is being drawn, the pandemic is not the cause (in part it is more likely a result) of societal fragilities. The pervasive system failures result from willingness to ignore the *damages we do not see*. In almost every one of the sectors above, we are where we are because we engineered systems ignoring the complexity of the problems they were designed to solve.

Much of 20th and 21st century science is dominated by reductionist thinking rather than complex systems science thinking. These two robustly different traditions influence the way questions are framed, solutions pursued, and investments made in the infrastructure for pursuing research. The pressing problems pertinent to the quality of human life in terms of climate, health and wellbeing, social structures and inequities, economic stability, and educational effectiveness are complex and require approaches that honor complexity. Sadly, acting as though the complex is simple will not make it so.

Unseen Costs of "Efficiency"

By prioritizing "efficiency," built systems have eliminated the traits, such as redundancy, that natural complex systems have evolved to remain robust and adaptive. Centralized hub-and-spoke configurations are "efficient" only because of the damages and fragilities we do not see.

- Networked but nonadaptive transportation systems often fail to move people from where they are to where they want to be on a good day. Introduce natural or man-made disruptions and movement can grind to a halt.
- Sophisticated instructional technologies claim to solve the need to efficiently advance educational goals but, when tested, their effectiveness is stymied by an inability to ensure equal access and determine meaningful outcomes.
- Industrialized food provides a plentiful calorie-dense diet, but its nutrient-poor nature is adding to the health issues faced by many of the world's most vulnerable citizens.
- Funders have spent billions of dollars pursuing medical interventions using highly artificial and overconstrained laboratory models that efficiently produce data but fail to deliver effective therapies because the reductionist science ignores the reality that diseases occur in the context of a complete adaptive organism.

In all of these examples and in many other arenas of our engineered world, the damages we do not see are the costs to individuals and to society when perturbations knock our fragile systems to their knees.

Looking Ahead

Could we "build back better?" In a word, yes. But the difficulties of doing so cannot be swept under the carpet. Progress and improvement require will and dedicated effort to shift the dominant school of thought toward one that embraces both robustness and adaptation. New values need to be adopted, rewarding and incentivizing the difficult task of meeting global needs rather than fulfilling parochial goals. Doing so means educating a generation of scientists and engineers in the theories, concepts, tools, and mathematics of complex systems science.

The massive shock that covid-19 dealt the global community is already creating an opportunity for novelty and creativity. Airlines and other transportation sectors are reconsidering the distributed point-to-point model over the centralized hub and spoke. Clinical trial specialists are exploring opportunities for carrying out their work in “messy” community healthcare settings. Urban vertical farms are looking to grow healthy, nutritious food locally, reliably, sustainably, and affordably. Schools are seeking effective teaching strategies that serve all children and will meet the needs of mid-21st century learners.

Perturbations allow novelty to be introduced into stable systems. The pressures of war allowed the military to consider an unintuitive solution and lives were saved. The time is now for the scientific and engineering communities to likewise identify the damage we are not seeing, advance progress by fulfilling the demands for new knowledge, and engineer solutions that better serve all of us.

Reference

Krakauer D, West G. 2020. The damage we’re not attending to. Nautilus, Jul 8.

Building a Meta-University

Darryl L. Farber, Douglas Melton, and Monty Alger

Darryl Farber

Douglas Melton

Monty Alger

Engineering practitioners, researchers, and educators struggle with complex systems. They keep us humble. Even as understanding improves about the complexity of both the natural and the artificial worlds and the interactions between them, and with growing knowledge about how complexity is generated through the development and deployment of engineering systems, new problems arise that need to be solved. These are "wicked" problems where defining the problem itself is a problem. Personal and social values complicate the problems further.

Darryl Farber is a professor of engineering at Pennsylvania State University in the School of International Affairs and the College of Engineering. Douglas Melton is program director at the Kern Family Foundation. Monty Alger (NAE) is a professor of chemical engineering at Penn State and president of the American Institute of Chemical Engineers.

How then can new competencies and capabilities be developed to understand and learn about complex systems and associated problems? We focus here on prospects for higher education, specifically the idea of a "meta-university."

What Is a Meta-University?

As conceived by Charles Vest (2007), the meta-university would function as a distributed and decentralized network of universities. They would rely on a variety of means and platforms for sharing scholarship—teaching materials, archives, and research laboratories—in physical and virtual spaces to increase access, affordability, and learning effectiveness both for personal growth and development and for societal impact. Since Vest's initial formulation, the concept of the meta-university has grown to include partnerships with business, nongovernmental, and government entities.

The Value Net

Another way to describe the workings of a meta-university is through the lens of a "value net" (Brandenburger and Nalebuff 1996), which portrays relationships among participants in a market with one firm or enterprise, such as a university, at the center of a network of customers, suppliers, complementors, and competitors. The value net provides a *unified* view of the market playing field and the "players," to highlight the interactions that add value. The value net grounds different scenarios of learning and learners and recognizes added or subtracted value in each of them. In effect a value net describes how the meta-university will emerge and evolve.

Relevant Initiatives

We are encouraged by two initiatives in our practice areas, call them working prototypes toward the meta-university concept.

The American Institute of Chemical Engineers' Institute for Learning and Innovation is developing new pathways for students, faculty, and professionals to better serve the "marketplace" of chemical engineering. And the Kern Entrepreneurial Engineering Network has engaged 51 universities in developing a digital platform, EngineeringUnleashed.com, for sharing practices across a variety of topics. The platform expands the horizons of and access to engineering education to nurture an entrepreneurial mindset, collaboration, and ethical character.

Challenges

These initiatives and others, such as edX and Coursera, also point to challenges:

- How to develop a learner-focused platform that has rapid cycle time, offers options for a diversity of learners, provides extensive feedback, and is affordable and scalable
- How to break down the legacy silos across natural, engineering, and social phenomena and be accessible in multiple ways that do not require a linear progression and that connect diverse communities
- How to instill a sense of judgment to assess and manage risk and to decide and act ethically.

These are new capacities and competencies that need to be developed.

The concept of the meta-university has grown to include partnerships with business, nongovernmental, and government entities.

Strengths

The meta-university facilitates understanding and unification of complex systems in at least three ways:

1. It unifies diverse participation over an expanding value net focused on education and the learner. The meta-university is not a brick-and-mortar place but a network of participants, and its essence is the interactions of the participants focused on the advancement of learning. It is a system for learning that enables an individual learner teamed with an intelligent machine agent to construct an engaging and unified course of study (personalized learning) that is recognized in the labor market. Learners enabled through human-machine teaming have access to a much greater universe of educational offerings.
2. The meta-university is a catalyst for new systems thinking. It is self-organizing and unifies value net stakeholders into a coherent "academy" where the participants' attention (a scarce resource) can be

focused on addressing specific problems or issues from multiple viewpoints, like the NAE's Grand Challenges for Engineering (e.g., advancing personalized learning, managing the nitrogen cycle, or preventing nuclear terror). It serves as the catalyst for integration and convergence—*a unifying viewpoint*—among disciplinary perspectives that enables a higher, general level of understanding of complex systems.

3. The meta-university reaffirms that a universalizing viewpoint is necessary to comprehend and address "the big picture" of global circumstances and problems. A larger conception of the relationship of engineering systems to society is needed to address what appears as a fundamental transformation in society primarily enabled by digital technologies that is like the transformation brought on by the Industrial Revolution. It raises such questions as the following: What will be the new roles of workers especially with the increase in teaming with machines, an arrangement that promises to augment human intelligence and abilities? What capacities, capabilities, and competencies need to be designed, developed, and sustained?

Democratizing Higher Education

Deep uncertainty about technical workforce needs over the next 10–20 years highlights the need for strategic analysis and scenario planning to better understand the possible futures of higher education and engineering systems education.

For standalone universities, such an analysis would inform transition plans, which would include new reward, culture, and collaboration practices. The enterprise model for the standalone university may require a restructuring of its processes and systems, which heretofore have resisted change. Clusters of universities that are willing to experiment, especially those that have experimented in scalable online tech, will likely be the first to test and find alternatives to current standalone university models.

As Charles Vest noted, the meta-university may become the dominant form of higher education in the 21st century, rising above the barriers and inertia of existing capacity to become the unifying force for democratizing a quality, accessible, and affordable education. The "new education" will help develop the capacity to understand and resolve the world's most complex systems problems.

References

Brandenburger AM, Nalebuff BJ. 1996. Co-opetition. New York: Currency Doubleday.

Vest CM. 2007. The American Research University from World War II to World Wide Web: Governments, the Private Sector, and the Emerging Meta-University. Berkeley: University of California Press.

Modeling and Envisioning Complex Systems

Katy Börner

Katy Börner is the Victor H. Yngve Distinguished Professor of Engineering and Information Science at Indiana University.

Most systems that matter are complex. Common to all complex systems is the fact that they are composed of many different components, whose interaction leads to emergent behavior that is hard to predict.

Human evolution has favored local, short-term thinking and action. We are the children of those who specialized in short-term survival. Not surprisingly, many of the reward systems humans have built so far favor those that win attention and support in the short-term, not those that ask for sacrifices today to avoid major catastrophes tomorrow. Given humankind's capability to change Earth dramatically, this is no longer a winning strategy.

The Power of Models and Visualizations

High-quality data, computer models, and advanced data visualizations can enhance understanding of the structure and dynamics of complex real-world systems. In general, this can be done via conceptual models (e.g., causal loop diagrams to communicate system dynamics), mathematical models (e.g., dynamical equations to capture trends), computational models (e.g., network model algorithms that compute the growth of interrelationships), or physical models developed for real-world experimentation or demonstration (e.g., sand piles to understand avalanches).

Some models use empirical data and algorithms exclusively, others rely solely on expert opinions (e.g., gathered via workshops, panels, or surveys).

Computational modeling approaches employ empirical data, which they mine, model, and visualize using computational algorithms.

Most models are designed by individuals from different domains (e.g., sociology, economics, physics, engineering) and sectors (academia, industry, government). Basic requirements in these collaborations are that user needs are properly communicated and understood to guide model design, coding is done in a correct and efficient manner, and results are transparently articulated—including information on model limitations.

Data visualizations can help communicate model effort requirements, model implementations and runs, as well as model results to different stakeholders. A recent special issue of the *Proceedings of the National Academy of Sciences*[1] presents exemplary models and visualizations that aim to support decision making in education, science, technology, and policy. And the *Places & Spaces: Mapping Science* exhibit features 100 maps and 24 interactive data visualizations, called macroscopes (http://scimaps.org).

Designing Models and Data Visualizations

To support the use of data visualizations when designing, optimizing, and communicating complex systems models, a theoretical data visualization framework (DVL) was expanded to cover model design–specific aspects. The resulting ModelDVL covers analytic and predictive models and their visualization (explained in the forthcoming Börner 2021). The framework explains the steps needed to convert expert or empirical data into actionable insights and includes a typology of key terminology.

The process starts with stakeholders (e.g., those that have questions about a complex system yet must manage it resourcefully). Stakeholder information needs must be identified and operationalized (this is similar to translating a verbal math problem into a formula that can be solved). Based on the stated information needs, which include basic insights (e.g., understanding trends, clusters, relationships) as well as emergent phenomena (e.g., oscillation, synchronization, diffusion, growth, adaptation), appropriate datasets are compiled, descriptive and predictive models are selected and run, and visualizations are designed to help communicate the model design, runs, and interpretation of the results. Visualizations are then deployed (e.g., printed or made available as interactive data visualizations), and results are validated and interpreted.

The framework typology covers key insight needs, data scale types, model types, and visualization types as well as graphic symbol and graphic variable types that can be used to map data variables to visual variables. Last but not least, there is a list of interaction types that might be supported by different tools and required to satisfy a certain insight need (e.g., filter by time is valuable for understanding trends or geospatial diffusion over time).

Expanding Use of Models and Visualizations

Today, more than ever before, it is important that anyone be able to model and visualize real-world or simulated data in support of effective communication among researchers, practitioners, and policy- and decision makers. While many may not be able to read formulas or code, an increasing number of experts can read data visualizations and use them to identify and call out problems and opportunities quickly.

Modeling and visualization efforts are heading toward methods and tools that anyone can use to gain insight, as articulated in recent popular books such as *Elevate the Debate* (Schwabisch 2020) and *Calling Bullshit* (Bergstrom and West 2020). Massive open online courses such as Indiana University's Visual Analytics Certificate (https://visanalytics.cns.iu.edu) empower thousands of students to render their own personal and professional data into actionable insights.

Many models and model visualizations are required to yield a holistic understanding of the world and our place in it. A key challenge is the assembly of models and model results into a mosaic that is larger than the sum of parts. Let's combine forces to model and visualize the complexity of our world!

References

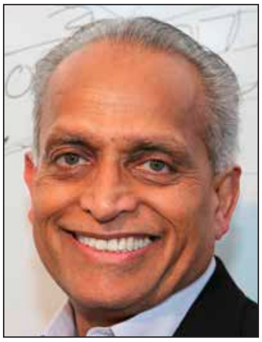
Bergstrom CT, West JD. 2020. Calling Bullshit: The Art of Skepticism in a Data-Driven World. New York: Random House.

Börner K. 2021. Atlas of Forecasts: Modeling and Mapping Desirable Futures. Cambridge: MIT Press.

Schwabisch JA, ed. 2020. Elevate the Debate: A Multilayered Approach to Communicating Your Research. Hoboken NJ: Wiley.

[1] Arthur M. Sackler Colloquium on Modeling and Visualizing Science and Technology Developments (Dec 4–5, 2017), PNAS 115(50), online at https://www.pnas.org/modeling.

Cyberphysical Integration



Chandrakant Patel (NAE) is chief engineer and senior fellow at HP, Inc.

Chandrakant D. Patel

In the 19th and early 20th centuries engineering was about the industrialization of physical and electromechanical systems like the steam engine and utility grid. The latter half of the 20th century was about information management, cybersystems, and the internet. The 21st century is about the integration of the two and the proliferation of cyberphysical systems that address challenges stemming from global social, economic, and ecological trends such as resource constraints, demographic shifts, and human capital constraints.

Cyberphysical Solutions

The burden of negative externalities, from pandemics to environmental problems, is accelerating the need for cyberphysical systems. Solutions in the cyberphysical era will involve operating technologies (OT) and information technologies (IT) that function at the intersection of domain theories, data organization, and data science.

Digital manufacturing is an example of a cyberphysical solution in which the OT are fabrication devices, power delivery systems, and other support systems, and the IT are integrated with the OT to collect data, perform analysis, and drive automated management of manufacturing. In 3D digital manufacturing, the OT is made up of 3D printers and the "art-to-part" cyberphysical pipeline starts with part design anywhere in the world, transfer of digital data to print parts in a given locality, and delivery to the customer. The need-based provisioning capacity of 3D digital manufacturing has shown that it can enable resilient supply chains.

The need-based provisioning capacity of 3D digital manufacturing will enable resilient supply chains.

Indeed, 3D printing has created new realities for on-demand creation of customized and individualized parts. This was recently realized in the production of personalized protective equipment, medical devices, and isolation rooms in response to the covid-19 pandemic. Workflow for a personal protection mask can start by scanning an individual's face, creating the "art" for custom-fitted design, and sending the design file to a local digital manufacturing site to produce the piece. Moreover, it is conceivable that 3D digital manufacturing units are distributed, resulting in microgrids of digital manufacturing supply near the sources of demand, such as in a hospital.

Design, Device, and Digital Factory

The success of 3D digital manufacturing necessitates a holistic perspective that encompasses design, device (3D printer), and digital factory (assembly of systems).

Design

Designers have immense possibilities in creating the art. With the range of additive 3D printing technologies they can create contours that were hitherto not possible in a cost-effective manner if at all. However, they must take into account new sources of variation in the final part outcome given the variable attributes of a given 3D printing technology and even a given printer.

Device

The 3D drawing digital "slices" enter the device (the 3D printing system), which uses a collection of sensors and actuators to additively build parts.

In the case of HP's 3D Multi Jet Fusion printers, the slices of drawing are converted by a controller to signals that drive tens of thousands of thermal inkjet technology–based nozzles in a writing system that traverses the length of the raw material powder bed. The nozzles dispense picoliter-scale drops of fusing and detailing agents at thousands of hertz, layer by layer, on to the powder bed. Fusion heaters apply heat energy that is absorbed in the regions where fusing agent has been dispensed to create disparate solid bodies.

Precise control of the raw material positioning, writing system, and heaters in synchronization is critical to ensure that the right amount of fusing agent is provisioned and heat energy is applied proportionately in exactly the correct place. This makes for a complex multiple-input, multiple-output (MIMO) system that cannot be formulaically represented by a domain-based model alone. The system design uses domain theories, machine-generated data, and artificial intelligence (AI) algorithms to create a "digital twin" that is tuned to predict the successful operation of the machine.

The 3D printer cannot be treated as a black box with the assumption that large amounts of data and AI alone will create the digital twin. Deep domain understanding of engineering systems is fundamental to a successful model. As an example, computer vision algorithms applied with domain theories associated with the powder bed can enable a machine vision system to discern the attributes of the powder bed and thereby control the deposition of the agents and heat flux from heaters in real time during production.

Digital Factory

The digital factory is a system of systems built with OT and IT. The heterogeneous mix of 3D printers is simulated with digital twins during the layout and design of the factory to allow for holistic factory optimization, minimizing operating costs while maximizing production output. For example, a digital factory with 100 3D printers draws more than 1 megawatt of power and thus requires appropriate power distribution system design.

The factory produces parts on demand based on customer service level agreements (SLAs), which spell out customization and engineering requirements given the application and the turnaround time. The SLAs are turned into service level objectives and applied to the pool of machines, managed via sophisticated enterprise resource management and manufacturing execution systems.

A communication layer collects machine-generated data from rich sensing subsystems (e.g., video sensors, actuators). In the future the communication layer for the 3D printers will be a 5G mm scale wavelength network, and a local microdata center (Cloud 2.0) may be used for storing and analyzing terabyte-scale data. Onsite computing will enable real-time analysis and action. Metadata and insights (e.g., tweets) will go to the current Cloud 1.0 for global coordination, which will facilitate other management such as software updates.

Digital factories can be further expanded for net zero operations with local power grids built using multiple sources of energy, creating a distributed network of such factories to meet growth in demand for need-based provisioning.

Cyberphysical Workforce Needs

Secure 3D printing suggests an exciting future in complex, unifiable cyberphysical systems. Multidisciplinary systemic instantiations show the impending need for cyberphysical systems professionals who operate at the intersection of domain, data, and AI. This is crucial given a prevalent, and often cavalier, view—particularly in light of AI success in ecommerce and social media—that any complex physical problem can be solved with data and AI alone.

AI for the 3D "art-to-part" pipeline is about detecting anomalies, prognostics, diagnostics, and closed-loop action to drive efficient operations of physical systems. It is not the same as cyber age examples of recognizing a cat or dog from pictures, recommending restaurants, or determining ad placement in social media based on an individual's profile. The "black box" around a cyberphysical system is transparent.

Cyberphysical contributors must have depth in engineering fundamentals of the machine age and breadth in information sciences of the cyber age. This can be achieved through a variety of learning paths such as dual degrees and continuing education. Above all, these contributors must have a "learn by doing" aptitude with T-shaped knowledge to build and integrate systems.

Complex Environments

Brian Collins is emeritus professor of engineering policy at University College London and former chief scientific advisor to the UK Departments for Transport and for Business, Innovation, and Skills.

Brian S. Collins

There's often a tendency to simplify complex systems. One should realize the risk in doing so. Simplification of complex matters does not improve the situation of the issue at hand. To deal with a system's complexity it is necessary to understand the scope and interdependencies of its subsystems.

The word *environment* has been captured by those interested in how (what is regarded as) the natural world functions. In recent years it has come to mean many things: climate change, biodiversity, and extreme weather. Humans are part of this environment and it is now clear that anthropomorphic effects on the atmosphere and oceans are at such a scale that they have significant impact on what is considered the natural environment and are now also affecting human existence. Thus, the tacit assumption that the separate consideration of human existence and the natural environment is reasonable is no longer valid.

Interdependence of Humans and the Natural Environment

The systems that make up the natural environment and those that have been regarded as describing human existence are individually complex and extremely closely linked. If they are dealt with separately and in an oversimplified manner, the reality of their interactions and the consequent emergent properties are not addressed.

It is therefore essential that the disciplines and approaches of complexity research be applied jointly to human beings and the environment to improve the situation for both.

An example of this is food production. To produce more food in the right places for people it is necessary to analyze the nature of the soil, weather, and water supplies; the presence of other species that may affect the crops and domesticated animals; *and* the economics of the communities, the cultural acceptability of certain food types, and the maturity of the social and physical infrastructure to support any new initiatives. Thus in conditions where little water is available, crops need to be developed that resist drought; for areas subject to locusts, food crops that locusts don't like should be researched; and if it were possible to rear animals such that what they eat produces considerably less methane, that would be advantageous for their effects on the atmosphere. All of these should be researched and delivered taking into consideration broad economic and social contexts.

Similarly, pollution of the oceans by plastics, fuel spillage, and runoff from agricultural practices should be considered when looking at fish stocks. Such pollution has critical impacts on the salinity of the water and its albedo and on very delicate food chain mechanisms in the deeper parts of the ocean.

Consideration of these examples of impacts of human activities that are meant to sustain the population (currently 8 billion and rising) is absolutely vital to understanding how to enable the human species—which has no more right to not become extinct than any other species—to survive the stresses and strains of life on planet Earth. As Carl Sagan famously said, when viewing the image (one pixel) of Earth from the Voyager satellite near the orbit of Saturn, "preserve and cherish the pale blue dot, the only home we've ever known."

Emergent Properties

The concept of emergent properties, which is core to how systems of systems are viewed through a complexity analysis lens, is also worthy of consideration. It may be that such properties are only those that people fail to understand because they are seeing them for the first time. It may also be that understanding of the basic mechanisms underlying system-of-systems interactions is so poor that it is difficult to forecast their likelihood. And it may also be true that in certain circumstances the statistical properties of those interactions, when analyzed through an appropriate mathematical process, show that it will be impossible to ever predict an emergent property.

The interaction between complexity science, on the one hand, and man-made and natural (if they can indeed be separated) environments on the other is vital to the continuing survival of humanity. Without global cooperation there will always be activities that put human lives at risk over the long term. Therefore forums for such cooperation (e.g., the UN Sustainable Development Goals) must be pursued with vigor and with mission-oriented, coherent, high-quality, and properly assessed research. Such activity must also include approaches to financing and valuing outcomes of activity in a broader way than pure financial growth.

Current efforts to improve understanding of the value to society of such activities are crucial to being able to achieve the necessary level, depth, scale, and speed of collaboration. Unfortunately some governance mechanisms do not lend themselves to this scale of collaboration and integration. This is where most efforts are needed.

Cultural Evolution and the Paradox of Diversity

Michael Muthukrishna is an associate professor of economic psychology at the London School of Economics.

Michael Muthukrishna

Humans are a different kind of animal, dependent on not just genes but culture. We rely heavily on this socially acquired knowledge.

Over generations culture has shaped the human genome. Our guts are too short and our jaws are too weak for raw food and yet we don't have instincts for cooking or even fire making, nor could we easily figure these out in isolation. Instead, we are born into a world of cooked food and plenty to learn, both of which are necessary for survival. That body of knowledge, what we call *culture*, has been evolving for generations through innovation and accumulation. This process of cultural evolution provides a framework for understanding innovation and designing policies that maximize innovation by leveraging policy levers like diversity.

The Paradox of Diversity

Diversity is a paradox. Governments and organizations often push for greater diversity and tolerance for diversity, because the human tendency is toward squashing difference and selecting others like ourselves. But diversity is a double-edged sword.

On the one hand, innovations are often diverse ideas recombined, a process of intellectual arbitrage—discoveries and technologies situated in one discipline, but drawing on a key insight from another. On the other hand, diversity is, by definition, divisive. Without a common understanding, common goals, and common language, the flow of ideas in social networks is stymied, preventing recombination and reducing innovation. Consider the challenge of collaborations between scientists and humanities scholars or even between scientists in different disciplines. The key to resolving the paradox is to find common ground through strategies such as optimal assimilation, translators and bridges, or division into subgroups.

Innovation is often assumed to be driven by genius innovators—the giants on whose shoulders we stand. What this view ignores are the scientists, engineers, and entrepreneurs of equal stature whose efforts led to dead ends. Instead, innovation is driven by collective processes as ideas flow through social networks, recombining in the minds of innovators and groups.

There would be a lot less simultaneous invention and people would be a lot less afraid of being scooped or beaten to market if innovation were truly a product of individual genius alone. But to understand this process, we need to understand a little more about cultural evolution.

Cultural Evolution

Cultural evolution is an extension to the mathematical toolkit of evolutionary biology into the realm of socially transmitted information. Any adaptive evolutionary system, whether genes or a genetic algorithm, requires three ingredients:

- things must vary,
- things must be transmitted without losing too much information, and
- things must be selectively transmitted such that more adaptive things persist better than less adaptive things.

Natural selection describes how these ingredients manifest and allow organisms to genetically adapt to environments over generations. Cultural evolution describes how these ingredients manifest and allow societies to culturally adapt faster than genes.

Limited Cognitive Capacity

Culture (knowledge, norms, tools, and technologies) has been accumulating to the point that today not even the smartest person could recreate the current world. Indeed, many adaptations and societal changes have evolved to deal with better ways to store and manage collective capabilities that exceed the storage capacity of any individual brain.

Humans excel at social learning, started teaching, and got better at both. Many hunter-gatherers mostly let children hang around to learn with no direct instruction. Pastoralist societies and chiefdoms do some deliberate demonstration.

Without a common understanding, common goals, and common language, the flow of ideas is stymied, preventing recombination and reducing innovation.

Since the Industrial Revolution, societies have focused on one particular institution and made it compulsory: formal schooling, which helps each generation efficiently catch up on several thousand years of human progress. And despite ongoing pressures for educational innovation, we still spend longer learning, extending childhood and then creating a cultural adolescence (the period between when a person can reproduce and when she actually does) to the point that the challenge is less the ability to birth a big head and more the ability to give birth at an older age.

Most effective of all, we divided up knowledge and labor—we specialized, creating the paradox of diversity.

Specialization

Specialization makes it possible for society to exceed the capacities of a single brain.

Imagine that there are 10 things that are required to survive—food, housing, shelter, clothes, the rules of society, defense, and so on. And imagine that any individual's cognitive capacity is a maximum of 10 units. Bigger brains can store and manage more information, but it's difficult to birth anything bigger until medical interventions like Cesareans are invented.

If humans must learn all 10 things to survive, we can achieve 1 unit on each skill; 10 brain units, 10 things, skill level 1. But imagine you only have to learn half those things because there are enough people that even if some die, enough others know the other half. Now you can dedicate yourself to getting better at 5 things and reach skill level 2. Now imagine you only need to learn 1 thing: society can now reach skill level 10. Divide it further and the sky is the limit, despite a limited 10-unit brain.

Further specialization means further increases in the average skill of a society. In a small town, there may be one general physician, but in New York a doctor may specialize on a small part of the renal system and get very good at treating that one part. Society is then able to compute almost as a collective brain.

But this creates a new challenge. Individuals become smarter at a few things and stupider at everything else, siloing specialists into disciplines and creating a challenge for coordination among different specialists.

Many of the most impactful research papers and patents are the result of intellectual arbitrage—leveraging common knowledge in one discipline to solve problems in another. The solutions to common problems are sometimes stored in separate disciplines, sometimes spread across the brains of many people.

Enhanced Innovation through Cultural Evolution and Diversity

Cultural evolutionary theory predicts three key processes that lead to innovation. Incremental innovation is the product of small improvements through partial causal models—Edison's 99 percent perspiration. Experts often understand a small part of their larger discipline better than others do, but large innovations are typically recombined ideas or simply serendipity.

Cultural evolution predicts three levers of innovation that increase the likelihood of discovery:

- *Sociality* describes the size and interconnectedness of a society—larger, more interconnected societies have more ideas that can more easily flow through denser social networks to meet and combine.
- *Transmission fidelity* denotes better means of communicating information to allow information compression, easier learning, simplified steps, discovery of fundamental principles, and more information stored per head.
- *Diversity*, as explained above, is the double-edged sword, which can help or harm innovation.

Resolving the tension between diversity and selection is at the core of a successful innovation strategy. And there are many possible solutions.

Some dimensions of diversity matter more than others—without a common language, communication is difficult. On the other hand, food preferences create little more than an easily solved coordination challenge for lunch. But between these are many dimensions where optimal assimilation may be desirable and traits can be optimized, such as psychological safety so people feel free to share unorthodox ideas.

Other strategies include interdisciplinary translators. In my role at the Database of Religious History—a large science and humanities collaboration—we have benefited from a few scholars trained in both to bridge the gap. Innovation can also be divided into independent groups, coordinating within the group but competing against others trying different strategies, as is the case in competition between firms.

Cultural evolution and dual inheritance theory—the culture-gene coevolutionary framework—represent the best approximation of a theory of human behavior. Like other formal unifying frameworks of the past, from natural selection to the periodic table, it helps us both make sense of existing knowledge and design new approaches to tackle the challenges of the future.

The Complexity of Increasing Returns

César Hidalgo holds a chair at the Artificial and Natural Intelligence Toulouse Institute (ANITI) at the University of Toulouse, and has visiting appointments at the Harvard Paulson School of Engineering and Applied Science and the University of Manchester Business School.

César A. Hidalgo

While the idea of increasing returns—the tendency for what is ahead to get further ahead—has been part of economics since the pin factory, it was long resisted by economists. The reasons were both simple and profound.

For decades, economists had a strong preference for models with a single equilibrium. This preference was incompatible with the idea of increasing returns.

Imagine a farmer choosing whether to use her land to grow food or raise cattle. She begins by planting her most fertile land. When that runs out, she moves into worse land, where the returns for her efforts will decrease. Eventually, the next patch of land is not worth tilling so she dedicates it to cattle instead.

In this story, diminishing returns lead the farmer to allocate land optimally among crops and cattle. It follows that diminishing returns are the secret behind the invisible hand. They imply that economies allocate resources optimally among multiple activities, leading to a strong policy implication: markets find an equilibrium that is both efficient and fair.

Increasing Returns: VHS vs. Betamax

But there are also increasing returns. These lead to multiple equilibria, runaway monopolies, and sensitivity to initial conditions (chaos). Yet it was by embracing increasing returns that economists like Brian Arthur (1996) were able to transcend economics' fear of complexity and blaze the trail that embraced it.

Increasing returns can emerge from multiple sources, such as knowledge accumulation (learning) or network externalities.

Remember the 1980s, when VHS and Betamax battled for home video dominance? This is a case where network externalities led to increasing returns. The more people used a standard (VHS), the more lucrative it became to produce content and hardware for it. In this case, markets do not reach a competitive equilibrium between both options. They select one of them in a symmetry-breaking dynamic.

But increasing returns turned out to be unpalatable from both a theoretical and a policy perspective. They implied that economies had multiple equilibria and, even worse, that luck could play a role in choosing them. This meant that, in the presence of increasing returns, markets could no longer be argued to be optimal or fair, opening the door to a more proactive view of industrial policy.

Cornering the Market

In his 2018 address to the Schumpeter Society, Keun Lee, a professor of economics at Seoul National University, shared the story of Korea's triumph in the LCD market.[1] He explained that LCD manufacturing technology was characterized by generations. This meant that every now and then a new way of printing LCDs was discovered. These changes in technology enabled the production of larger, better, and cheaper displays, but only after manufacturers climbed a learning curve in which they produced screens at a loss while learning the new technology.

Although LCD technology first became available in the 1960s, it only became a commercially viable display technology in the '90s. It was then that South Korea decided to outsmart Japan and skip an entire manufacturing generation. That meant producing LCDs at a higher cost than their competitors, in a bet to be the first to climb the next learning curve.

Korea's bet was risky, but it worked. During the 2000s the country became a dominant player in the LCD market, surging from about a 5 percent share in 1995 to about a 20 percent share in 2012. This was in a rapidly growing export market, which ballooned from less than \$5 billion in 1995 to more than \$80 billion in 2010.[2]

Of course, there is more to this story than increasing returns. Korea was already involved in related activities that increased its chances of success (Hidalgo et al. 2018); it had, for example, executed similar industrial policies in the past (e.g., for auto manufacturing). Yet the moral of the story is not about Korea but about industrial policy in a world of increasing returns.

Outpacing the Invisible Hand in the Knowledge Economy

Back in the 1890s, putting an engine on a horse carriage was enough to become a cutting-edge car manufacturer. Thirty years later, that manufacturer had to compete with the industrial complex of Henry Ford.

Knowledge, and more precisely learning, implies increasing returns and narrow windows of opportunity. Seizing these short-lived windows of opportunity requires timely industrial policies. This represents an extremely uncomfortable reality for developing nations, especially those that have enjoyed some success with policies that are compatible with decreasing returns. When business leaders are involved in industries where diminishing returns are the norm, they tend to resist policies that would make no sense in their sectors.

But as the knowledge economy accelerates, those who wait to see how things play out will be left behind. By the time they know what is next, early adopters will be atop mountains of knowledge that will be even harder to climb. The challenge is to conquer a spot on the mountain before it grows taller, if one wants to escape the grip of the invisible hand.

Acknowledgment

The author acknowledges support from ANR-19-PI3A-0004.

References

Arthur WB. 1996. Increasing returns and the new world of business. Harvard Business Review, Jul-Aug.

Hidalgo CA, Balland P-A, Boschma R, Delgado M, Feldman M, Frenken K, Glaeser E, He C, Kogler DF, Morrison A, and 5 others. 2018. The principle of relatedness. In: Unifying Themes in Complex Systems IX, pp. 451–57. Cham: Springer.

[1] https://www.youtube.com/watch?v=xh7MvzCY8Xw

[2] Observatory of Economic Complexity, "Which countries export LCDs? (1995–2018)," https://oec.world/en/visualize/stacked/hs92/export/show/all/189013/1995.2018/

Addressing Social Displacement

Christopher G. Glazner

Christopher Glazner is a senior principal systems engineer and chief engineer of the Systems Engineering Innovation Center at The MITRE Corporation.

For decades this country has seen the decay of former industrial centers, the rise of opioid addiction, an increase in chronic homelessness, widening economic inequality, and the overrepresentation of minority populations in the criminal justice system.

No one desires these outcomes, and there usually is no shortage of ideas for how to fix them, especially after an event brings them to the public's attention. Laws have been passed, policies enacted, and funds appropriated to address these symptoms of social displacement, yet they continue to fester, resistant to all efforts. Why?

Focusing on Symptoms Instead of Systems

These pernicious symptoms are the proverbial "tip of the iceberg" that result from the dynamic behavior of complex systems. Social systems, like all complex systems, are highly interdependent with significant feedback and nonlinear relationships. For every action, there are second- and third-order effects, which are often not anticipated.

While it may be possible to understand a small part of a system, it is not usually possible to predict how changes to that part will change the behavior

---

The author's affiliation with The MITRE Corporation is provided for identification purposes only and is not intended to convey or imply MITRE's concurrence with, or support for, the positions, opinions, or viewpoints expressed by the author.

of the larger system over time. For example, in a community with a large number of homeless persons, emergency housing shelters may be funded to give them safe shelter and the opportunity to rebuild their life. Over time, however, it becomes clear that the presence of these shelters can act in multiple ways to limit society's long-term ability and willingness to help the homeless population make a lasting recovery.

Actions that address a symptom of a system may work temporarily but do not address underlying drivers and so eventually fail.

For many thorny social issues, the focus is often on "quick fixes" that are intuitive, easy to communicate, and closely related to the symptoms to be addressed. However, quick fixes, like the funding of emergency shelters for the homeless, often fail over the long run. "Fixes that fail" appear so frequently in public policy that they are deemed a systems thinking archetype: a common pattern in systems that leads to expected system behaviors.

In the classic application of fixes that fail, short-term actions are taken to address a symptom of a system. The fix may work temporarily, but it does not address important underlying drivers of the symptom, which eventually overwhelm the fix.

The Iceberg Model

In all complex systems, but especially social systems, people respond first to events that they can directly observe. They see the unjust actions of police, homelessness encampments, a town's closed factory. The first impulse is to take immediate action to address these events, and that becomes the goal in implementing social policy.

A complex system requires looking deeper than events to understand where to take action. The practice of systems thinking provides the *iceberg model* to help guard against premature solutions in systems. In the iceberg model, events in a system are the visible tip of the iceberg; system understanding comes from looking at successively lower levels "underwater" for opportunities to effect change.

The first level "below the waterline" involves understanding events as part of patterns of behavior over time. Patterns of behavior in systems are driven by underlying structures of causal effects and influences, which is the next deeper level in the iceberg. At the deepest level are the underlying mental models and beliefs of the system.

We can have more impact in a system with less resistance by influencing the underlying structure that gives rise to behaviors, or, even more effectively, by shifting the mental model of the system through changes in the policy objectives of a social program. Social policies based on a deeper system understanding can have more lasting effect compared to the common fixes that fail.

Effective VA Efforts for Homeless Vets

In the early years of the Obama administration, the US Veteran's Administration (VA) took on the daunting challenge of ending homelessness among veterans. The VA leadership understood that this was a complex system; for many years the number of homeless veterans, who were disproportionately represented in the homeless population, had proven very difficult to reduce despite a number of funded, supporting programs.

In an effort that began in 2010, the VA adopted a systems engineering approach that brought together a variety of stakeholders, from social scientists to statisticians, who developed a holistic plan to reduce homelessness among veterans. As a member of this group, I worked with colleagues from government, academia, and the nonprofit sector to develop dynamic systems simulation models that helped us understand why programs had performed as they had. We developed models to support budget requests to Congress for new programs designed to break the "fixes that fail" archetype and lead to a long-term reduction in veteran homelessness.

This model-driven analysis provided confidence in the VA's program design and contributed toward the full funding of programs such as VA Supportive Housing for thousands of veterans, which helped break cycles of their flow between shelters and the streets. This was possible in part because diverse stakeholders came together, communicated their mental models of the system from different perspectives, and used data and simulation models to explore what could be.

Stakeholder Mental Models

In efforts to address any social problem, stakeholders and policymakers must commit to sharing mental models explicitly in order to build deeper system understanding. Once a shared understanding is achieved, the tools and approaches of complexity can be brought to bear.

For example, if stakeholders team up with modeling experts, they can use graphical techniques such as causal loop diagramming to visually develop their mental models. This process requires stakeholders to make their reasoning and understanding explicit and visual, enabling them to more effectively communicate their perspective to others.

If this process is repeated for multiple stakeholders with different perspectives, the models can be used in conjunction with data to build simulations, exposing competing mental models to analytical scrutiny and providing a rigorous platform to evaluate ideas to solve social challenges before testing them on the general population.

Conclusion

While this approach does not pretend to solve all social problems, it is more likely to identify leverage points deeper in the iceberg and thus yield lasting impact. It also provides a powerful tool to test potential solutions and better understand their impacts from all angles.

A systems approach can avoid quick fixes that address only the symptoms of a problem and inevitably fail to effect the broader systems changes that are so desperately needed.

Complexities of Civic Life

Peter Levine

Peter Levine is the Lincoln Filene Professor of Citizenship & Public Affairs and associate dean of academic affairs in the Jonathan Tisch College of Civic Life at Tufts University.

Imagine that some college students have volunteered to serve meals at a homeless shelter. They love the experience because they are helping others. During the reflection session after the meal, one student remarks, "Serving the homeless was so great! I hope this shelter will still be open 50 years from now so that my grandchildren can also serve here."

The progressive educator who has organized this experience is horrified and says, "No! Our goal must be to *end* homelessness. You must think about root causes, not treat the most superficial symptoms. What are the fundamental causes of homelessness?"

Chastened, the students debate the root causes. Some argue that homelessness results from poverty, which, in turn, is a byproduct of capitalism. Others counter that the root cause is the cost of real estate, which is inflated by zoning laws. They are deep into a discussion of capitalism and the state when the Brazilian legal theorist and former cabinet minister Roberto Mangabeira Unger happens to walk by.

"Stop this!" cries Unger. "You are looking for fixed, simple, law-like causal relationships. We human beings have *made* the social world. What we have made, we can also change—not just the components, but also the many ways they fit together and affect each other."

Unger (who is famous for long speeches) continues, "By looking for root causes, you are limiting your imaginations, assuming that the only important changes are the hardest ones to accomplish. Be more creative. What if we got rid of all zoning and rent control but also gave everyone a voucher for free rent? What if public buildings were retrofitted to allow people to sleep comfortably in them at night? What if houses were shared, and homeless people occupied the temporarily empty ones? What if…?"

The Myth of the Root Cause

I have invented this fable and Unger's words, but I am paraphrasing portions of his *False Necessity* (2004) to support a serious point.

A *root cause* is a metaphor. The root is literally the vital part of a plant that is hidden from sight; digging it up will kill the whole organism. The word *radical* derives from the Latin word for *root*. The educator in my fable thinks he is radical because he directs his students to the deepest, least visible, and least tractable aspect of the problem, assuming that attacking a root is the way to a permanent solution.

But a social problem rarely has one root cause or leverage point. Many factors combine to determine results. The same variables that are outcomes are also inputs or causes. Virtuous and vicious circles and feedback loops are common phenomena that illustrate a broader point: any society is a complex *network* of causes and effects. Interventions are possible at multiple points.

Strategies and Skills for Networks of Causes

Like a root, a network is a metaphor (or mental model) for describing reality, but the difference is important. To improve a society viewed as a complex network requires particular skills and strategies—not those favored by would-be "radicals" who insist on focusing only on "the root."

First, strategies should be tailored to an individual's or organization's location in the network. Management scholar Alnoor Ebrahim (2019) argues that organizations differ in how reliably they can predict outcomes in a system as a whole. They also differ in how much control they can exercise over their portions of the system.

These are two distinct dimensions. With low control but the ability to make reliable causal predictions, a wise strategy may be to identify a specific niche where the organization can operate effectively.

Ebrahim's example is an Indian NGO called Ziqitza Healthcare Limited (ZHL) that focuses on transporting very poor patients to hospitals. Because it cannot control public health, ZHL limits its responsibility to free and rapid ambulance services, which it can predict. It has adopted a linear strategy, connecting just a few nodes within a much more complex social system. But if an organization can exercise wider control, then it should be more ambitious, mapping out a whole social system and addressing multiple linked components.

A social problem rarely has one root cause or leverage point, and variables that are outcomes are also inputs or causes.

Second, objectives, targets, and demands should be appropriate to the system. For example, the heroic phase of the American civil rights movement began with the Montgomery bus boycott. The *objective* of Dr. Martin Luther King Jr. and his colleagues in Montgomery was to dismantle white supremacy in the United States or even in the world. They chose as their *target* the local bus company, not because it was the worst offender (Montgomery's police chief was an avowed racist) but because African American customers could boycott buses. They chose as their *demand* a fairly modest change in the company's seating policy because they believed they could achieve that. From their first victory, they went on to many more, without necessarily attacking what could be called a root cause. Indeed, leaders of the movement disagreed about the fundamental cause of white supremacy—drawing on Afrocentric, Christian, Marxist, and other sources—but they often shared targets and demands.

Third, institutions should value and develop *system leaders*, whose core capabilities include seeing the larger system, fostering reflection and more generative conversations, and "shifting the collective focus from reactive problem solving to co-creating the future," as Peter Senge and colleagues (2015) have explained.

Finally, people should learn methods for combining their individual insights and experiences to form shared understandings of the complex social systems they face. Such methods can include face-to-face meetings in which groups physically diagram problems (an approach that is common in engineering design) or tools to derive system models from data provided by large numbers of people.

Civic Strength through Systems Approaches

People who organize and lead communities, associations, and social movements have always made informal mental maps of the complex social systems around them. The engineering of complex systems can be applied to make such analysis more sophisticated and explicit.

The practices and perspectives of complex systems engineering can be used to strengthen civic education so that young people learn to understand and intervene in their societies (understood as systems). Professional development can be enhanced for adults who play civic roles, whether they work for governments or nonprofits or simply participate in their own communities. And tools and processes can be developed for complex systems analysis to make civic leaders and organizations more effective.

References

Ebrahim A. 2019. Measuring Social Change: Performance and Accountability in a Complex World. Stanford Business Books.

Senge P, Hamilton H, Kania J. 2015. The dawn of system leadership. Stanford Social Innovation Review, winter.

Unger RM. 2004. False Necessity: Anti-Necessitarian Social Theory in the Service of Radical Democracy. London: Verso.

Disproportionalities, Disparities, and Discrimination

Cora Marrett is professor emerita of sociology at the University of Wisconsin–Madison and former deputy director of the National Science Foundation.

Cora Bagley Marrett

Consider the trifecta of forces that have recently shaken the United States: the coronavirus pandemic, economic dislocations, and social justice protests. All three show that the actions and dispositions of individuals matter, as do group processes, community forces, and directions in the broader society. They indicate, too, the interplay across these developments. I relate complex systems thinking to each of these three problems to examine the racial and ethnic inequalities that persist and to illuminate the patterns of inequality.

Racial and Ethnic Disparities Highlighted by the Coronavirus Pandemic

It's been clearly shown that across the nation, racial and ethnic minority groups are more likely to fall ill and die from covid-19 than are Whites. Such discrepancies result from health-related disparities as well as social and economic ones. Members of racial and ethnic minority groups are more likely than Whites to have diabetes, cardiovascular diseases, morbid obesity, and kidney disease. Additionally, minority group members are more likely to live in areas with poor air quality and other adverse conditions.

Individual attitudes and behaviors also bear on health outcomes. In some instances, members of the majority group behave in ways unfavorable to minority group members. In other cases, concerns lie within the minority community, as appears in research about trust: Studies show that Blacks are less likely than Whites to trust physicians and hospitals (Blackstock 2020).[1] One consequence is that these patients are not inclined to either seek treatment or comply with plans for treatment.

These factors add to the complications in unraveling the conditions that explain racial differences in health outcomes, including those connected with covid-19.

Disparities Associated with Economic Dislocations

Recent headlines show a plunging US economy, reflecting the shuttering of businesses and unemployment rates unseen in recent years. During the second quarter of 2020, the gross domestic product underwent its worst drop since 1947. Unemployment rates have skyrocketed to levels unknown since the Great Depression. Covid-19 has been pivotal to these economic dislocations.

But not all groups have been affected identically by the economic downturn. The unemployment rate for White Americans stands at 12.4 percent; for Blacks, at 16.8 percent; and for Hispanics, at 17.6 percent (Garcia and Vanek Smith 2020). Differences between minority- and majority-group persons before the pandemic worsened after its onset.

Social justice exists when the administration of law does not depend on a person's ethnicity, race, gender, or standing.

Unraveling the conditions accounting for economic disparities requires assessing the broader economy. Over the past two decades, changes in the economy—in tax rates, for example—have redounded to the benefit of the highest income groups. Blacks are almost completely absent from those groups and hence profit little from the changes.

There are extensive studies of the character and correlates of economic disparities in American society and explanations for the patterns (e.g., Chetty et al. 2020). These studies and other sources undoubtedly could be mined and augmented to delineate the interconnections—and not merely the elements—associated with the prevailing disparities.

Disparities in Social Justice

Social justice exists when the administration of law does not depend on a person's ethnicity, race, gender, or standing. Protests erupted in 2020 after the police-related deaths of George Floyd, Breonna Taylor, and other Blacks. Although actions spawned by similar events had taken place earlier in the decade, they paled in comparison with these recent ones. People mobilized after the police-related deaths of Michael Brown and Eric Garner in 2014 and Freddie Gray in 2015: In the 2 weeks following the death of Michael Brown, over 25,000 persons participated in 130 protests. Two weeks after the death of George Floyd, over 690,000 participants were counted in 1900 protests.

Of course, public protests centered on racial matters did not appear only in this decade. Marches, sit-ins, and similar activities marked the civil rights movement of the 1960s, although to some observers a systems perspective applies less adequately to that movement than to current developments. The principal reason: nationally visible persons—such as Martin Luther King Jr.—and organizations such as the Student Non-Violent Coordinating Committee. Analysts tend to separate activities with clear leaders from ones without positions of authority.

Social justice issues cover more than police-related deaths. Blacks and Latinx Americans are arrested, charged, and sentenced to jail time more often than are Whites, even for comparable offenses. Significant differences appear, then, in the composition of the prison population. Blacks constitute 14 percent of the total US population, but 36 percent of the population in state and federal prisons. Whites, representing 64 percent of the general population, account for 31 percent of the imprisoned. Latinx persons represent 16 percent of the nation's citizens but 24 percent of those in prisons.

The conditions accounting for these patterns are remarkably intricate. Some lie in the criminal justice system and others outside it. Legal factors (conditions internal to that system) include the nature of the offense and the record of the offender. Extralegal cir-

[1] See also the current research project of Wilkins CH, Griffith DM, Engendering Trust: Efforts to Measure and Increase Trust among African American Men (grant period: 07/15/18–01/14/21; information available at https://www.academyhealth.org/page/engendering-trust-efforts-measure-and-increase-trust-among-african-american-men).

cumstances are not tied to the offense itself but may include a person's educational and income level and social networks.

But differences between groups need not indicate discrimination. Sometimes a reported difference is *disproportionality*, indicating statistical over- or under-representation of a group. In other cases, the contrast reflects *disparity*, meaning that given outcomes are more favorable for one group than for another. *Discrimination* obtains when the disproportionality or disparity results from actions taken deliberately to foster inequities.

Developments affecting social justice are not limited to actions taken in the legal system or by protesters, they are much broader. Therefore, what should more systemic and unified work on racial and ethnic disparities produce?

Using a Systems Approach to Understand Disparities

Quite likely, few would dispute the need to eliminate the disparities, to reduce the inequalities found widely in US society. Does such an outcome move inevitably toward assimilation?

Analyses undertaken in earlier decades assumed that reductions in levels of discrimination signaled, and probably demanded, the assimilation or acculturation of minority groups. These groups, however, have challenged the view that removal of disparities requires absorption into the larger society. Multiculturalism emerges as the alternative. With multiculturalism, groups maintain distinctive properties but are neither censured nor denigrated for doing so. Discussions of complexity, then, should consider the question, Can models be generated that reduce disparities but simultaneously allow for differences?

All the corporate press releases and timely public statements—including by the leadership of the National Academies—have not invariably generated the results their authors intended. Critics have depicted the statements as patronizing, inconsistent with practices within the organization, or subtly promoting assimilation. The mixed responses suggest, again, the importance of understanding complexity, including the recognition that different participants in a system need not have identical experiences or goals.

Complicating any response is the reality that not all conditions, and their consequences, can be fully explicated. This should not eliminate a quest to consider social inequalities in a systems framework. It does, nonetheless, raise an issue whether complex systems can be changed, or designed, through deliberate actions.

Clearly, there are interdependencies in the world of racial and ethnic relations, but the extent to which they are systematic—or subject to principles associated with unity or unifiability—remains to be more clearly specified. What, in the case of the inequalities, is the system of interest? What are its interacting components? How might we grapple with several aspects of the system simultaneously, if disparities emerge and are sustained through various forces?

Discrimination obtains when disproportionality or disparity results from actions that foster inequities.

A focus exclusively on race or ethnicity as the defining characteristic might well ignore the multiple roles and identities involved. The concept of *intersectionality* designates the multiple positions a given individual might occupy, each of which could carry its own unique modes of discrimination and privilege. What a Black working-class mother experiences could depend on whether her race, her economic status, or her gender is of paramount importance for the given context or problem.

Concluding Thoughts

The racial and ethnic disparities found with covid-19, in economic outcomes, and in social justice arenas all have connections to historical forces, cultural conditions, and social configurations. This circumstance raises a third problem: the impossibility of mapping every element, relationship, and activity. Despite these challenges, complexity science could help advance research on race relations by sharpening the notion of systems of relations.

Recognizing that social inequalities derive from complex forces does not invariably plot a path toward action. But social movements and research on specific topics illustrate cases in which deliberate changes have been wrought in complex systems. The effects seen might depend on the nature of the system under analysis, such as its size and intricacies.

Complex unifiable systems thinking offers possible new ways to think about inequalities and new questions that should be posed and answered rather than concrete steps that should be taken. This implies that analyses of racial and ethnic inequalities might not merely draw on complexity science and engineering but offer directions for them.

References

Blackstock OJ. 2020. How did we get here? Historical perspectives. Conf on Addressing Medical Mistrust in Black Communities: Implications for COVID-19, HIV, Hepatitis, STIs and Other Conditions, Aug 29.

Chetty R, Hendren N, Jones MR, Porter SR. 2020. Race and economic opportunity in the United States: An intergenerational perspective. Quarterly Journal of Economics 135(2):711–83.

Garcia C, Vanek Smith S. 2020. Unemployment and the racial divide. NPR, Jun 5.

Policing as a Complex System

Brendan O'Flaherty

Rajiv Sethi

Brendan O'Flaherty and
Rajiv Sethi

Policing in the United States is decentralized. There are more than 17,000 law enforcement agencies, many with overlapping jurisdictions. They each have their own organizational culture, their own protocols for selection and training, and even their own procedures for recording and reporting data. They interact with local prosecutors and judges. They exchange personnel—officers dismissed or disciplined at one location can often find employment at another. And they operate under different laws and guidelines concerning the use of force, including deadly force.

Historical Context

The relationship between police and African American communities has historically been fraught. As Randall Kennedy (1997, p. 26) observed in *Race, Crime, and the Law*, for centuries it was a crime "for blacks to do all sorts of things deemed to be permissible or admirable when done by others," including learning to read, defending themselves from abuse, or fleeing enslavement. The police were called on to enforce laws that were oppressive in the extreme, resulting in cycles of mistrust, as Terrence Cunningham,

---

Brendan O'Flaherty is a professor of economics at Columbia University. Rajiv Sethi is a professor of economics at Barnard College, Columbia University and an external professor at the Santa Fe Institute.

then president of the International Association of Chiefs of Police, acknowledged and apologized for in 2016 (Kennedy 2016).

Even as explicitly discriminatory laws were repealed, police practices continued to contribute to mistrust. In 1966 James Baldwin observed that black neighborhoods were "policed like occupied territory." And "since [the police] know that they are hated, they are always afraid…a surefire formula for cruelty."

Over the past few years, the proliferation of smartphones, security cameras, dashcams, and bodycams has vividly brought many instances of fear and cruelty to light. The killing of Philando Castile and the nonfatal shooting of Levar Jones revealed unwarranted fear, and the killing of George Floyd callous indifference to human life. The latter, in particular, appears to have marked a watershed in American discourse on police use of force. The mass protests in June 2020 were on a scale unseen in recent history, with millions of people joining demonstrations in more than 500 cities.

No officer was killed with a visible knife over the period 2008–13. But more than 100 civilians with knives are killed by police annually.

When egregious incidents of deadly force come to light, a natural response is to seek accountability. The focus is on the officer's conduct and on the response of the justice system. However, criminal prosecutions of officers involved in deadly force incidents have been rare, and convictions rarer still.

Under a federal standard established by a 1985 ruling in *Tennessee v. Garner*, police officers may use deadly force if they believe that a suspect "poses a significant threat of death or serious physical injury to the officer or others." But fear of death is a subjective state of mind, not easily verified, and prosecutors and jurors have been reluctant to second-guess claims that such fear was present and reasonable under the circumstances. Since a criminal conviction requires unanimity among jurors that a defendant is guilty beyond a reasonable doubt, an increased willingness to prosecute officers is unlikely to have much impact on the incidence of deadly force.

Criminologist Lawrence Sherman (2018, p. 434) has argued that, in addition to focusing on the officer directly responsible, police homicides should shine a spotlight on "the complex organizational processes that recruited, hired, trained, supervised, disciplined, assigned, and dispatched the shooter before anyone faced a split-second decision to shoot." In his view, policing is a system with interactive complexity and tight coupling, much like air traffic control, which similarly leaves little room for error and can give rise to catastrophic failures. He notes that "historical evidence from other complex systems suggests that their collateral death rates decline more substantially by re-engineering their social and technical systems than by increasing the certainty, speed, or severity of punishment" (Sherman 2018, p. 422).

Reengineering Policing

How might policing be reengineered to achieve a substantial reduction in the use of deadly force? And can this be done through piecemeal reform, or does it require agencies to be reconstituted root and branch?

To begin with, training needs to focus not only on how an officer responds to threats but on how to prevent interactions from evolving in a manner that results in a dangerous situation. Attempting deescalation, calling for backup, and assessing conditions from a distance can all help.

Patience is especially appropriate when a suspect shows signs of mental illness or is armed with a knife. In many jurisdictions, police are trained to shoot individuals brandishing a knife if they approach to within 21 feet. There is no scientific basis for this rule. For instance, no American officer was killed with a visible knife over the period 2008–13 (Zimring 2017). Meanwhile, more than a hundred civilians with knives are killed by police annually. They can be disarmed without recourse to lethal force.

Even if a shooting is justified under the legal standard, fewer shots will result in fewer fatalities. Police can be trained to fire one or two shots and reassess the situation. In 1991, 41 shots were fired by four plainclothes officers at Amadou Diallo, who was unarmed and innocent of any crime. And after a shooting, officers need not simply wait for an ambulance to arrive. They can offer medical assistance, including the application of hemostatic bandages, and transport victims to hospitals in their own vehicles.

More generally, police homicides could be investigated not just to determine individual culpability but to examine procedures and training in much the same manner as regulators respond to airplane crashes, or hospitals to preventable deaths, or the military to battlefield accidents, with a view to identifying all contributing factors so that such incidents are less likely to be repeated.

Police agencies vary enormously in the propensity to use force. Consider, for instance, those in Phoenix and Philadelphia, cities of comparable size. Over 2013–18, Phoenix Police Department officers were responsible for 103 civilian deaths, while Philadelphia officers were responsible for 34. In fact, the number of police homicides in Phoenix over this period even exceeded the 61 fatalities in New York City, which has five times the population.

Differences across these cities in the rate of violent crime per officer, or the number of officers per capita, are too small to account for such disparities in the use of deadly force. Though hard to quantify and measure, differences in organization culture are a significant factor. Rather than bad apples, the problem may be one of bad orchards (O'Flaherty and Sethi 2019). In this case, agencies with the most serious problems may be the most reluctant to change course, and attempts at piecemeal reform will be ineffective.

But neither bad agencies nor good practices can be reliably identified if police homicides are not accurately counted. Mayors and departments can't be held responsible unless somebody knows how many police homicides are occurring, what the trend is, and how it compares with good practice. Right now, there is no official count of police homicides, or even an official definition. A number of media outlets and crowd-sourced projects have admirably helped to fill the gap, but they don't have agreed-upon definitions or a regular source of funding.

If you can't count, you can't manage. If Black lives matter, then Black deaths—and the deaths of other police homicide victims—must be properly counted.

References

Baldwin J. 1966. A report from occupied territory. The Nation, Jul 11.

Kennedy M. 2016. Head of police chiefs group apologizes for "historical mistreatment" of minorities. NPR, Oct 18.

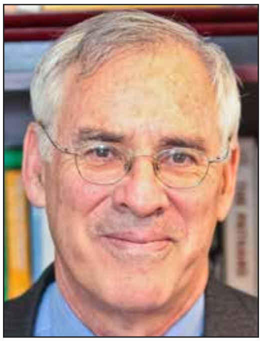
Kennedy R. 1997. Race, Crime, and the Law. New York: Random House.

O'Flaherty B, Sethi R. 2019. Shadows of Doubt: Stereotypes, Crime, and the Pursuit of Justice. Cambridge MA: Harvard University Press.

Sherman LW. 2018. Reducing fatal police shootings as system crashes: Research, theory, and practice. Annual Review of Criminology 2018(1):421–49.

Zimring FE. 2017. When Police Kill. Cambridge MA: Harvard University Press.

Vaccines as Instruments for National Security



Richard Danzig is senior advisor to the Johns Hopkins Applied Physics Laboratory and former secretary of the US Navy.

Richard J. Danzig

The 2018 report *A Preface to Strategy: The Foundations for American National Security* pointed out that the United States "cannot wisely respond to twenty-first-century challenges predominantly by increasing traditional military investments" (Danzig et al. 2018, p. 14). Indeed, "Borrowing a metaphor from Emerson, [national strengths] are like the fingers of a hand—together they can grasp things that are impossible for one alone. Occasionally we preach this gospel, but the United States rarely practices it across competing executive agencies and congressional committees or between the federal government and state or local governments. Systematic cooperation between the American private and public sectors is still rarer" (p. 25).

A year later, the wicked problem of a coronavirus global pandemic triggered a range of US government actions designed to protect Americans from the new pathogen. Less considered was how the United States could also use this challenge to further its goals for the international order. Neglect of this second dimension had significant costs for both America's health and its security.

This brief essay focuses on one example of this failure: how a complex system of vaccine producers was orchestrated for a health mission but left disorganized from a national security perspective.

The US Approach to a Covid-19 Vaccine

A decade is a normal timetable for developing a new vaccine. Even a concerted effort over more than that time has not yet yielded a vaccine for HIV/AIDS.

Early in 2020, policymakers universally spoke of 12–18 months as an exceedingly ambitious target for a covid-19 vaccine. By the spring, some of us prevailed with the argument that, in the face of extraordinary need, a vaccine could be achieved in half that time. Government leaders in the European Union, the United States, and China embraced that goal and threw unprecedented resources behind it.

More than 100 efforts to develop a vaccine were nurtured around the globe. Among these, six major programs—four in the United States, the others in England and France—were funded for vaccine development and production by the US Department of Health and Human Services. The goal was to produce safe and effective vaccines in quantities sufficient for the American population. No arrangements were pursued by the US government to improve production capacity for other nations, nor were relationships developed for sharing vaccine trial and production experiences among nations.

Goals Not Pursued

From an American perspective, engagement with a broader range of multinational efforts could have been pursued with one of three goals that are both self-interested and humanitarian:

- *Self-protection*. Sharing information about progress and failures would improve prospects of success for all; the risk that vaccines might fail could be hedged by agreements to share vaccine production capabilities, so that others would have access to effective US vaccines and we to theirs in the event that our own failed or were inadequate; proliferation of vaccine production would reduce disease in other countries and thereby reduce the risk of its reentering the United States.

- *Alliance relationships*. Sharing and cooperating could extend and improve political relationships.

- *An improved international order*. Sharing vaccines and vaccine information with China, for example, could mitigate Sino-American tensions; sharing with China, Russia, and less developed countries could build a foundation for enhanced cooperation on problems such as global warming and disease surveillance to lower the risk of future pandemics.

These opportunities were not pursued. Ideology, tensions in global relationships, and domestic priorities, including political considerations, disposed American decision makers in other directions.

Impediments and Challenges

Complexities in US systems of governance and of vaccine production were also significant impediments. Many longstanding problems have repeatedly impeded cooperation between the US government and vaccine producers. For example, in previous pushes for new vaccines, corporate planning and corporate incentives have not been well matched to government budget cycles and, despite government assurances, government funding has typically not been sustained after epidemics or terrorist events.

Despite government assurances, government funding has typically not been sustained after epidemics or terrorist events.

A program of multinational and multicorporate cooperation would add other challenges. It would, for instance, warrant giving weight to simplicity of distribution under rudimentary conditions. It would place a higher premium on diversity in clinical trials. It would require grappling with the fact that a small American corporation had essentially its entire value rooted in its intellectual property for using messenger RNA as a new vaccine technology. How could this company be compelled or induced to share its technology and compensated or protected if it did? How would expert personnel in limited numbers be shared between countries? And how might an unprecedented number of parallel vaccine development programs share information in a similarly unprecedented fashion?

Risks in Navigating Unmapped Terrain

The incentives and the capabilities for addressing these questions were scarce and scattered in the US government. It is challenging to build a new weapon or to deploy military forces to a distant place, but there are well-paved roads for experienced travelers who undertake these tasks. Linking national security and vaccine production is more like traveling across unmapped terrain.

The American vaccine program, "Operation Warp Speed," involved a mélange of agencies and more than $10 billion for contracting under the guidance of leaders in the Department of Defense. Despite this location, the program largely ignored international opportunities and nonhealth priorities.

Corporations, ironically more attuned than the Department of Defense to international opportunities, were left free to produce for foreign markets or to share capabilities with foreign producers according to their own preferences, pursuing initiatives based on prior relationships, profit motives, and opportunities for clinical trial sites. A potpourri of arrangements resulted: contracts for some vaccines, but not others, with a major Indian producer; various arrangements with Japan and Canada, some with South Korea and South Africa, and a few with nations in the Southern Hemisphere.

Chinese pharmaceutical companies, by contrast, were orchestrated to respond to government priorities for supply to nations of diplomatic interest. These are being used to improve the PRC's relationships with populations and governments in Southeast Asia, Africa, and Latin America; to gain insight into their medical systems; and to gain a foothold for Chinese businesses and information systems.

How to Do It Better

The ingredients for a different, better-orchestrated result are easy to enumerate but hard to achieve and maintain. They are likely to apply to other medical countermeasures and include building:

- enduring US government relationships with pharmaceutical companies not normally thought of in the national security context;
- government expertise in understanding the structures and incentives of companies important for vaccine production (including producers of bioreactors, adjuvants, and finish-fill supplies like vials);
- cooperation across the complex systems of the US federal bureaucracy to marshal tools and incentives;
- budgetary freedom to work across established categories; and
- international cooperation to align national priorities and systems to minimize redundancies, expand the range of approaches, share results, and maximize production capacity.

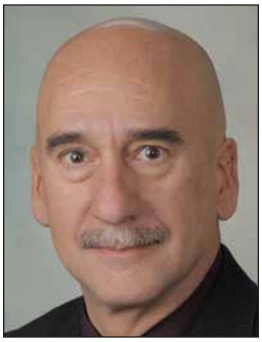
Some of these challenges were addressed by a few enlightened foreign leaders (e.g., France's President Emmanuel Macron), some established international organizations (e.g., WHO), a few small but admirably ambitious NGOs (e.g., the Coalition for Epidemic Preparedness Innovations and Global Vaccine Alliance), and some private foundations (e.g., the Gates Foundation). The system remains, however, remarkably suboptimal and the most pronounced failures are by the United States government. Can we do better?

Reference

Danzig R, Allen J, DePoy P, Disbrow L, Gosler J, Haines A, Locklear S III, Miller J, Stavridis J, Stockton P, Work R. 2018. A Preface to Strategy: The Foundations for American National Security. Baltimore: Johns Hopkins Applied Physics Laboratory.

A New Model for National Emergency Medical Care

Denis Cortese



Curtiss Cook

Denis A. Cortese and Curtiss B. Cook

The current US healthcare "system" is not meeting the needs of patients or society. This is not a novel conclusion, but the need for change has been made much more salient by covid-19.

What is the biggest lesson of the pandemic? The US healthcare delivery system, social systems, and federal agencies were simply not ready: they were ill equipped and unprepared to work together. The parlous state of these systems has been known, and ignored, for years. The covid-19 pandemic must force improvements.

Lessons Not Learned

Over the past 2 decades, the US emergency response system has been repeatedly tested by a series of emerging infectious diseases (e.g., SARS1 and avian influenza H5N1 in the early 2000s, swine flu H3N2 in 2008, MERS, Ebola, Zika) and three serious flu seasons in 2017–20.

These events provided multiple opportunities to evaluate and improve national readiness for "the big one." Covid-19 emerged as the big one and exposed multiple vulnerabilities in the US healthcare delivery infrastructure.

Denis Cortese (NAM) is Foundation Professor and director of the Center for Healthcare Delivery and Policy at Arizona State University, and emeritus president and CEO of the Mayo Clinic. Curtiss Cook is a professor of medicine and chair of the Division of Endocrinology at Mayo Clinic Arizona.

Moreover, when self-limited natural disasters (e.g., hurricanes, wildfires) are superimposed on a prolonged event such as a pandemic, the system becomes further strained.

Any lessons learned from the earlier events were either forgotten or went unheeded. Lack of a robust national public health system; the absence of an effective supply chain for personal protective equipment, medical equipment, and testing supplies; and contradictory messaging leading to low compliance with risk mitigation strategies (e.g., mask wearing, physical distancing) all exacerbated the pandemic and its impacts.

Problematic Payment Models

Medical facilities were required to preserve hospital beds to accommodate anticipated surges in hospital admissions, thus reducing access for patients who required ongoing care for other health conditions. Consequently, many delivery systems sustained substantial financial losses due to fee-for-service payment models. These financial losses affected healthcare workers with layoffs and furloughs—just when they were most needed.

Although there are tools to help stabilize the economy, there are none to stabilize the US healthcare infrastructure.

Lacking a reserve medical corps, the hardest-hit geographic areas depended on volunteer medics (some coming out of retirement) or agencies that provide temporary medical help to both augment staffing and to backfill for healthcare workers sidelined with covid-19 infections themselves. However, with widespread infection rates, even this is not possible as healthcare workers need to stay and support their home facilities and competition for a limited supply of temporary heathcare workers has increased.

The covid-19 pandemic has shown starkly that the existing fee-for-service structures serve neither patients, healthcare delivery organizations, nor the public health. When the nation gets hit by a pandemic an effective healthcare system should play an important role in maintaining economic stability, and vice versa. Although there are non-healthcare-related economic tools to help stabilize the economy, there are no such tools to stabilize the US healthcare infrastructure. The financial impacts have been evident in the fee-for-service environment.

Is it possible that prepaid, capitated healthcare delivery systems fared better? The answer will emerge in time. Regardless of the healthcare payment models, it is essential to simultaneously ensure both the economic viability of the organizations that provide care and the effectiveness of the medical workforce in order to safeguard the health and welfare of patients.

Indeed, there's much more to learn and reflect on from the global covid-19 pandemic.

A Civilian National Emergency Medical System

We envision a new model of preparedness and response to medical emergencies and crises to ensure a constant state of readiness. It's based on the different, sometimes competing, simultaneous roles of civilian healthcare organizations: (1) provide care for those affected by the emergency; (2) provide ongoing care for regular patients; and (3) maintain a healthy workforce.

We propose a Civilian National Emergency Medical System (CNEMS), a collective of civilian US healthcare organizations that would collaborate with local, state, federal, and nongovernmental organizations to provide a broad spectrum of medical capabilities as needed. Its roles and responsibilities would include the following:

- Create an integrated, seamless civilian national emergency medical response system.
- Recruit, train, and retain a rapidly deployable force of medical professionals to support onsite needs of victims of natural disasters, epidemics, and other national emergencies.
- Identify treatment facilities with advanced capabilities to support onsite and remote medical care for complex and highest-risk cases.
- Identify gaps in care delivery and coordinate delivery of medical relief operations.
- Create innovative strategies in medical response to natural disasters, epidemics, and other national emergencies.
- Collect and analyze data on processes of care to ensure the highest levels of safety and outcomes for victims

of natural disasters, epidemics, and other national emergencies.

- Operate at the national, regional, or local level as needed.

The CNEMS would involve a tripartite structure of facilities, personnel, and logistics under a unified civilian command and control. It would operate in the civilian sector, coordinating with governmental and nongovernmental organizations.

New Mission, Vision, Leadership, Collaboration

Unlike most natural disasters, the response to a pandemic requires a system that is capable of sustaining operations over a prolonged period. Covid-19 showed that it is time to get serious about preparedness and readiness at both national and regional levels. A new vision and mission of readiness will require organizational, operational, and people skills to develop effective levels of cooperation, coordination, and policy.

What is different from the current national incident response system is that the CNEMS would draw from the civilian healthcare workforce and institutions and would remain in a state of ready reserve to augment existing national response systems. It would enable the civilian healthcare sector to deploy its capabilities and expertise in the field in the event of a national emergency. Delivery systems would work with group purchasing organizations and supply chain service companies that would provide logistical capabilities.

This change will require bold leadership and collaboration from the civilian healthcare sector. Complex systems require evolving mindsets—counter to current ways of thinking about how to deliver and be reimbursed for health care in the United States. Unity of effort will be required, putting aside traditional competition between healthcare delivery systems in favor of meeting a common challenge. A CNEMS is one potential means of achieving an effective, coordinated response to the current and any future event.

Reducing Systemic Vulnerabilities in US Health Care

Hamilton Moses III and George Poste

Hamilton Moses

George Poste

Health care in the United States, unlike most developed countries, has no central system for prioritization, coordination, or financing of care and services. This void has been filled by insurers and employers, spawning a host of intermediaries that direct the flow of patients, information, and payments to networks of provider organizations, supported by a parallel ecosystem of academic and corporate research innovation and global supply chains for products and services.

US Health Thwarted by Complexity

The US health[1] ecosystem transcends all other sectors in the diversity of participants and the logistics to deliver highly specialized services to heterogeneous populations over their lifetimes. It is unmatched in the coalition of

[1] *Health* and *health care* refer here to the direct provision of clinical care to individuals, including that provided by physicians, nurses, and other professionals; institutions (hospitals, extended care, and others); and drugs, medical devices, and laboratory and information services.

Hamilton Moses is founder of the Alerion Institute, formerly partner of the Boston Consulting Group and chief physician of the Johns Hopkins Hospital and Health System. George Poste is Regents Professor, Del E. Webb Professor of Health Innovation, and chief scientist with the Complex Adaptive Systems Initiative at Arizona State University.

scientific, clinical, engineering, and computing expertise involved in innovations, many of which are subject to stringent regulation. The result is an estimated 450,000 entities that drive this complex system.

Complex systems are notoriously difficult to change because they are neither entirely closed (and thus amenable to centralized command and control) nor completely open (so they are partially shielded from externally imposed change). These hybrid features explain the long history of frustrated attempts to improve the effectiveness of US approaches to care of individuals with overt disease (medical care); population-based initiatives for disease prevention and disease risk mitigation (population health); and preparedness for large-scale disasters and epidemic/pandemic infections (biosecurity).

Despite America's strength in the biomedical sciences and technologies, beginning in the 1990s a century-long improvement in population health began to reverse. Compared to other developed countries (the G7), the United States has been the worst performer, with declining lifespan, greater mortality among those under 30, lower rates of childhood and adult vaccination, and higher rates of preventable diseases, institutionalization for chronic conditions, mental illness, drug addiction, and disabilities that prevent employment. In not a single measure of health does the United States consistently outperform other developed countries.

Obstacles to Reform

Deconvolution of the interdependencies that affect the performance of specific subsystems in the health sector is necessary but not sufficient. Meaningful progress cannot occur until health is no longer viewed by policymakers both within and outside the health sector as divorced from critical interdependencies with other systems in relentless competition for investment priorities in the national agenda (defense, infrastructure, education, energy, agriculture, among others).

Spending on health is approaching 20 percent of US GDP, with no imminent prospect of blunting cost. The accumulating shortcomings in patient- and population-centric services have the potential to adversely affect future societal resiliency, not just in economic consequences but, more insidiously, as a catalyst for channeling public dissatisfaction about the adequacy of political leaders and institutions to manage complexity, whether in health or in hyperpartisan politics, geopolitical threats, climate change, and US competitiveness in advanced technology.

Abrogation of free market principles combined with ineffective regulation has created a Byzantine system of opacity and information asymmetries among payers, providers, innovator companies, and supply networks about how prices are set, often without rigorous evaluation of value in improving care or controlling cost. Policy reforms to confront these market distortions are thwarted by lobbying by insurers, the professions, suppliers, and multiple private sector interests.

Progress cannot occur until health is no longer viewed by policymakers as divorced from other critical systems in competition for national investment.

Reform inertia is reinforced by political reluctance to explore potentially effective solutions, thus discouraging new ideas and innovations. Disagreements between those who view health care as a right versus a privilege often dampen rational political action, resulting in a narrow focus on cost control and fear of deliberate limitations of access to care, either by explicit rationing or tolerance of queues.

Instabilities in complex systems arise from decays and disrepairs in adaptive evolution. When the entropy of cumulative inefficiencies and burden of external stresses reach a critical threshold affecting sufficient interacting components, resiliency is lost and instabilities cascade across the system. Whether failure manifests as a sudden catastrophic collapse or slow sclerotic decline, the underlying etiologies are the same: multiple points of cumulative and convergent failure, with the signals of distress undetected or ignored.

Individual Care vs. Population Health

The covid-19 pandemic is a stark illustration of how prolonged neglect and cumulative vulnerabilities in population-centric health systems for global biosurveillance and public health can spill over to expose myriad weaknesses across the spectrum of patient care. The pandemic revealed the consequences of imbalance in investment in public health preparedness (est. US annual cost $3–5 billion) relative to patient care ($4 trillion annually) and how the resiliency of the latter has been compromised by reduced reserve capacity and reliance on fragile supply chains.

Notwithstanding the imperative to reinvigorate international commitments to global public health as a bulwark against future pandemics, the overarching question facing the US health system is how much of the mission should be devoted to individual care versus population health, and which organizational structures best meet the distinctive needs of each?

The cost of care for aging populations with multiple chronic diseases, compounded by unaddressed inequities in disease burden arising from socioeconomic disparities, is economically unsustainable. Reduction of these high-cost and personally devastating conditions will require better integration of care delivery for the ill with parallel initiatives for mitigation of the socioeconomic factors that affect disease prevention, access to care, and education about the role of lifestyle and behavior in disease risk. The latter are largely beyond the control of physicians and care providers, who have few tools to address them.

Need for Large-Scale Information Systems

Remedy of the looming systemic failures in health care will require the development of large-scale information systems for facile data capture, analysis, and real-time situational awareness to better detect and respond to emergent failures.

Biomedicine lags other sectors such as transportation, banking, and telecommunications in adopting advanced information systems. Vast amounts of data remain inaccessible, trapped by inadequate standardization of reporting formats, database design that does not reflect clinical needs, and lack of systemwide interoperabilities, reinforced by commercial, administrative, and cultural barriers to data sharing between institutions.

US government efforts to establish electronic health records (EHRs) as a critical asset in care decisions have been protracted, fraught with expensive failure, end-user frustration, and as yet uncertain benefits on outcomes and cost savings. The core limitation in EHR design is failure to recognize that clinical decisions stem equally from tacit (intuitive) and explicit (codified) knowledge. Technology that impairs clinicians' cognitive activities and workflow can produce unintended consequences that are not compensated by system adaptability.

Belief that the entry of the Silicon Valley data behemoths will resolve these shortcomings remains as yet unjustified. To date their efforts are largely task specific. More ambitious forays for holistic systemwide integration will be the true test of their strategic value.

Conclusion

Gains in health and medicine through the use of engineering and computing have been incremental, focusing on performance optimization of narrow systems largely separate from interacting complex systems. Targeted, limited remedies have recognized value. But the scale and adverse implications of the myriad fragilities embedded in the health ecosystem demand urgent and more ambitious redesign.

Interventions must occur *simultaneously* from outside and within the system itself. A prerequisite is clarity in defining the desired future state(s) and establishing waypoints to measure progress.

Success will depend on forceful leadership from public and private sector payers, providers, and patients/consumers as well as continued academic and corporate innovation. Ultimately necessary is political will to implement sustainable change, despite the painful choices involved. Meeting this challenge will require that concepts and methods of systems engineering move beyond the predominant focus on bounded systems to examine higher-level interdependencies.

The ravages of covid-19 and growing burden of chronic illness highlight the urgency of these imperatives.

Public Health: Designing for Effectiveness

Karen B. DeSalvo

Karen DeSalvo (NAM) is chief health officer at Google Health.

Public health is what society does to create the conditions in which everyone can be healthy. The US public health community and its partners have been striving for years to articulate the structural and mission challenges of the country's public health system. But the covid-19 pandemic has thrust these challenges to the forefront in a way that the community's more deliberative efforts have not. A series of major policy decisions, chronic underresourcing of the US public health infrastructure, and political actions that put individual over community created a crisis in public health infrastructure concurrent with the SARS-CoV-2 crisis.

In this historic moment, the US public health system is called to stand up, but it is stumbling. It should not be a surprise that the system has incomplete capacity and capabilities to meet the acute and chronic demands during this pandemic. Despite the US economy's longest expansion in its history, spending on public health infrastructure has failed to return to prerecession levels. Funding seems a perpetual concern.

During the last great pandemic, caused by an influenza virus in 1918, the US medical establishment was only beginning to emerge as a separate professional practice. Since then, with the advent of a formalized medical infrastructure, coupled with the marvels of therapeutics such as antibiotics, treatment for acute myocardial infarction, and therapy to prolong and even save life for those with cancer, medicine has taken center stage in thinking about ways to address health. There are calls for better coordination between medicine and public health, but such coordination would take not only willingness but likely also shared accountability or other significant external pressure.

I experienced these issues firsthand in a different catastrophe.

Role of Public Health vs. Medicine

When Hurricane Katrina struck New Orleans in 2005, I saw how important it is for medicine and public health to collaborate and coordinate—and what happens when they do not.

At the time, I was on the faculty at Tulane School of Medicine and only vaguely aware of the city's health department and its role. But it soon became clear to me that public health tools and expertise would be needed to bring back the community. Only the public health sector could handle foundational needs such as the restoration of potable water, a public health laboratory for communicable and other diseases, and ongoing population surveillance for environmental exposures from the flood waters. These and other essential functions of public health complement medical care for acute and chronic disease. My admiration of the role of public health following Katrina was a major reason I later went into public service as health commissioner for the City of New Orleans.

Covid-19 has similarly highlighted that medicine alone is insufficient to improve the public's health, particularly in the absence of the right tools. Early reassurances to the public that the healthcare system would be able to provide life-saving treatments like ventilators if people got sick became questionable and made it apparent to the public that treatment is an insufficient approach to communicable disease. There is a clear need for help from the public health system to leverage authorities to require public health measures like masks and social distancing or to do effective contact tracing to mitigate new outbreaks.

Evolution of the US Public Health System

The history of the US public health system reflects the concurrent development of national and local structures aimed at addressing communicable disease outbreaks at the local level.

At the national level, the US Public Health Service emerged in the late 18th century principally as a means of protecting US ports from the import of infectious diseases on ships. Local public health efforts got a much later start with the establishment in 1911 of the first county-level health department in Yakima, Washington, following a typhoid outbreak. The success of local informal public health action led to a groundswell of support, including from the business community, for the formal establishment of a county-level health department. This model was soon adopted across the nation, leading to the current decentralized, locally funded public health system.

The Centers for Disease Control and Prevention is the country's national "brand" for public health, but has no real authority to promote and protect public health at the local level. Rather, its role is to convene and to provide grant funding, epidemiologic insights, and communication tools for state and local public health officials who have the actual authority.

Challenges and Ways Forward

Government and local public health agencies were struggling to keep up with the expectations of addressing the public's health in the 21st century even before the covid-19 pandemic. Their efforts during this pandemic have been nothing short of heroic with staff working long hours daily for months. But the workforce is too small for the needs, whether for surveillance, contact tracing, or laboratory capacity. And with shrinking state and local budgets due to the covid-19-related financial crisis, layoffs were announced. Leaders of state and local health departments resigned because of personal death threats. And roles and responsibilities of public health at the national, state, and local levels—from surveillance to testing and contact tracing—were stripped.

The challenges facing US public health are not insurmountable if we—the public and policymakers—are willing to ask and address difficult questions about the current paradigm to protect and promote the public's health. And do so with urgency given the crisis the system is facing.

Medicine should become a vocal, durable, and visible partner in the efforts of public health to strengthen and modernize. And it should rally to support rational and reasoned public health requests to increase funding, update infrastructure, and modernize data and digital infrastructure.

Through alignment and allyship, medicine and public health can resume their vital partnership and reduce unnecessary complexity in the system to address and improve the health of the public both during a pandemic and every day.

A Global Pandemic as a Complex, Unifiable System

Harvey Fineberg (NAM) is president of the Gordon and Betty Moore Foundation, and former president of the Institute of Medicine (now National Academy of Medicine) and provost of Harvard University.

Harvey V. Fineberg

Global pandemics result from an emerging infection that causes notable disease in many countries in different parts of the world. At the margins—exactly how many countries and continents and with what degree of disease severity—public health authorities may dicker over the definition or its applicability to a situation. But when beset by a raging outbreak such as covid-19 that can cause more than a million deaths around the world—in every global region, in countries large and small, rich and poor—we can confidently declare a global pandemic.

A global pandemic is by nature a complex system both in its cause and in its expression. This means that the triggers and the consequences of a pandemic each have components with deep interdependencies: couplings that are loose or tight, direct or indirect; causations that are alternately necessary, joint, conditional, and relative; feedback loops that are amplifying or dampening; and indeterminacies that are partly stochastic features of the natural world and partly an expression of the limits of understanding. In sum, everything that makes a system "complex."

Causation

In terms of causation of an emerging infection, it is often convenient to identify system components, attributes, and relations at four levels: the infectious organism in question; human and social activity and behavior;

animal populations[1]; and the environment and ecosystems in which the organism, animals, and humans interact. These are the building blocks of the systems approaches in the interdisciplinary fields of One Health and Planetary Health.

Most emerging infections, including those that produce a global pandemic, begin as a zoonotic transmission, that is, from an animal reservoir to a human. Many of these zoonotic infections are limited because the organism that infects the human has not adapted to spread readily from one person to another. However, in instances where the organism does spread easily from one human to another—such as with SARS-CoV-2 (the organism that causes the disease covid-19)—an outbreak or pandemic may ensue.

A global pandemic is by nature a complex system both in its cause and in its expression.

This understanding of causation puts a special premium on the interactions among humans, animals, and infectious organisms—in systems terms, on the dynamics of the relations among the components. Human populations have grown in number, intensified the density of urban environments, and spread to live in more rural areas (case in point: Lyme disease and proximity to deer, mice, and ticks). Worldwide, domesticated animal populations have grown an order of magnitude faster than the human population. And wet markets popular in various parts of the world bring humans and live animals regularly into proximity with one another; civets, a delicacy in China, are believed linked to the origin of the first SARS outbreak in 2002.

Various organisms have different propensities to cross species. Influenza is notorious for its ability to reside and genetically recombine in a variety of avian and mammalian species, including humans.

Prepandemic global travel conveyed millions of individuals, including any who may be infected, within a day's time to any other spot on the planet. A systems understanding of emerging and pandemic infection thus requires a unifying portrait of a complex set of components and interactions.

Expression

The expression of a pandemic is similarly complex and occurs at multiple levels:

- as disease in an individual;
- as a public health problem of community transmission, morbidity, and mortality;
- as a medical system challenge to care for the sick and protect the health of caregivers;
- as an economic crisis that puts millions out of work and undermines economic activity;
- as a social crisis that throws into question the role of science, confidence in political and health leaders, and the role of international cooperation and agencies such as the World Health Organization.

Each outbreak or pandemic has distinctive clinical and public health features, even among related organisms, such as different strains of influenza or different coronaviruses. For example, in 2002 the first SARS outbreak spread to about 8000 persons, with a mortality rate of about 10 percent. The SARS-CoV-2 virus spreads more readily but produces a wider spectrum of illness (including up to half who will remain asymptomatic) and lower mortality rate among cases. However, since so many millions more are infected by SARS-CoV-2 compared to the original SARS virus, the number of fatalities is more than a hundred times greater, even as the mortality rate among cases remains lower.

Each component of the pandemic's expression—as an individual health problem, as a public health problem, as a healthcare challenge, and as economic and social crises—contains subsystems that adumbrate the scope of the challenge. For example, as an individual health problem and medical care challenge, key subsystems include the development, evaluation, and deployment of diagnostics, treatments, vaccines, and other modalities of intervention; adequacy of hospital and intensive care beds, ventilators, and personal protective equipment; numbers of trained health personnel; and smoothing strategies to spread the load of patients with covid-19 and to care for others in need of medical treatment.

For the vaccine component of a solution, as another example, subsystems include public and private research,

[1] When a disease may be spread by an insect vector, special attention to that component of the ecosystem is warranted.

product development, testing for safety and efficacy, evaluation of performance and risk, regulatory standards and approval mechanisms, manufacturing and distribution (locally, nationally, globally), priorities for use, and, very importantly, capacity to administer the vaccine to large numbers of people in a condensed time period.

Unification for Effective Intervention

Coping with such complex systems and subsystems in a global pandemic introduces the question of unifiability across systems. In fact, unification across systems is essential to successful intervention. The requirements for preparation, prediction, assessment, response, and adaptation in relation to global pandemics all depend on a unified approach, one that simultaneously takes account of actions and relations among system and subsystem components.

Systems models, at different levels of abstractions with some more precise than others, are one way to articulate the unity of a complex system such as global pandemics. In general, the models may be descriptive (allowing focus on one part of the system without losing sight of the whole), predictive (allowing manipulation of one or another set of variables to determine effect on results), or decision support (laying out scenarios, probabilistic events, and possible outcomes). Any model is necessarily a simplification of the actual situation, and its utility depends on the completeness of inclusion of relevant attributes, accuracy of understanding of dynamic dependencies, and ability to estimate attendant uncertainties.

Beyond modeling, the unifiability of a global pandemic as a whole system finds its expression in leadership (that begins with a unified command structure), strategic emphasis (that takes account of priorities and interdependencies across subsystems), and communication (that consistently conveys a coherent sense of what steps will be taken, what will be accomplished by when, and what needs to be learned).

In a complex and overwhelming systems challenge, such as a global pandemic, the ability to unify understanding and response through leadership, strategy, and communication may make all the difference to success or failure and to lives lost or saved.

Evolving an Ecological Perspective

Simon Levin (NAS) is the James S. McDonnell Distinguished University Professor in Ecology and Evolutionary Biology at Princeton University.

Simon A. Levin

François Jacob (1977), in his essay "Evolution and Tinkering," brilliantly made the case that the world has self-assembled, constrained by history: Organisms have not been designed from scratch as the best solutions to the puzzles of survival and reproduction, but are the products of a sequence of modifications to address strings of abiotic and biotic challenges. In fact, Stephen Jay Gould (1989, pp. 45ff) proposed the thought experiment of "replaying the tape of life" and concluded that doing so would produce a different outcome.

Evolution and Interdependence

Ecosystems are complex, with interdependencies and, in the words of Charles Darwin, a "tangled bank" that is not the work of a master craftsman but, in Jacob's metaphor, a tinkerer. The complex processes by which species come to exploit one another, compete for common resources, or depend on one another directly or indirectly have arisen by evolutionary self-organization.

Over time, to some extent the biosphere has become more and more interconnected, and the interdependencies in general confer a robustness through selection processes that distinguish them from what a randomly assembled system would look like. Ecosystems and the biosphere are, like physical and social systems, complex adaptive systems, made up of individual agents that adapt behaviorally, physiologically, or through genetic modification. Those changes produce emergent properties at higher levels of organization that feed back to influence dynamics at the level of the agents.

The word *adaptive* here refers to processes at the level of the individual agents, and there is no guarantee that what is myopically good for those agents will improve the long-term success of the system. The existence of patterns and processes on multiple organizational scales leads to conflicts both between the agents and the groups to which they belong and between the groups and the interests of the whole ecosystem or biosphere. People and the planet are suffering from conflicts today as selfish interests lead to activities that degrade the world and its resources. Garrett Hardin (1968), building on the ideas of William Forster Lloyd, described this as the "tragedy of the commons."

Evolution and Robustness

In addressing the challenges facing humanity, much can be learned from the evolution of ecological systems. Natural selection has led to mechanisms that confer robustness, or else organisms would not survive to reproduce. At the system level, tight interdependencies have similarly been selected; but the process of transformational evolution, as elucidated by Richard Lewontin (1977), or what Tim Lenton and collaborators (2018) have termed *sequential selection*, can serve as a filter that ultimately produces more robust systems.

The features that lead to success through this transformational process are those that lead to better integration of lower-level mechanisms, akin to Elinor Ostrom's (2009) notions of polycentricity. Local feedback loops, including direct and indirect mutualisms such as syntrophy, can create coherent units that are key to the robustness of the larger system. Such hierarchical arrangements, built on modular units, can be seen in genomes as well as in higher-order ecological assemblages. They provide the basis for system integration and suggest the adaptive value of modular organization in systems more generally.

This raises questions about what features make systems robust or resilient, and even whether robustness is a good thing. The answer depends to a large extent on the scale. In general, robustness at the system level is crucially dependent on the lack of robustness at lower levels—that is, the ability of the system to reconfigure or replace components to adapt to change. Influenza A, for example, remains a scourge for humanity because individual strains are rapidly replaced by others that allow the virus to escape the population's herd immunity. Robustness does not mean stasis; variation and exploration are common features that are essential to adaptation in the face of changing environments.

Identifying System Features of Robustness

To what extent has natural selection and transformational or sequential evolution led to increasing robustness over time, and how is that robustness manifest at different scales? What are the generic features of systems that confer robustness?

All of life involves the interplay between processes that generate variation and those that winnow or restrain it; indeed, recognition of this essential coupling is reflected in the basic law of evolutionary change, the fundamental theorem of natural selection (Fisher 1930). The physiology of organisms depends on processes that drive dynamics and those that regulate it; when these get out of balance, pathologies result. In this way, financial systems, for example, are no different, in that high-speed trading and other innovations can outrun system regulation and lead to market crashes.

Robustness does not mean stasis; variation and exploration are essential to adaptation in the face of changing environments.

One of my favorite metaphors for designing for robustness is the vertebrate immune system, which has evolved to deal with both the predictability of assault by pathogens and the unpredictability of the nature of those pathogens and the timing of their emergence in populations. The immune system therefore involves the hierarchical and temporal deployment of generalized mechanisms, such as barriers and macrophages, and specific antibody responses that take time to develop.

General resilience is an important feature of any effective response system (Carpenter et al. 2012). Structural features that can confer such resilience include redundancy, variation, and modularity. Modularity is an essential component of both ecosystems and genomes, restraining systemic contagion and providing building blocks for reorganization.

Questions for Research

Efforts to understand the complexity of ecosystems, or indeed of any systems, raise a plethora of challenges that suggest an agenda for research. How do we scale from the microscopic to the macroscopic and characterize the emergence of pattern? What is the potential for major regime shifts, and are there early warning indicators? How and to what degree are the conflicts between levels of organization resolved over evolutionary time, and what can we learn from this as we endeavor to preserve the biosphere?

These questions reflect management challenges concerning optimal paths forward for biological and socioeconomic systems alike, and they fall clearly within the domain of systems engineering. The challenges certainly will keep scientists and engineers occupied for decades to come.

References

Carpenter SR, Arrow KJ, Barrett S, Biggs R, Brock WA, Crépin A-S, Engström G, Folke C, Hughes TP, Kautsky N, and 12 others. 2012. General resilience to cope with extreme events. Sustainability 4(12):3248–59.

Fisher RA. 1930. The Genetical Theory of Natural Selection. Oxford: Clarendon Press.

Gould SJ. 1989. Wonderful Life: The Burgess Shale and the Nature of History. New York: Norton.

Hardin G. 1968. The tragedy of the commons. Science 162(3859):1243–48.

Jacob F. 1977. Evolution and tinkering. Science 196(4295):1161–66.

Lenton TM, Daines SJ, Dyke JG, Nicholson AE, Wilkinson DM, Williams HTP. 2018. Selection for Gaia across multiple scales. Trends in Ecology & Evolution 33(8):633–45.

Lewontin RC. 1977. Adaptation. Enciclopedia Einaudi Turin 1:198–214.

Ostrom E. 2009. A Polycentric Approach for Coping with Climate Change. Policy Research Working Paper 5095. Washington: World Bank.

Complex Maladaptive Systems

David Sloan Wilson

Guru Madhavan

David Sloan Wilson and
Guru Madhavan

Here is a provocative fact: Searching Web of Science for articles with the words *complex adaptive system* in the title yields 1006 results as of this writing; searching for articles with the words *complex maladaptive system* in the title yields zero results.

Why such an imbalance? Granted, complex systems that count as adaptive might warrant more attention, but 1006 to *zero*? Furthermore, when complex systems go wrong, such as an economic collapse, a disease pandemic, an invasive species, an immune system disorder, or the breakdown of democratic governance, it is hard to pay attention to anything else.

Understanding Complex Adaptive Systems

We attribute the imbalance to widespread confusion about what the phrase *complex adaptive system* means and the stringent conditions that are required for a complex biological, human, or technological system to function well *as a whole system*. Clarifying these issues and appropriately directing engineering efforts can go a long way toward transforming complex maladaptive systems into complex adaptive systems in myriad aspects of daily life.

David Sloan Wilson is SUNY Distinguished Professor Emeritus at Binghamton University, State University of New York. Guru Madhavan is the Norman R. Augustine Senior Scholar and senior director of programs at the National Academy of Engineering.

Digging deeper into the phrase *complex adaptive system* yields diverse examples such as cities, firms, markets, governments, industries, ecosystems, social networks, power grids, animal swarms, traffic flows, social insect colonies, the brain, the immune system, a cell, and a developing embryo. This list comes from Wikipedia, which can itself be regarded as a complex adaptive system.

Some of these—social insect colonies, the brain, the immune system, a cell, and a developing embryo—are complex systems that clearly function well *as systems*. They are also clearly products of natural selection, whereby better-functioning systems replaced worse-functioning systems over a large number of generations.

A political regime may have stability but not function well as a system for the good of all its citizens.

The others are complex systems composed of agents that follow their own adaptive strategies, such as a driver negotiating traffic in a city, a politician trying to stay in office in a government, a species maximizing its fitness in an ecosystem, or a company trying to maximize its profits in an economic system. But these systems do not necessarily function well *as systems*. Indeed, we know that in many cases they do not, resulting in traffic jams, political gridlock, ecological and economic collapse. Wikipedia functions remarkably well as an encyclopedia but still suffers from imperfections, such as misinformation that serves the interests of the authors.

An Evolutionary View

We distinguish between two meanings of the phrase *complex adaptive system*: a system that functions adaptively *as a system* (CAS1) and a system composed of agents that *separately pursue their own adaptive strategies* (CAS2). The fact that these two meanings are usually not distinguished is a major source of confusion.

From an engineering and public policy standpoint, systems should function well as systems (CAS1), such as smooth traffic flow, efficient governance, and ecosystems that maintain diversity and provide various services. There are two major possibilities for how this can be accomplished: (1) *CAS2 can self-organize into CAS1* or (2) CAS1 systems can arise only from a certain process—namely, *selection at the level of the whole system*.

The first possibility is suggested by the metaphor of the invisible hand in economics and the concept of a balance of nature in ecology. In both cases, the presumption is that the system, left to itself, results in some kind of harmonious balance. Both of these concepts can be historically traced to pre-Darwinian notions of nature as harmoniously organized from top to bottom by a benign and all-powerful creator. Darwin's theory of evolution challenged this notion and provided a stark alternative: that nature can be harmoniously organized at lower levels, as evidenced in the exquisite design of a single organism, but discordant at higher levels, as seen in a war among members of a single species or of species in ecological communities. In one of Darwin's most unsettling metaphors, he described nature as a multitude of inwardly pointed wedges being driven against each other.

Modern evolutionary ecologists have largely abandoned the balance of nature as an antiquated concept. Left to itself, nature is frequently out of equilibrium or settles into one of many local stable equilibria. The term *ecological regime* is often used, which aptly invokes what we already know about human political regimes. A human political regime has a degree of stability, but that doesn't necessarily mean that it functions well as a system for the good of all its citizens. There are despotic and corrupt regimes in addition to enlightened regimes. Single-species societies and multispecies communities are no different.

CAS1 systems do exist above the level of individual organisms in nature, but only when they have been units of natural selection, such as colony-level selection in the eusocial insects and ecosystem-level selection in the case of microbiomes. Human social and economic systems are no different. The metaphor of the invisible hand, which makes it seem as if the pursuit of individual- and corporate-level self-interest robustly benefits the common good, is profoundly misleading except in the narrowest of contexts seldom realized in real-world economic systems. Just as for all other species, lower-level entities that compete against each other are far more likely to lead to complex maladaptive systems than complex adaptive systems of the CAS1 variety, unless a process of system-level selection organizes the interactions among the lower-level agents.

Yet system-level selection cannot take the form of centralized planning because most systems are too complex to be comprehended by any group of experts. Instead, system-level selection must be cautious and experimental, weighting alternatives and selecting those with the best whole-system consequences. It must truly be an evolutionary process in which the target of selection, variation oriented around the target, and the selection of best practices are managed with the welfare of the whole system in mind.

Engineering Systemic Selection

Where does the engineering profession stand with respect to all of this? In some respects, it is old news. The simplest engineering projects can be straightforwardly designed, but a tipping point of complexity is quickly reached where a more experimental variation-and-selection approach is required. And it goes without saying that the whole system cannot be optimized by separately optimizing its parts. The engineering profession is in accord with modern evolutionary theory on these points.

But what most people regard as engineering—both inside and outside the profession—is a very small subset of the complex systemic problems that need to be thought through and addressed, ultimately at the global scale. Hence, there is an urgent need for complex systems thinking in engineering to be integrated with modern evolutionary thinking in guiding responses to complex systemic problems.

In short, CAS1 systems require a process of system-level selection. Otherwise, complex maladaptive systems will be the inevitable result.

The Simplicity and Complexity of Cities

Christopher Kempes

Geoffrey West

Christopher P. Kempes and Geoffrey B. West

One of the most striking phenomena that has dominated the planet over the last 2 centuries is the extraordinary rate of urbanization. Averaging to the mid-21st century, this is now equivalent to adding a metropolitan New York City every few months or a country the size of Germany every year.[1]

Cities have evolved as marvelous machines for facilitating social interactions to create wealth, produce knowledge and ideas, innovate, and thereby increase standards and quality of life. This has come at a huge cost dictated by the second law of thermodynamics: the inevitable production of social entropy in the guise of increases in crime, disease, pollution, and climate change, as well as systemic inequality in both wealth and power.

Clearly, the future of the planet and its long-term sustainability are inextricably linked to cities. Consequently, there is an increasing urgency to develop a deeper understanding of their dynamics and organization to help mitigate and minimize this plethora of problems.

---

[1] Metropolitan NYC comprises the Bronx, Brooklyn, Manhattan, Queens, Staten Island; Elizabeth, Jersey City, Newark, the Oranges, Paterson, and adjoining communities in New Jersey; and Nassau and Westchester counties—some 18.35 million people. Germany's population is about 83 million.

Christopher Kempes is a professor and Geoffrey West is the Shannan Distinguished Professor and president emeritus at the Santa Fe Institute.

Cities as Complex Adaptive Systems

From almost any perspective, cities are quintessential complex adaptive systems that have much in common with ecosystems and organisms. Like them, energy and resources are distributed through networks to sustain their multitudinous constituents, whether individuals, organs, or cells. Evolutionary pressures typically result in all of these systems manifesting an economy of scale; indeed, optimizing these networks leads mathematically to explicit scaling laws for the ways almost all physiological and life history characteristics of organisms change with size.

For example, within a taxonomic group, the energy required to support a unit mass of tissue decreases systematically as the quarter power of body mass. More generally, such scaling laws are typically sublinear power laws whose exponents are simple multiples of one quarter. This remarkable regularity is a reflection of the generic constraints that are embodied in the mathematics and physics of the multiple networks that support life and that typically manifest self-similar fractal-like properties.

Given these results it is perhaps not surprising that the physical infrastructure of cities also satisfies similar sublinear scaling laws originating in the dynamics and geometry of the various transport and resource networks that sustain them. Metrics such as the number of gas stations, the length of the roads and electrical lines, the volume of buildings, all scale in a similarly "universal" fashion in different urban systems across the globe.

Simply put, the degree of infrastructure per capita, whatever it is, systematically decreases with city size with an exponent of about 0.15 (rather than 0.25 as in biology). On average, therefore, predictably fewer gas stations, roads, or electrical lines are needed to support an individual citizen the bigger the city.

But cities are much more than their buildings, roads, and electrical lines. Infrastructure provides the physical framework for facilitating social and other interactions where information is exchanged and socioeconomic activity stimulated.

Social Networks and Scaling Effects

Social networks have a very different character from the physical networks that dominate biology and the infrastructure of cities: their dynamics embody positive feedback mechanisms that underlie the creation and exchange of wealth, knowledge, and ideas. This is engendered in formal institutional and business settings such as universities, convention halls, and company boardrooms—and, equally importantly, in informal settings such as parks, sports arenas, and concert halls.

The increased connectivity of social interactions and its multiplicative enhancement are the very essence of a city, leading to superlinear scaling of socioeconomic activities and an increasing pace of life. It is this dynamic that sets cities apart from biology and makes them more than just "superorganisms." As size increases so do per capita metrics: wages, patent production, and GDP—but also crime, disease, and inequality, all happening at a predictably faster rate. As noted above, all of these very different metrics scale with city population size with a similar exponent, around 1.15, in urban systems around the world.

Naïvely, the existence of universal scaling laws in evolving self-organized complex systems is very surprising given that history, geography, contingency, and their associated huge space of possibilities would seem to make it impossible to understand particularities of a single species or city. Can the structure of Paris really be understood without considering Napoléon III or Los Angeles without regard to its benign California climate?

Almost all critical features of both organisms and cities obey systematic, quantitative scaling relationships.

History and geography certainly matter. Yet the amazing fact is that almost all critical features of both organisms and cities obey systematic, quantitative scaling relationships. This suggests that the coarse-grained behavior of their dominant degrees of freedom is determined by a small set of constraints and that the continuous feedback implicit in evolution by natural selection over long periods of time—the survival of the fittest—tends to drive the resulting system and its subcomponents toward an optimization that becomes manifested in scaling relationships.

Like organisms, cities and social organizations operate in competitive markets, though over significantly smaller time scales, resulting in greater variance around the predicted idealized scaling laws. It is this variance that reflects the history, geography, and individuality of a city; its dominant behavior is determined by the universal dynamics of the infrastructural (physical) and social (informational) networks common to all cities.

A Framework for Urban Interdependence

Understanding in detail the fundamental mechanisms, including the structure and dynamics of the underlying networks, is critical for mitigating the problems and minimizing the unintended consequences that have traditionally plagued urban development, whether in existing cities or in the design of new ones. Of particular importance is the recognition that *all* of the multiple characteristics of a city are strongly coupled and interdependent—the very essence of a complex adaptive system. Treating each problem, such as traffic gridlock in one local area or housing development in another, as if it were disconnected from everything else can be a recipe for long-term dysfunctionality.

Having a framework that is quantitative, systemic, and principled and that, at the same time, naturally incorporates this fundamental interdependence is crucial for dealing with the multiple challenges and trade-offs facing 21st century urban systems.

For instance, knowing that overperformance in total wealth production or wages in a city (relative to expectations from scaling curves) is correlated with increased inequality or crime provides a quantifiable metric for making an informed scientific judgment regarding trade-offs and policy decisions. Similarly, knowing that different broad organizational strategies lead to different scaling relationships, as is the case for categories of higher education institutions, indicates which constraints are universal and which are malleable.

Another timely example is the recent observation that the covid-19 spreading rate systematically scales with city size following an exponent of approximately 0.15. This result has huge implications for how cities respond to pandemics because, for example, a city of a million people will double the number of cases in approximately half the time of a city of 10,000. This fundamental difference in cities of varying size should be built into every pandemic plan of action at both the local and national levels.

All of these examples highlight that the ideal framework should serve as a complement to the traditional but necessary methods focusing on specific issues in specific cities.

This work is still at an incipient stage, but the very existence of systematic laws across cities offers hope for understanding mechanisms sufficiently well to know how to optimize cities for a variety of important outcomes, including not only their long-term sustainability but that of the entire planet.

Unity of Engineering Disciplines

Zachary Pirtle is an engineer and has served as cochair of the Forum on Philosophy, Engineering, and Technology.

Zachary Pirtle

To help engineers exploring how best to unify complex systems, I offer observations from the history of the philosophy of science, focusing on unity (and disunity) among engineering and scientific disciplines. Unity involves the extent to which different disciplines share common features, but this can still mean many things, and different disciplines approach problems in seemingly discordant ways. I draw on the work of logical empiricists to explore how disciplines vary in their language and methods as well as in their scientific laws, theories, and causal explanations.

Why Does (Dis)Unity Matter to Engineers?

Most engineers recognize that different disciplines can be incongruous: some disciplinary confusion is a part of any major systems development.

Consider airplanes. Engineers specializing in thermal, stress, electrical, propulsion, and aerodynamics disciplines will all see an airplane system differently, and focus only on their subset of the system. For example, stress engineers see the loads on the plane and the vibration frequencies caused by flight, and their design goals may want materials that are high strength to stiffen the plane and survive loads during operations. But the heavier mass of those materials might make the job of the aerodynamicist harder, as she seeks to protect speed and to design an efficient profile of the plane.

Managers and systems engineers interacting with discipline experts have to tie everything together, balancing the competing needs of individual disciplines. Many engineering systems today are more complex than airplane design, especially when interwoven with society and a broad array of actors. In combining engineering disciplines with physical and social sciences, the variety of intellectual disciplines requires some art in bringing them together usefully to solve a problem.

To explore what unity is, I discuss a vignette from the long history of interdisciplinary philosophy. Beginning in the 1930s, the logical empiricists Rudolf Carnap and Otto Neurath led a movement studying the unity of science. They both sought to define its nature and to create bridges across disciplines.

Practitioners create knowledge differently, making unique inferences based on the language they use.

Starting in 1934 Neurath and others convened six International Congresses for the Unity of Science, bringing together physicists, psychologists, philosophers, economists, and others. Through the Institute for the Unity of Science, established 2 years later, Neurath and others solicited monographs from experts who described their disciplines in an encyclopedic way that would be accessible to those outside their field of expertise. These monographs eventually included Thomas Kuhn's *Structure of Scientific Revolutions* (1962), which established much of modern thinking about paradigm change and revolution.

Dimensions of (Dis)Unity

What are the key dimensions of (dis)unity across scientific disciplines, and how unified are the sciences? I will briefly illustrate this by building on some of Carnap's (1938) terms.

Unity of Language and Method

Carnap first decomposed the question of unity by asking if the language of science was unified across disciplines. While most disciplines use terms that vary significantly, they all describe features that are eventually observable in the physical world and make claims that should be publicly testable through observation.

Unity of language might additionally be interpreted to reflect questions about the differing methods of scientific disciplines and to what extent practitioners create knowledge differently, making unique inferences based on the language they use. The above airplane example helps illustrate the divergent terms and methods that engineers in different areas of expertise may use to analyze the same system.

Unity of Laws and Theory

Carnap asked whether there is a unity of scientific law across disciplines. We might view unity of law here more broadly, considering whether the collected scientific theories underlying a given discipline are compatible and unifiable with one another.

Breakthroughs in general relativity were changing the nature of laws in physics in Carnap's time, raising questions about getting to a unified set of laws of physics and whether those laws could inform progress in chemistry, biology, and other fields. Unity of theory was not taken for granted among the logical empiricists, and Carnap viewed the extent to which theory across different disciplines like biology and physics could be unified as an empirical question, where actual success in combining theories and laws would trump any armchair philosophizing.

Engineers might care a lot about the extent to which their theory is unifiable, if not derived, from physics and other fields. Walter Vincenti (1990) showed that many engineers create knowledge that is distinct from science, and suggests the importance of dedicated support for engineering knowledge independent of applied science.

Recognizing Plurality in Complex Systems

Today, both scholars and practitioners more frequently recognize the disunity of science, in their use of varying language, methods, laws, and theory. Most philosophers of science, like Stéphanie Ruphy (2016), speak of the "plurality of science" to recognize the ways scientific disciplines are unique, and she encourages detailed study of varied scientific practices.

While many see some commonality in the fundamental language of science, philosophers like Ruphy and Nancy Cartwright (1999) argue that it is not possible to unify laws and theory across disciplines. Practicing engineers may believe in the eventual possibility of unifying theory across disciplines, but they likely sympathize with the incongruous disciplinary perspectives that I noted above, and may wonder about a disunity of theory.

However, the need to take action to shape complex systems does not let us rest easily with accepting the disunity of science. If a multidisciplinary team of experts seek to explain why a system problem occurs and how to resolve it, it matters if they see the same causal mechanisms underlying the problem. Recognizing that differing experts have different theories on what causes change in a system is important, and should lead teams to recognize uncertainty around individual expert recommendations.

Conclusion

Deeper reflection could proceed on two main paths: as engineers and scientists, we can either accept disunity across disciplines and study how to usefully combine a plurality of independent disciplines to guide action. Or we can try to clarify the conceptual underpinnings across disciplines, to create unity by conceptually engineering shared theoretical understandings and methods, for particular problems if not in general.

The work of Carnap and Neurath serves as a reminder of how complex the concept of unity can be, and as a great programmatic example for how engineers can have an inclusive, accessible, and proactive movement to bridge gaps across engineering and scientific disciplines.

References

Carnap R. 1938. Logical foundations of the unity of science. In: International Encyclopedia of Unified Science, Vol 1, eds Neurath O, Carnap R, Morris CW. University of Chicago Press.

Cartwright N. 1999. The Dappled World: A Study of the Boundaries of Science. Cambridge: Cambridge University Press.

Kuhn T. 1962. Structure of Scientific Revolutions. University of Chicago Press.

Ruphy S. 2016. Scientific Pluralism Reconsidered: A New Approach to the (Dis)Unity of Science. University of Pittsburgh Press.

Vincenti W. 1990. What Engineers Know and How They Know It: Analytical Studies from Aeronautical History. Baltimore: Johns Hopkins University Press.

Complexities of Higher Education

John V. Lombardi, Michael M.E. Johns, William B. Rouse, and Diane D. Craig

John Lombardi

Michael Johns

William Rouse

Diane Craig

Complexities in higher education are due to cultural legacies, differences among disciplines, and resource disparities across institutions. These differences suggest that one-size-fits-all higher education policies will be ineffective. Policies need to both be tailored to these differences *and* foster potential unifiability.

The ways higher education is organized, financed, and delivered varies immensely across the United States. Yet the structure of the University of Bologna formulated in 1088 persists today in most institutions. This time-honored structure of colleges, schools, departments, and programs imposes

---

John Lombardi is a professor of history and former chancellor of the University of Massachusetts Amherst. Michael Johns (NAM) is a professor of medicine and public health and former chancellor of Emory University. William Rouse (NAE) is a research professor and senior fellow at the McCourt School of Public Policy of Georgetown University. Diane Craig is a research associate at the University of Florida.

substantial complexity, fostering “guilds,” as in humanities versus medicine versus engineering. Well-resourced institutions thrive on and can sustain this model; lesser-resourced institutions not so much.

The ecosystem of higher education has been criticized as costs have steadily risen. The financial impacts of the coronavirus pandemic have been enormous, giving rise to many fundamental questions for the enterprise. Technology has rescued teaching in the short term, but diminished the value of brick-and-mortar campuses. These challenges are happening while the nature and priorities of students are morphing.

Statistical Snapshot of US Higher Education

According to the Center for Measuring University Performance, student enrollments have grown from 1.5 million in the 1940s to almost 20 million. The number of degree-granting institutions has more than doubled, from 1700 in 1940 to over 4000, and the number of degrees awarded has greatly increased, particularly at the graduate level.

Higher education is perceived to be composed of interchangeable institutions, reinforced through a curricular structure that leads to a 4-year degree with relatively standardized content. Accrediting institutions and various state and federal regulatory organizations reinforce this notion.

But public (33 percent) and private (66 percent) institutions have very different governance mechanisms, financial structures, and size and scope. In terms of enrollment, 88 percent of private institutions have fewer than 2500 students, while 87 percent of public institutions have more than 30,000. Among students, 73 percent of undergraduates are enrolled in public institutions and 27 percent in private institutions; at the graduate level, 53 percent are at public institutions and 47 percent at private institutions.

Institutions are classified into ten categories of the Carnegie Classification®. Those with very high (R1) or high (R2) research activity account for only about 5 percent (219) of all US degree-granting institutions. This subset includes many of the well-resourced institutions with very large research budgets and endowments.

The curriculum generally provides a liberal arts core and a specialization (major), relatively comparable across institutions. External accreditation agencies set specific requirements for disciplines such as engineering and health care.

Governance is shared: the board of trustees or regents has final authority, but faculty typically control curriculum, hiring, promotion, and tenure. These processes can differ significantly for public vs. private and large vs. small institutions (size here relates to resource availability rather than number of students).

Differences in Institutional Brand Value

Institutions differentiate themselves in the marketplace by emphasizing the context (versus the content) in which activities take place. This context translates into a brand value designed to project a quality image, which reflects a range of attributes provided at significant cost.

Among these attributes are high-visibility and high-quality student activities and a wide range of personal and academic support services, as well as a high-quality physical environment and facilities. Faculty with stellar credentials and accomplishments enhance the brand by offering students the possibility of engaging with the best minds.

Brand value differentiates institutions and determines their ability to recruit students and secure resources.

Brand value is a key element differentiating institutions. The ability to sustain the cost of brand value leads institutions into various competitive niches, determining their ability to recruit students and secure resources.

Rising Costs

The competition for brand value has driven costs higher. Only the most well resourced institutions can sustain these costs.

The principal sources of funding for all institutions are tuition and fees, state and federal instructional support, private gifts and grants, and federal, state, or private research support. The differential ability of institutions to obtain funding affects their brand value.

High-brand-value institutions established themselves early in the postwar years and set the standard for excellence, which other institutions may seek to emulate. Top performers maintain their positions by capturing larger shares of educational and research revenue. The hierarchy of institutions has consequently remained remarkably stable.

In the 1970s, roughly 80 percent of faculty members were in tenure tracks. This has fallen to 20 percent, driven by needs to make faculty costs contingent on enrollments. This has led to growing employment of much lower paid adjunct faculty members, and a bit of unrest.

Poor K-12 student preparation is pervasive, so institutions spend very large amounts on remedial services to compensate.

Beyond the normal educational services, there are health services (including for mental health), career counseling, placement services, dispute resolution services, management of intramurals and clubs, etc.

Activities associated with university and discipline-specific accreditation, certifications of workload distributions, auditing of travel expense reports, compliance with policies and procedures, and sundry other forms consume significant faculty and staff time, increasing costs.

The covid-19 pandemic has caused many in higher education to recognize that online learning is better than expected in terms of efficacy and ease of use, thanks in part to programs hosted on platforms developed by major institutions (e.g., Coursera, edX, and Udacity). This can enable much lower tuition, but only a few better-resourced institutions have lowered prices.

Increasing equity of foreign institutions, immigration headaches in the United States, and now pandemic worries are steadily decreasing enrollments of full-tuition-paying foreign students, threatening almost $50 billion of revenue to US universities.

Possible Futures for Higher Education

Top-ranked institutions have the resources and confidence needed to explore potential innovations. Lower-ranked institutions understand pending changes and will emulate successes if resources allow. Poorly resourced institutions will struggle to sustain their seriously threatened business models. Different disciplines will address needs to change in different ways.

- *Online education*. Everyone has to entertain the prospect of greater use of online teaching. However, disciplines may differ in emphases based on content. The extent that face-to-face interactions are central to a discipline and can be technologically mediated is also important.
- *Interactive technologies*. Technologies can enable compelling interactive portrayals of phenomena ranging from chemistry and physics to human physiology and behaviors to social and cultural interactions. The quality of these immersive portrayals has steadily improved and costs have decreased. The economics of such technologies depend on the number of students across which costs can be amortized.
- *Knowledge management*. The nature of knowledge artifacts differs substantially across disciplines. In particular, the technological infrastructure associated with science and technology has benefited from substantial sustained investments; humanities have seen important investments and innovations but not on the same scale (the knowledge artifacts of the humanities were seldom originally created digitally).
- *Process improvement*. This is affected by the extent to which educational processes are interwoven with operational processes. This is greatest for medicine, where much education happens during delivery of clinical services. In engineering, considerable research happens with industry and undergraduate cooperative education programs are pervasive. Humanities have few similar processes. Scale is also important so that investments can be amortized across many students.

Conclusion

It is critical to understand the overall economics of education, despite the fragmentation among federal, state, and local stakeholders. Such understanding could enable sharing of investment resources (e.g., in technology platforms) while minimizing cost shifting downstream because of upstream underperformance (e.g., if K-12 education poorly prepares students, then higher education has to provide remedial services, which increase costs).

Thinking in terms of unifiability, policies need to address the education ecosystem of K-12 schools, community colleges, and universities.

Leadership for a Complex Enterprise

Jeffrey Wilcox

Dinesh Verma

Jeffrey Wilcox and
Dinesh Verma

A decade ago we participated in a small colloquium on systems thinking.[1] The people gathered were interested in defining complexity from a pragmatic perspective. The views were different, subjective, even confusing. We were tempted to conclude that complexity may be no different from beauty: it was all in the eye of the beholder. This is often the case with meetings and conferences on complex systems.

For an organization to successfully develop and deploy complex systems, first it must transform itself into a complex enterprise. We posit this based on our practical experience with Conway's law, which states that "organizations are constrained to produce systems that mirror the information structures of the organization." Each of us has over 30 years of experience dealing with complex systems challenges and the organizations that seek to address them, and can testify to the fundamental truth of this adage. To solve a complex challenge it is necessary to build a complex organization with the richness of structure sufficient to the task at hand.

---

[1] Research Colloquium on Complex Systems, June 24, 2010, Hoboken, New Jersey, sponsored by the School of Systems and Enterprises at Stevens Institute of Technology.

Jeffrey Wilcox is vice president for digital futures at Lockheed Martin Corporation. Dinesh Verma is executive director of the Systems Engineering Research Center and former dean of the School of Systems and Enterprises at Stevens Institute of Technology.

Complex Enterprise as Operating System

What does it mean to transform into a complex enterprise? A useful analogy is the operating system. Every enterprise has a set of communication structures, behavioral norms (i.e., culture), incentive structures, learning mechanisms, sensing mechanisms, and processes for allocating decision rights. This operating system represents the platform from which an organization engages with the world, and its limits represent the limits of the organization's potential impact.

> *Complex systems are more than the sum of their parts, and something essential is lost in the decomposition and reconstitution of a problem.*

The operating system of today's organizations evolved from over a century of attempting to eliminate complexity from operations in favor of predictability. Today's organizations attempt to model the work of the organization and break it down into components that can be solved separately and then recombined.

Complex systems, however, are more than the sum of their parts, and something essential is lost in the decomposition and subsequent reconstitution of a problem. It will take a new kind of operating system to engineer complex adaptive enterprises. This will in turn require new considerations for leadership.

Enterprise Leader as Gardener vs. Chess Master

Leaders are the heartbeat of the operating system. They determine who gets access to what information and when. They determine who has decision rights and they set the incentive structure that guides behavior. Leadership in the age of complexity looks very different from the leadership norms in today's enterprises. This can be thought of in the often-used analogy of the chess master and the gardener.

The operating system of today follows a leadership model focused on command and control. Like a chess master, the leader is expected to deploy the pieces (resources, employees) in predictable moves toward a clear goal. Limited assumption of individual autonomy (chess pieces move only in specified ways) prevents people from contributing based on the fullness of their abilities.

But complex enterprises often have to contend with a dynamic context, evolving goals, and changing rules. What is required is a leader who acts more like a gardener, whose focus is on creating and holding space for the team to reflect and feel empowered to serve the mission of the organization. The leader embraces complexity by allowing the resources to self-organize in pursuit of the mission, while protecting them from external forces and weeding out bad actors. The leader uses the following tenets in this new operating system:

- *Default to open*. Perhaps nothing is more important in a complex operating system than the free movement of ideas and knowledge throughout the enterprise. The old model is based on "need to know": Who gets to be in what meetings, who is on what email distribution? The new model is a "need to share" presumption that all work is done in the open. If everyone has access to information, they are better able to contribute to the team's mission.
- *Choose principles over rules*. Former US treasury secretary Henry M. Paulson (2006) observed that the *International Financial Reporting Standards* were "principles-based, rather than rules-based." He suggests that a system organized around a small number of principles (concepts or ideas) is better able to deal with emergent (new or unique) situations than a rules-based system. He characterizes the consequence of a rules-based regulatory approach as "an ever-expanding rulebook in which multiple regulators impose rule upon rule upon rule." This leads to a system that is "prescriptive and leads to a greater focus on compliance with specific rules."
- *Foster cognitive diversity*. To create a rich dialogue that expands the palette of possibility the leader must build diverse teams from the outset and ensure that every member is able to contribute to the fullness of their gifts.
- *Experiment, then reflect*. The leader must foster an environment of experimentation and reflection. Complex systems need to be explored through constant tinkering and questioning. The goal is not to focus on a zero-failure mindset, which breeds fear, which quashes creativity. Mistakes are opportunities

to learn and explore new space. A useful analogy here is an orchestra versus a jazz combo. A mistake by a player performing an orchestral piece can be devastating to the performance. A "wrong" note played by a jazz musician can send the combo off in a new—and potentially richer—direction.

Until the enterprise leadership model changes, it will not be possible for leaders, companies, industries, or the economy to tap the fullness of their technical prowess or of people's gifts, and they will continue to fall short of solving the world's complex challenges. As Donella Meadows (2008, p. 167) reminds us, "Systems thinking makes clear even to the most committed technocrat that getting along in this world of complex systems requires more than technocracy." Indeed, we must summon our full humanity.

References

Meadows DH. 2008. Thinking in Systems: A Primer. White River Junction VT: Chelsea Green.

Paulson HM. 2006. On the competitiveness of US capital markets. Remarks, Economic Club of New York, Nov 20.

True Complexity and False Simplicity

Jason Crabtree is CEO and cofounder of QOMPLX, Inc.

Jason Crabtree

Today's digital societies are more connected and interconnected than ever before. Nevertheless, subtle and substantive long-term changes have been afoot. Current thinking about risk management across organizations and practices has not kept pace with this emerging reality, in part because the changes are at the same time very fast and very slow.

The digitization of *everything* in our workplaces and our personal lives is accelerating with each successive shock to the economy. If the primary purpose of risk management is to improve outcomes for stakeholders, then the participants in risk-related functions need to account—and be accountable—for the structural, behavioral, and physical realities of pressing societal challenges on several spatial and temporal scales. This includes dealing with often ignored systems concepts such as ergodicity—a too often applied hypothesis that allows for replacing dynamical models with probabilistic ones in certain constrained cases—noting that in many nonequilibrium human systems of interest and importance, *when* does not equal *if*.

Fast vs. Slow Changes

Fast changes are easiest to see, comprehend, and explain. Covid-19's threat to human health has rapidly driven hundreds of millions of people to the daily use of videoconferencing technologies at work and at home. The security implications of this newfound dependence on key providers of these services are profound.

Slow changes are more difficult to understand, both for casual observers and for the people charged with quantifying emergent risks. Simple cases of technology outages in today's consumer-facing applications and services abound. More complicated cases, however, like the Travelex ransomware incident that disrupted numerous downstream banking services, lurk just beyond the public consciousness. Deeper trends, as exemplified by the 2003 essay "Cyber*Insecurity:* The Cost of Monopoly" (Geer et al. 2003) on the security implications of modern computer operating systems, dominate the professional conversation below the popular discussions about nation-state threats and cyber norms.

Neither globalization nor corporate consolidation has by itself driven this migration of risk from individual entities into more systemically important institutions. Complexity and the falling cost of information technology have driven a rapid yet inefficient interest in the proliferation of software. To say that "software is eating the world" is a naïve formulation of a slow but emergent truth: universal computing has made complexity more economical than simplicity.

Complexities of Digital Dependence

Society's dependence on all things digital is irreversible and inestimable. Since both digital dependence and interdependence continue to grow, predicting the exact effects of specific changes to the digital world is impossible.

It is possible, however, to approximate scenarios useful to both professional and public discourse about design choices and incentives. Exposure to systemic risk and the ongoing economic risk migration demands it. Even simple things like a dependence on managed IT providers can lead to a severe accumulation of risk by creating a limited number of unintentionally important counterparties whose successful operation is suddenly crucial to providing critical services ranging from education to health care.

The widespread use of complex but highly standardized and mass-produced contraptions with flexible and rapidly improving CPUs and favorable production economics at scale makes it possible to simulate simpler machines. The flexibility of modern operating systems and programming languages at their core has exacerbated the recent phenomenon of numerous machines whose functionality widely surpasses the tasks to which they are applied. Threats to digital society now have the advantage of low-cost complexity and can exploit the false simplicity that is so often foolishly implemented in systems.

Hacking is often merely the exploitation of system complexity, triggering an outcome not considered by an engineer. It is a repurposing of a system's design, much as a parasite or disease organism repurposes an existing biological function. As yet, however, there is no digital immune system that will dynamically deploy a hierarchical and temporal set of response mechanisms as does a human immune system. Each integrated digital value chain will respond differently to the repurposing, based in no small part on how well designers have *constrained* the potential uses of software that can run on the flexible universal computers embedded throughout the connected world.

Universal computing has made complexity more economical than simplicity.

This minimalist perspective of *security as the effective constraint of generalized capability* will require hierarchical cooperation across the integrated value chain in the economy. It will be a dance between enabling and constraining action in diverse sociotechnical contexts in which different actors will benefit disproportionately from each successive choice.

Security is functionally best thought of as a subset of reliability, that is, fitness for purpose as employed by users, not only as intended by engineers. Software is showing the effects of a decoupling between cost and consequence. Mass ransomware, major data breaches, and widespread information technology outages are all part of the emerging asymmetry between defenders of civil society and entities that seek to harm, disrupt, or coerce others.

Growing exposure to the transitive risks associated with digital interdependence demands the disclosure of breaches and sharing of metrics, and will require the difficult work of ontology specification within and across specialized knowledge domains. Encouraging accountability and economically rational actions in a complex multiagent decision-making environment requires semantically consistent approaches. This is not limited to cybersecurity. It is equally applicable to understanding the propagation of demand shock due to covid-19 or to crisis modeling for financial events like the 2008 market collapse.

Conclusion

To thrive in an increasingly volatile environment, and perhaps even to survive in it, more dynamic, continuous, forward-looking simulation-based exploration of possible future events is needed. Society cannot afford to be limited to historical experience or extrapolative prediction. Generative modeling, parametric studies, and the ongoing curation of previously considered scenarios must be sought out and, indeed, enabled. Scenario-based narratives from specific analyses must be communicated to individuals and organizations using familiar terminology.

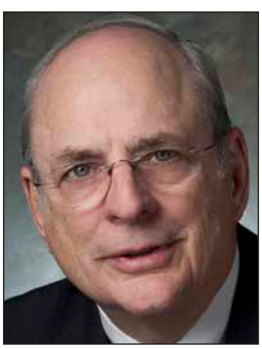
The best approach to this solution remains the celebration of the struggle for clarity on important issues, especially in an era of disinformation coupled with shifting social contracts between people, organizations, and governments. Poor thinking and turgid dialogue will be our collective undoing. Reasoned argument and the formal cataloguing of knowledge offer a glimpse into a more hopeful, collaborative, and unifiable future.

Reference

Geer D, Pfleeger CP, Schneier B, Quarterman JS, Metzger P, Bace R, Gutmann P. 2003. CyberInsecurity: The cost of monopoly. Computer & Communications Industry Association Report, Sep 24.

Epilogue

Toward an Engineering 3.0



Norman Augustine (NAE) is retired chair and CEO of Lockheed Martin Corporation and former chair of the National Academy of Engineering.

Norman R. Augustine

The history of major engineering projects traces back at least 5000 years. It began in earnest with the construction of large stationary structures: pyramids, walls, roads, bridges, and aqueducts—what became known as civil engineering. The need to construct objects whose parts move relative to one another gave identity to the practice of mechanical engineering. Then the ability to separate, combine, and capitalize on the elements of matter enabled chemical engineering. The eventual ability to control the behavior of electrons defined the province of electrical engineering.

A second era followed in which needs and capabilities arose that did not neatly fit the traditionally defined engineering categories. As a result new, more specialized engineering disciplines were born: petroleum, aerospace, biomedical, computer, entertainment, and many more.

Then dawned the era that might be termed Engineering 3.0, a pursuit to better engage with complex systems of systems demanding great breadth as well as depth of knowledge. The engineering profession, well founded in methodology, nonetheless found itself ill prepared to deal with the inter-connectedness and enormity of connected but uncoordinated systems and their consequences.

Given the profusion of knowledge in each of the traditional engineering disciplines, the teaching of engineering had over the generations become highly compartmentalized to the point of occasional disconnection with society and reality. The "stovepiping" trend was exacerbated by such forces as the academic accreditation process, which encouraged this narrower focus. Similarly, industries largely structured themselves around highly specialized disciplines.

Complex Systems Challenges

It is clear that complex systems require far more than traditional engineering. For example, how can the natural environment be preserved when any solution demands that literally dozens of autonomous geopolitical entities work in concert? How can America's public pre-K-12 education system, with its 14,000 independent school districts, be made to produce students who are uniformly competitive on a global scale? How can health care be provided to over 300 million people without bankrupting the nation? And how can congestion and gridlock on the nation's 8 million miles of roads serving 247 million motor vehicles be eliminated?

Any objective assessment of the current state of the art in engineering such complex systems would likely conclude that there is a great deal of room for improvement and unifiability—"a target-rich environment," as they say in the Pentagon.

> *How can health care be provided to over 300 million people without bankrupting the nation?*

Beginning with climate change, the carbon concentration in the atmosphere has now risen to well over 400 ppm for the first time in at least 900,000 years. In education, US 15-year-olds finish in 25th place on international tests in combined reading, science, and mathematics scores—even as this country spends more per student than any other nation but one. America now devotes 7 more percentage points of its GDP to medical care than the next highest spending nation, yet has a declining life expectancy and fails to impress across many other health indices. The average adult American wastes 54 hours a year in traffic delays, and 36,000 Americans die in automobile accidents each year.

Two Complications for Engineering 3.0

Two particular complications confront the opportunities for Engineering 3.0. The first is that it involves… humans. Many systems include people and they appear not only as individuals but also collectively as society.

Humans can be not only inconsistent but notoriously irrational as well. They may refuse to take vaccines that are known to save lives. They are more frightened of shark attacks than bee stings although the latter kill 60 times more people in the United States each year. They may oppose the prospect of nuclear fusion energy because there have been accidents in nuclear fission plants and because of a fear of nuclear weapons. As research in behavioral sciences has repeatedly shown, people implausibly value something they have more highly than the identical thing they don't have. Attempts to model the behavior of the stock market or project election outcomes provide classic examples of systems tortured by such idiosyncrasies.

The second emergent complexity multiplier concerns a relatively recently discovered colorless, odorless, weightless substance called…*software*. It flourishes in complex systems but the accidental omission of a single bar among many thousands of lines of code can cause a spacecraft mission to Venus to fail (see Mariner 1). Further, adding a few lines of code to a major system is usually not very costly on the margin—but has led to the adage among some engineers that "If it isn't broken, it doesn't have enough functions yet." A modern automobile contains around 100 million lines of code—about a thousand times the number of lines in the Apollo spacecraft. It is a software app on wheels—and driverless cars are still in the future.

Further Challenges

Systems of systems involve feedback, interconnectedness, instabilities, nonlinearities, and discontinuities. Philosophers and metaphysicists over the generations have puzzled over Lorenz's conundrum that asks whether a butterfly flapping its wings in, say, New York, can cause a hurricane in China. (We now know the answer: a microbe in China can shut down New York.) Similarly, the assassination of an archduke in Sarajevo can trigger a world war. Or an argument between a street vendor and a police officer in Tunis can spark an "Arab Spring" throughout much of the Middle East when connectivity is provided through the widespread availability of cell phones. And a tree branch in Ohio can trigger a cascade of events that shuts off electric power for over 50 million people in the northeastern United States and part of Canada for up to 4 days (see 2003 blackout).

Further, the challenge of designing and analyzing interdisciplinary systems usually requires accommodating legacy components of existing systems, while maintaining operability as change is introduced: the classic problem of rebuilding an airplane in flight—or restructuring a national healthcare system or introducing resilience into the nation's existing electric grid.

Friedrich Wiekhorst of the Max Planck Institute derived the equation that describes the number of states in which a system of *n* elements can exist, assuming each element can affect each other element in the simplest of possible manners, a binary connection. A system of two elements thus has four possible states. But a system of just seven elements has a number of possible states that approximates the number of stars in our galaxy. While in most actual systems every element is not directly connected to every other element, the magnitude of the number of theoretical possibilities does suggest, among other things, why many failure modes are not caught in testing.

The pace of technological change intensifies the challenges faced by the modern systems engineer when a system can be out of date by the time it is deployed: the number of transistors on a chip has increased by a factor of about 10 million in just 50 years; the cost of gene sequencing has declined by over 6 orders of magnitude in less than 20 years; the number of smartphones in use has grown from zero to 3.5 billion (half the world's population) in 13 years.

Further, complex unifiable systems are often adaptive, as is particularly true of biological systems. Engineering such systems may entail compromises and trade-offs of unlike qualities.

Limitations of Modeling and Simulation

The rigorous practice of modeling and simulation as part of systems engineering can offer important insights into the design and analysis of complex systems of systems—sometimes aptly referred to as *wicked problems*. But even with these tools challenges abound. When it comes to systems of systems, the optimum of the whole rarely equals the sum of the optima of its parts. Contrary to ritual, the best way to eat this kind of elephant is *not* one piece at a time.

If a model is too encompassing it may defy analysis. But if it is too narrow it may omit critical aspects of a system's behavior. Unfortunately, it is not uncommon for system failures to be caused by elements that did not rise to the level of adequate concern by system designers. It was, for example, not one of the 25,000 tiles that received so much attention on the Space Shuttle's thermal protection system that caused the failure of the *Challenger*. It was an O-ring.

A regional telephone company performed an extensive analysis of what would be needed in order to recover from a major hurricane in its operating area. It stockpiled wire, telephone poles, vehicles, and more. But when the hurricane struck, the bottleneck that emerged was absent from the models: it was daycare centers for children. With schools closed, employees' families with two working parents had to have one parent remain at home to care for the children, just at the time a full workforce was critically needed.

The pace of technological change intensifies the challenges when a system can be out of date by the time it is deployed.

So fundamental an issue as identifying figures of merit can be ambiguous in complex systems. There is, for example, the tension between controlling system cost and ensuring system resilience; e.g., just-in-time inventory vs. "just-in-case" inventory. Is it better to be efficient or resilient with regard to stockpiling empty beds in a hospital?

Beyond Established Equations

Evaluating systems involving humans may require placing a value on a human life, a year of human life, a quality-adjusted year of human life, or some other such measure. Should a new highway be constructed through the middle of a city that will save thousands of travelers many hours but will create a barrier to community life in the affected neighborhood? What is the exchange rate between tons of carbon emitted into the atmosphere and its social cost? Is it appropriate to put millions of people out of work, many of them into poverty, in order to save thousands of lives in a pandemic? Engineering complex systems not uncommonly finds itself more engulfed in the field of ethics than engineering—confronting issues that have no standard equations for their solution.

As essays in this issue point out in various styles and substance, when it comes to engineering complex unifiable systems, both the profession and the practice may be better at reflecting on questions and offering insights than in delivering absolute solutions.

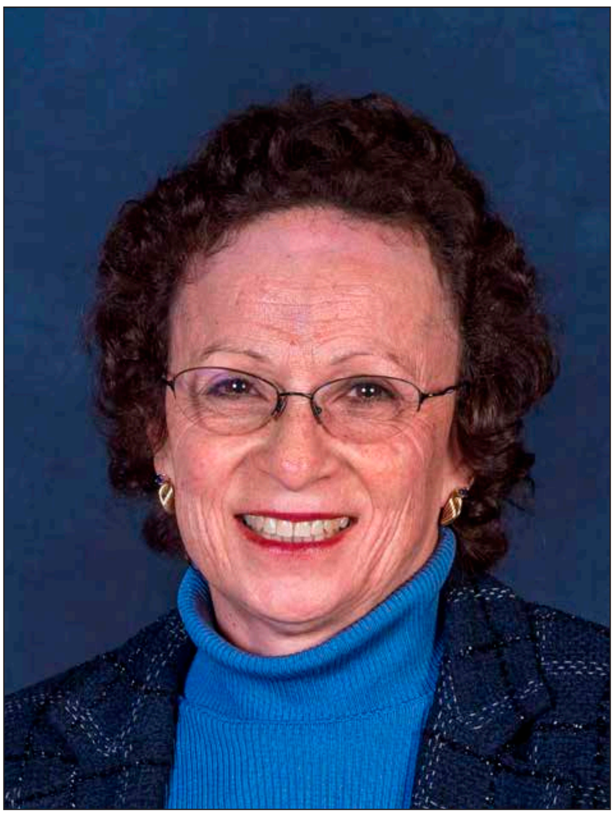
Finally, a critical factor that the construction of many complex systems often fails to adequately address is their vulnerability to external interference, intentional or otherwise. The design of the World Wide Web does not appear to have adequately accounted for the impact of malevolent individuals or nations—or even of nature itself—disrupting the intended functioning of the system.

America's electric grid is a canonical example of this problem. With 7300 power plants and 160,000 miles of high-voltage line, the latter owned by some 500 independent firms, the US grid possesses substantial vulnerabilities, and a massive failure of the system could prevail for months, creating disruption of a magnitude even beyond that of covid-19. Communications would be curtailed, pumps in filling stations would not operate, refrigerators storing food would fail, entire regions would go dark. A near-term task will be to take hostile threats into consideration when designing self-driving cars that will be used on connected highways.

As ordained in the variously attributed euphemism, "Every system is perfectly designed to get the result it gets." Even, unfortunately, unwanted results.

An Interview with . . .

Jill Tietjen, Electrical Engineer, Women's Advocate, Author



RON LATANISION (RML): We're delighted that you're available to talk with us about your experience as both an electrical engineer and as a writer and speaker and mentor, encouraging young women in science and engineering—all these things are so important.

MS. TIETJEN: Thank you. It is very fun. I'm also former CEO of the National Women's Hall of Fame, and I've written the award-winning and best-selling books *Her Story: A Timeline of the Women Who Changed America* and *Hollywood: Her Story, An Illustrated History of Women in the Movies*.

I've spent more than 40 years encouraging young women to be engineers. I don't think I could be where I am if I hadn't been an engineer. In fact, when I was inducted into the Colorado Authors' Hall of Fame I specifically asked and then answered the question, Why did I have to be an engineer first? And what did I learn from that process and what were my reasons?

So many things I had to learn! I had to be a member of the Society of Women Engineers because I had to see the idea for an outreach program for an essay contest about historic women engineers and scientists. I didn't know any of them! When we started that outreach program, we had to do the research on those women. This was in 1987, when kids had to go to the library and use books. We had to determine what the available resources were and who the women were so that the kids could write essays on great women in engineering and science.

I had to be an engineer because engineers solve problems and I love to solve problems. I started doing jigsaw puzzles when I was 2 years old. I have very strong pattern recognition skills.

RML: That's a very interesting perspective. I'm an engineer as well and I often get involved in trying to perform what are called *root cause analyses*: if there's a failure, you try to understand why something happened. I always tell people this is like working a puzzle: There are a lot of different pieces, and you have to put them together in a way that makes a final product. That's a root cause analysis. A puzzle is a very good analogue for the process we go through: We collect all the pieces, put them together, and see whether they make sense in terms of understanding why something happened.

MS. TIETJEN: There's another piece, too, and that's the word problems. In engineering school one of the things you have to discern is which pieces of information are relevant to the problem you're solving.

RML: Would it have made a difference if you were an electrical engineer or if you were a civil engineer?

MS. TIETJEN: I don't think so.

CAMERON FLETCHER (CHF): Why did you choose electrical as opposed to one of the other fields?

MS. TIETJEN: Well, my degree is actually in applied mathematics. I grew up in Virginia and wanted to go

---

This interview took place September 2, 2020. It has been edited for length and clarity.

to the University of Virginia. I am very fortunate that the university admitted women as undergraduates for the first time in the fall of 1970. I entered in the fall of 1972 as a mathematics major because no one, not even my PhD engineer father who worked at NASA Langley, told me that engineering was probably the right place for me and that I should apply to the engineering school. You're supposed to start in the engineering school; you don't generally transfer later. And my guidance counselor had told me not to even bother applying to the University of Virginia because I wouldn't get accepted.

I applied early decision and was accepted as a mathematics major in the College of Arts and Sciences. Halfway through my first semester, I knew I was in the wrong place: I needed to be in engineering. I made all the arrangements to transfer and I was very excited. There was an applied math major available in the School of Engineering and Applied Science. I had to take a minor, that's how the applied math program worked. I can't stand chemistry. I did electrical engineering because it was cool.

In engineering you have to discern which pieces of information are relevant to the problem you're solving.

My first job was with Duke Power Company in Charlotte, NC. I didn't know until after I took the fundamentals of engineering exam and received the results that my degree was not ABET accredited. That was a very strong influence on me. But I am licensed: I'm a PE in Colorado, and I served for 10 years as an electrical engineering accreditor through IEEE.

RML: Duke Power is also where you began your public speaking career, isn't it?

MS. TIETJEN: Yes, my boss recognized my abilities and I was trained as a member of the company's speakers bureau.

CHF: That is so unusual—the fact that Duke hired you for your technical degree, because at that time women were most often hired as secretaries, which may have been a way to get a foot in the door but for many women, that was it, it became their career. So I'm impressed that you started your career in your technical field *and* were recognized for your abilities.

MS. TIETJEN: Duke was absolutely wonderful. Actually, they wanted my fiancé, my first husband. We weren't getting married until we had jobs in the same place because we are both engineers and that's how we thought. And there was a lot of competition. I had seven job offers at the time, and every single one was as an engineer.

CHF: That's very impressive, Jill.

MS. TIETJEN: Thank you. I didn't really know there was an alternative.

After Three Mile Island in 1979, Duke established a speaker's bureau and my boss's boss recommended that I be trained as a speaker. I went to one of the best training experiences I've had in my entire life and started my speaking career.

RML: It seems to me that engineers are typically reluctant to speak in public. They are very good at what they do, but not all that comfortable, not all that forthcoming when asked to speak in public. It's just not typical. I'm wondering, how did the folks at Duke Power capture or gauge your capacity to become a company spokesman, given your technical skills? What was it about your interaction that led them to think that preparing you as a speaker would be in their interest?

MS. TIETJEN: Well, I was very involved. I've always been very involved, in high school, in college, in everything. At the University of Virginia, I was an officer of the Engineering School, which then made me a member of the honor committee. I played the violin for many years. Maybe that was it. I've been performing since I was 8.

RML: I understand you were testifying before federal and state regulatory commissions. Did you speak to lay audiences as well?

MS. TIETJEN: Oh, yes. When I was trained by Duke Power, it was to go talk to lay groups—the Garden Club, the Rotary Club, the Optimist Club, 39 and Holding…. I didn't start testifying until 1987, when I was at Stone & Webster, and the best training that I got there for expert witness prep was in Maine in 1993.

After Three Mile Island, companies had to have what were then called *crisis management drills* (they have nicer names now). My role was as a technical briefer. The vice president of engineering would get up and give some technical explanation of what incident was being simulated in these drills, then it was my job to talk to the reporters and say, 'When the vice president said this, this is what he was talking about and this is what he meant,' so the reporters could write their articles "in English" for their readers.

Jill Tietjen addresses teachers, parents, and students, STEM Women and Our Daughters Changing the World, November 2, 2013, Ranch View Middle School, Highlands Ranch, Colorado. Photo courtesy of STEM Ventures.

RML: I'm very interested in things related to nuclear systems, so I'm curious: if you were speaking to a lay audience and someone said, 'What are we going to do about nuclear waste?,' how would you have answered that?

MS. TIETJEN: France knows how to deal with nuclear waste. Here in the United States we don't have the political will to deal with it. Right now, the only thing we're doing is trying to figure out how to bury it in the ground forever, which is what Yucca Mountain was supposed to be, and of course the Yucca Mountain proposal is dead because it got so politicized. You chemically convert it and put it into a glass form so that it is immobilized, or after you've recycled the parts that can be reused. But that got stopped way back when. We just don't have the political will to deal with it.

Maybe some of it is the fact that the only country that has ever used the nuclear bomb happens to be us. It did stop the war, but it was catastrophic.

When you talk about nuclear, it's very difficult to get the American public to understand the difference between a bomb and a nuclear power plant.

RML: Yes, political will and public will just don't seem to come together on this. And I don't think it's sensible for us to be building nuclear electric generating capacity when we don't have the means of handling the waste.

You have a great interest in educating young women and encouraging them in science and technology. Could you tell us about the motivation for that and how you came to interact on those topics?

MS. TIETJEN: Some of it I've mentioned. Nobody encouraged me, my guidance teacher *dis*couraged me, and I graduated without an ABET-accredited degree. All three of those were significant motivators for me to say to myself, 'There is a young woman out there and she has talents and abilities that need to be encouraged and it is incumbent on me to figure out a way for her to not have the experiences I've had and for her to be encouraged.'

RML: How do you encourage them?

MS. TIETJEN: Through the Society of Women Engineers and other ways as well. I found SWE in 1979 at a card table at a career fair in a gymnasium at North Carolina State University where Duke Power had sent me to do on-campus recruiting. There was a table for the Society of Women Engineers, and I walked up to them because I had never heard of them and I said, 'What do you do?' They said, 'We encourage young women to think about pursuing engineering as a career and we provide professional development for women who are in the field.' I signed up.

I told you I was always pretty active. I started the Charlotte-Metrolina section of SWE. Then I moved to Colorado. At the time, the *SWE Magazine* listed the presidents of the sections. A week after I got to Denver, I called the woman who was president, who is now a very dear friend of mine, Alexis Swoboda, and I said, 'Alexis, I'm here, put me to work.'

Jill Tietjen accepting the National Medal of Technology from President George H.W. Bush for Admiral Grace M. Hopper, September 1991.

In 1987 I thought I had agreed to serve on SWE's National Awards and Recognition Committee. Apparently, I had agreed without knowing it to chair the committee.

Then in 1988 they put me on the ballot for vice president. I did agree to that. I saw the slate and thought, 'whew, good, there are six candidates and only three slots, I'll never get elected.' I got elected. And in 1991–92 I was national president.

After I moved to Denver in '81, I started nominating women to be SWE fellows. Then my first big nomination for a national award was Admiral Grace Murray Hopper for the National Medal of Technology, which I received for her in September of '91. She was the only woman there to get the National Medal of Technology. I just thought that was not right. Where were the women?

I started nominating women for all kinds of awards, and I also began to realize that women's stories were not told, women were not written into history. When Charlotte Waisman and I met in 2003, we decided we were going to write the book that became *Her Story: A Timeline of the Women Who Changed America*.

The problem was across all the fields, not just engineering and science. I learned that when I was director of the Women in Engineering Program at CU Boulder. I was assigned to the Status of Women Committee, and I just assumed that women were full professors in English and history and Spanish and all the liberal arts fields, but they weren't. How could that be?

I realized that women had to be advocated for across all fields of endeavor. Writing the book with Charlotte helped me understand more about the women in US history.

I told my friend Barbara Bridges in 2016 that I was planning another book in the *Her Story* series and I was thinking it would be *Her Story: Africa*. She said 'No, we need to do women in the movies.' That resulted in *Hollywood: Her Story* (2019), my ninth book. My tenth book just came out in the Springer series on Women in Engineering and Science, and now I'm doing the *Her Story: Africa* series.

If women aren't valued in society—and one of the ways that women are not valued is that they are not written in the history—one of the ways to fix that is by writing women into history and documenting what they've done.

For the first story in the Africa series, I was in Tanzania in 2017, interviewing women. The draft of the Tanzania volume was distributed there in 2018. We're looking for a publisher.

The Zambia volume was distributed there as a draft in 2019 and it looks like we have a Kenyan publisher. I'm working very hard on identifying all the women for the Kenyan volume because they say they'll publish that first and then help us find publishers in other African countries.

RML: I have a particular interest in all of this. I have four granddaughters, all early teenagers. If I were to recommend one of your books for them to read—and hopefully to put some perspective on how women become involved and change America and so on—which one should I start with?

MS. TIETJEN: *Her Story: A Timeline of the Women Who Changed America* is a beautiful book that demonstrates women's capabilities across a very wide breadth of endeavor. There are more than 850 women from 1587 to 2011. And there's an index in the back by profession—engineers, scientists, governors, singers, Nobel Laureates, politicians, doctors, attorneys, fashion designers, athletes…every kind of person.

Jill Tietjen with Yvonne Brill after the National Medal of Technology and Innovation award ceremony, October 21, 2011.

CHF: You've made some headway among countries in Africa. Do you have your sights set on other continents and countries?

MS. TIETJEN: It's very interesting that you would ask that. I have a coauthor to do a book on women in the food industry. We would do North America first, then—I don't know in what order—Europe, Asia, Africa, and South America.

I'm also working on three other books. One is the history of women in magic, with an international focus—at least every country where we can find a woman magician. My coauthor is a magician here in Denver; we met when she performed at a SWE conference. We've identified almost 900 women all over the world.

As male-dominated and as sexist as any other field is, magic is worse. And one thing that's interesting is what women magicians wear when they perform. If you're wearing a strapless, sleeveless gown, where are you going to put the stuff?

And then another woman who is an attorney who writes children's books has ideas about *Her Story* children's books.

RML: I'm interested in the concept of writing on women's issues of the kind you're describing in a global sense. Do you think the problems that women have, for example, in North America are similar to those of women in Japan or China? I have a little experience in those two countries. There seems to be a tremendous cultural difference between the opportunities that women have in, for example, China and those they have in Japan. Do you sense that?

MS. TIETJEN: I don't have enough knowledge to answer that question.

RML: You mentioned that you've taken the initiative to nominate women for awards. How do you go about identifying the people you nominate?

MS. TIETJEN: Well, when I started with Admiral Hopper and the National Medal of Technology, it was women I had identified through research for the SWE essay contest. Once I know about the women, sometimes I find awards. Sometimes it's the other way around. I nominated Stephanie Kwolek to the Hall of Fame of Delaware Women. I've known about her for a long time. She invented Kevlar and I knew she was from Delaware, so I took it upon myself to nominate her.

I've nominated women to the National Inventors Hall of Fame for a long time and was on the selection committee.

And I nominated my friend Yvonne Brill for the Fritz Medal of the AAES. When she heard that the Fritz Medal was being awarded to Yvonne Brill she actually called me and said 'Jill, is there another Yvonne Brill?' I said, 'Oh my goodness, Yvonne, that's ridiculous, it's you!' Once she was selected for the Fritz Medal, I decided to nominate her for the National Inventors

Hall of Fame. And, since she's from New Jersey, for the New Jersey Inventors Hall of Fame.

When she was inducted into the National Inventors Hall of Fame, I thought, 'oh my gosh, now I have to nominate her for the National Medal of Technology, since she's gotten all these awards.' So I nominated her for the National Medal. That was in 2010.

But she didn't get it in 2010. I contacted the guy and he explained that she couldn't be considered until 2011, that's the way it works—when you submit in 2010, the first time the nomination can be considered is in 2011. In May of 2011 Yvonne's daughter Naomi told me her mother had stage IV breast cancer that had metastasized to bone cancer. She said, 'Jill, you have to do everything you can.' I said, 'Naomi, I've done everything I can.'

In June of 2011, Yvonne called me and said, 'Jill, the White House contacted me and they want my Social Security number. Do you have any idea why?' 'Yes, Yvonne, I do have an idea why. Why don't you verify that the person who contacted you is at the White House Office of Science and Technology?' She did, and received the National Medal of Technology in October 2011. [She died in March 2013.]

And Yvonne was an amazing nominator herself. She nominated many, many women for AIAA Awards and for NAE membership and for all kinds of things. She was very active in SWE as well.

CHF: These are delightful testimonials of your impact. I'm also interested, what feedback do you hear from people about the impacts of your books?

MS. TIETJEN: The most significant feedback from the first one was, 'This gives women credibility.' 'They weren't written into the history before.' 'We didn't know that they did this.' 'We didn't learn about any of this in school.' I didn't learn it in school either. It's because of the research I've done that I know it. There are role models and there are women who have pioneered and it's important to learn about those stories.

The Hollywood book hasn't yet had its full impact, but it will. For me the biggest lesson from that book is that women were involved in every facet of the movie industry in the silent film era. They were directors. They were producers. They were making films—Alice Guy-Blaché was making movies in 1896. They were writing films. They were acting in films. They were stunting in films. They were doing everything. That story is very important.

But when the movies started making money in the 1920s the women got pushed out. Women have been trying to produce films and can't get the money. There have been exceptions, but you can count them on one hand. Women have known how to make movies from the beginning and they should be directing movies now and producing and writing and editing.

CHF: You're really performing a public service in terms of opening people's eyes and changing their perceptions about who is capable of what.

MS. TIETJEN: That's part of my personal mission statement, to inspire and motivate an army to change the perception of women around the world.

RML: I'm so pleased to know that there is someone like you who takes such a determined and dedicated interest in making sure all this happens.

CHF: And you are clearly indefatigable.

RML: From my perspective this requires someone who is really determined and willing to take the initiative, it's a matter of personal will, maybe more than political or public will. You have demonstrated a capacity here that I think is remarkable. You're an engineer who cares about our society, our culture, and particularly the women in our society. As I said, I have four granddaughters and I'm concerned about them all the time because I just don't see a very equitable world for them. What you're doing is a step toward changing that reality and I applaud you for that. I'm delighted we had this opportunity to talk with you, Jill.

CHF: Yes, thank you. In this interview series we look for people who have a technical background in engineering but have *made their mark* in other ways on society and/or culture. You so clearly are doing that and we can all be grateful for your considerable efforts. Thank you.

MS. TIETJEN: That's very nice. I really appreciate it.

RML: It's been a very engaging hour, Jill. I thank you again on behalf of the NAE—and my granddaughters.

MS. TIETJEN: Well, I want a good world for them and I want a world in which women are valued and appreciated. I'm working in every way that I know to help make that happen.

CHF: We can tell you are. Thank you so much.

RML: Yes, thank you. Take care. Stay safe and stay well.

MS. TIETJEN: You're welcome. You too. Bye.

NAE News and Notes

NAE Newsmakers

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 received the **2020 Dickson Prize in Medicine**, the University of Pittsburgh School of Medicine's highest honor. The prize is given annually to an American biomedical researcher who has made significant, progressive contributions to medicine. Dr. Collins is a pioneer in synthetic biology whose ideas have contributed to novel diagnostics and treatments targeting infections and complex diseases. Using engineering principles to design and construct synthetic gene networks, he was one of the first to harness the biochemical and biophysical properties of nucleic acids and proteins to create biological circuits. As the Dickson winner, he will deliver the keynote lecture at the university's annual campuswide showcase of scientific research, which has been postponed to 2021 because of the covid-19 pandemic.

George R. Cotter, retired director, Information Technology, and chief information officer, National Security Agency, was **inducted into the National Security Agency Cryptologic Hall of Honor** on October 16. For over half a century, he has fostered the adoption of advanced technology in support of NSA's mission. He led the agency in adopting high-performance computers and adapting them to the mission, and was founding director of the National Computer Security Center. His influence on computerization extended to the entire intelligence community and foreign partners.

Joseph M. DeSimone, professor, Department of Radiology and the Molecular Imaging Program, Stanford University, has been chosen to receive the **2021 Charles Goodyear Medal**, the highest honor given by the American Chemical Society Rubber Division. He will be honored during a banquet at the 2021 International Elastomer Conference in Pittsburgh.

Michael F. Doherty, Duncan and Suzanne Mellichamp Chair in Process Systems Engineering, University of California, Santa Barbara, was the **John M. Prausnitz AIChE Institute Lecturer for 2020**. His lecture, "Innovation at the Frontiers of Chemical Engineering Practice and Science," was presented online November 18 at the 2020 AIChE virtual annual meeting. The lectureship is awarded to a distinguished member of the AIChE Institute who has made significant contributions to the chemical engineering sciences in his or her field of specialization.

Kenneth E. Goodson, Davies Family Provostial Professor and senior associate dean, School of Engineering, Stanford University, will share the **2020 University Research Award** with Ali Niknejad, professor of electrical engineering and computer sciences at the University of California, Berkeley. Professor Goodson is being honored for excellence in semiconductor technology research, notably his pioneering efforts to improve the industry's fundamental understanding of heat generation and transport in nanometer-scale transistors, as well as advanced cooling methods for integrated circuits. The award, given by the Semiconductor Industry Association and the Semiconductor Research Corporation, was presented to Drs. Goodson and Niknejad during the 2020 SIA Leadership Forum and Award Celebration, a virtual event that took place November 19.

Carol K. Hall, Camille Dreyfus Distinguished University Professor, Department of Chemical and Biomolecular Engineering, North Carolina State University, has been awarded the **Margaret Hutchinson Rousseau Pioneer Award for Lifetime Achievement by a Woman Chemical Engineer** sponsored by Pfizer and presented by AIChE. The award is given to an AIChE member who has made significant contributions to chemical engineering and who has paved the way for women to have a greater impact on the profession. Dr. Hall is being honored for her 4 decades of field-leading research accomplishments, her inspiring leadership in chemical engineering, and her tireless mentorship of colleagues—especially young faculty and women—at all levels of the profession.

Chris T. Hendrickson, Hamerschlag University Professor Emeritus, Departments of Civil and Environmental Engineering and of Engineering and Public Policy, Carnegie Mellon University, has been honored with the American Society of Civil Engineers **Richard R. Torrens Award** for his outstanding performance as editor of the *Journal of Transportation Engineering: Part A, Systems*.

Ahsan Kareem, Robert M. Moran Professor of Engineering, NatHaz Modeling Laboratory, University of Notre Dame, received the **International Award of Merit in Structural Engineering 2020** from the International Association of Bridge and Structural Engineering, Zürich. He was recognized for "fundamental contributions to quantification, modeling, and analysis of wind load effects in structural design through research, teaching, service, and practice." (In the last decade only two Americans have received this honor.) Professor Kareem was also **elected a foreign associate of the Engineering Academy of Japan**. He now holds the unprecedented distinction of being the only individual who has been elected to the US NAE, the Chinese Academy of Engineering, the Indian Academy of Engineering, and the Engineering Academy of Japan. In addition, the **2019 Hojjat Adeli Award for Innovation in Computing** was awarded to Dr. Kareem and his student Xihaier Luo by Wiley-Blackwell publishers for their paper titled "Deep Convolutional Neural Networks for Uncertainty Propagation in Random Fields."

Cato T. Laurencin, University Professor; Albert and Wilda Van Dusen Distinguished Professor of Orthopaedic Surgery; professor of chemical and biomolecular engineering, materials science and engineering, and biomedical engineering; director, the Raymond and Beverly Sackler Center for Biomedical Biological, Physical, and Engineering Sciences; and chief executive officer, Connecticut Convergence Institute for Translation in Regenerative Engineering, University of Connecticut, has received the **2020 Herbert W. Nickens Award** by the Association of American Medical Colleges. The award is bestowed on an individual who has made monumental contributions to promoting justice in medical education and healthcare equity throughout the nation. It was presented in November during the virtual AAMC annual meeting, where Dr. Laurencin gave a presentation entitled "Black Lives Matter in Science, Engineering, and Medicine." In addition, the University of Texas MD Anderson Cancer Center announced that Dr. Laurencin is the recipient of the **2020 Mike Hogg Award and Lecture**, the institution's most prestigious award. The award is granted to practicing scientists and physicians who have made and continue to make exceptional transformative contributions to the field of biomedical research.

Oliver C. Mullins, Schlumberger Fellow, Reservoir Characterization Group, Schlumberger Companies, received the first **Lifetime Achievement Award for Outstanding Technical Excellence to the Oil and Gas Industry**. The award was presented by the Abu Dhabi International Petroleum Exhibition Conference (ADIPEC).

Donald A. Norman, professor emeritus and director, UCSD Design Lab, University of California, San Diego; Breed Professor of Design and EECS Emeritus, Northwestern University; and Honorary Professor, Design and Innovation, Tongji University, Shanghai, was selected for the **Design Guru 2020** award, presented November 9. Dr. Norman received the award from JK Lakshmipat University, Jaipur, India, for his continuous support for advancing design curriculum around the world.

M. Elisabeth Paté-Cornell, Burt and Deedee McMurtry Professor of Management Science and Engineering, Stanford University, has been awarded the **2021 IEEE Simon Ramo Medal** for her work in systems engineering and systems science with a focus on risk analysis.

Roderic I. Pettigrew, CEO, EnHealth, Texas A&M University, is the recipient of the **Vannevar Bush Award** from the National Science Board. Dr. Pettigrew is noted for his passion and creativity that have spurred innovation in biomedicine and for his efforts to break down boundaries between those working in the physical sciences and engineering and those working in medicine. The award, considered one of the country's highest science awards, honors lifelong science and technology leaders who have made exceptional contributions to the welfare of the nation through public service in science and technology and in shaping public policy.

Darrell G. Schlom, Herbert Fisk Johnson Professor of Industrial Chemistry, Department of Materials Science and Engineering, Cornell University, won the **2021 James C. McGroddy Prize for New Materials** from the American Physical Society, "For pioneering the atomic-layer-by-layer synthesis of new metastable complex-oxide materials, and the discovery of resulting novel phenomena."

Lisa T. Su, president and CEO, Advanced Micro Devices Inc., has received the semiconductor industry's top honor. On November 19 she accepted the **2020 Robert N. Noyce Award** during the virtual SIA Leadership Forum and Award Celebration.

Norman J. Wagner III, Robert L. Pigford Chair of Chemical Engineering, University of Delaware, was selected for the **2020 Francis Alison Award**, the university's highest faculty honor. The award is named for the university's founder and recognizes contributions and distinction as both a scholar and an educator. Professor Wagner was chosen in recognition of his many contributions, innovative research, and impact on Blue Hens.

Warren M. Washington, senior scientist, Climate Change Research Section, Climate and Global Dynamics Division, National Center for Atmospheric Research, will receive a **2021 Lifetime Achievement Award for Science, Service, and Leadership** from the National Council for Science and the Environment. Dr. Washington was one of the first developers of groundbreaking atmospheric computer models in the 1960s. These models, which use fundamental laws of physics to predict future states of the atmosphere, have helped scientists understand climate change. The award will be presented during the NCSE Drawdown 2021 Conference January 5–9.

During its annual meeting in October the **National Academy of Medicine elected** four NAE members: **Gilda A. Barabino**, president and professor of biomedical and chemical engineering, Olin College of Engineering; **Kam W. Leong**, Samuel Y. Sheng Professor, Department of Biomedical Engineering, Columbia University; **Fei-Fei Li**, professor, Computer Science Department, and codirector, Stanford Institute of Human-Centered AI, Stanford University; and **Susan S. Margulies**, professor and chair, Biomedical Engineering, Georgia Institute of Technology and Emory University.

The **Royal Academy of Engineering** has this year elected **Asad M. Madni**, retired president, chief operating officer, and CTO, BEI Technologies Inc., and independent consultant, as an **international fellow** for remarkable contributions in engineering innovations and technology commercialization. NAE members elected as international fellows in 2018 are **Frances H. Arnold**, Linus Pauling Professor of Chemical Engineering, Bioengineering, and Biochemistry, California Institute of Technology; **Harry Shum**, executive vice president, Technology and Research, Microsoft Corporation; and **Ji Zhou**, president, Chinese Academy of Engineering.

These NAE members have been elected **fellows of the Royal Society**: **David Harel**, professor, Department of Computer Science and Applied Mathematics, Weizmann Institute of Science; **Ramamoorthy Ramesh**, Purnendu Chatterjee Chair in Materials Science and Engineering and Physics, University of California, Berkeley; and **Molly M. Stevens**, professor of biomedical materials and regenerative medicine, Imperial College London. **Frances H. Arnold**, Linus Pauling Professor of Chemical Engineering, Bioengineering and Biochemistry, California Institute of Technology, has been elected a **foreign member**.

2020 Annual Meeting Highlights

The 2020 NAE annual meeting was held virtually October 4–7, with the theme of Engineering for Pandemics: Preparedness, Response, and Recovery. The virtual format facilitated the participation of 800 members, family, and guests spanning national and international time zones.

Newly elected NAE Chair **Donald C. Winter** opened the public session on Sunday and set the stage for the program. President **John L. Anderson** affirmed Dr. Winter's remarks about the NAE's responsibility for independent service to the nation, and reminded members of the expectation of service and volunteerism—"*engineer* is a verb, implying action. It is a great honor to be elected to the NAE, but like a university commencement, it is just the beginning." He went on to briefly describe new NAE initiatives such as a cross-generational "Engineering Call to Action" to address the covid-19 crisis and the creation of a Racial Justice and Equity Committee to strengthen the NAE's commitment to diversity in its programs and membership.

This was followed by the introduction of the class of 2020 by NAE Executive Officer **Alton D. Romig Jr.** (The induction ceremonies for the classes of 2020 and 2021 will be held during the 2021 annual meeting.)

During the awards part of the program, the **Simon Ramo Founders Award** was presented to **Frances S. Ligler**, retired senior scientist, Naval Research Laboratory, and distinguished professor of biomedical engineering, Joint Department of Biomedical Engineering, North Carolina State University and UNC–Chapel Hill, "for the invention and development of portable optical biosensors, service to the nation and profession, and educating the next, more diverse generation of engineers." The **Arthur M. Bueche Award** was presented to **Arden L. Bement Jr.**, David A. Ross Distinguished Professor Emeritus of Nuclear Engineering and director, Global Policy Research Institute, and Global Affairs Officer at Purdue University, "for contributions to science and technology advancement, international relationships, policy development, and Academies studies, from executive positions in government, industry, and academia." The **J.C. Hunsaker Award in Aeronautical Engineering** was presented to **Alan C. Brown,** retired director of engineering, Lockheed Corporation, "for innovative contributions to the design of commercial and military aircraft, and particularly the leadership of the team that developed the F-117 Stealth Fighter."

Dr. Romig then introduced the two plenary speakers. **David R. Walt**, Hansjörg Wyss Professor of Biologically Inspired Engineering, Harvard Medical School; professor of pathology, Department of Pathology, Brigham and Women's Hospital; core faculty, Wyss Institute for Bioinspired Engineering at Harvard University; codirector, MGB Center for COVID Innovation, and HHMI Professor, spoke about "Lessons Learned: How to Prepare for Future Pandemics." Next, Pam Cheng, executive vice president, global operations & IT, AstraZeneca, talked about "Fighting Covid-19 with Resilience—A Race Against Time."

Monday began with the annual business session for members, followed by the forum on "Engineering for Pandemics: Preparedness, Response, and Recovery." The topics and panelists were "Lessons Learned: How to Prepare for Future Pandemics," **David R. Walt**; "Fighting Covid-19 with Resilience—A Race Against Time," Pam Cheng; "Keeping Society's Transportation Systems Operational," Daniel Work; "The Future of Work: 15 Million New Jobs," **William B. Rouse**; "Vaccine Pandemic Production & Scale-Up," **Paul McKenzie**; and "Charting Pathways Out of Poverty Before and During the Pandemic: Trends in Acute Multidimensional Poverty across the Developing World," Sabina Alkire. Deanne Bell, TV host and founder/CEO of Future Engineers, moderated the panel discussion and the many questions from the audience.

Tuesday was dedicated to the section meetings, most of which had record attendance thanks to the virtual format.

On Wednesday the NAE/AIAA 2020 Yvonne C. Brill Lectureship in Aerospace Engineering recognized **Alejandro Miguel San Martín** for his role in the Mars Science Lab. He gave a very engaging presentation titled "From Airbags to Wheels: The Evolution of GN&C for Entry, Descent, and Landing."

Remarks by NAE Chair Donald C. Winter

It is my great honor and privilege as the NAE chair to welcome all of you to the 2020 annual meeting. It is most unfortunate that we must conduct the meeting in a virtual form, but the realities of the covid-19 pandemic must be accommodated. We will miss the informal dialogues with colleagues and a most meaningful induction ceremony for new members, but we will benefit from an agenda well suited to the current situation. I believe you will find that the NAE leadership and staff have developed a program that addresses many of the challenges posed by the pandemic to the engineering community. I for one am looking forward to hearing what our distinguished speakers have to say.

This is truly a challenging time in our nation's history. Even before the emergence of the pandemic, we were participating in what is arguably the most significant societal transformation since the Industrial Revolution two centuries ago. The digital transformation has not only changed the ways we communicate but challenged the nature of work, leisure, health care, politics, and relationships between nations.

The covid-19 pandemic has accelerated that transformation and added elements that challenge previously accepted beliefs. Supply chains are being reevaluated as the pandemic's impact compromises the integrity and assurance of critical sources of supply. We are finding both our electronic and physical infrastructure wanting as the role of cities adapts to changing forms and locations of both work and residences. And we are finding our educational systems from elementary schools to research universities challenged in concept and processes. Perhaps most significantly, these changes have created a new schism in society, between those who are able to conduct their business from the comfort and safety of their homes, wherever they may be, and those who must take on many risks and challenges—the risk of losing their job or business, the challenge posed by limited options for child care, and, of course, the risk of contracting the virus.

This transformation poses a great challenge to our federal, state, and local governments. Few politicians have any formal training in science, engineering, or medicine but they are being asked to make profound decisions based on what are often highly technical considerations. We hear the claim that they will "follow the science" but that is not easily done. The science is rarely clear and it is evolving rapidly. It often requires expert interpretation and evaluation, and it must be put into context. Furthermore, it is often the application of science, the engineering of systems and solutions, that represents crucial public policy considerations.

The National Academies have played a critical role as advisors to the nation since the establishment of the National Academy of Sciences in 1863. They have been relied on to provide independent, objective, and nonpartisan advice with the highest standards of scientific and technical quality and integrity. To do so, they call on the nation's preeminent experts in science, engineering, and medicine. In this process, the often critically needed engineering perspective has been, and will continue to be, a major demand function for the NAE.

I would like to take this opportunity to thank those of you who have served on NRC committees, boards, or programs, and ask that you continue to do so, perhaps at even greater levels of involvement. For those of you who have not yet done so, I encourage you to participate. I believe you will find this form of service to be both intellectually challenging and most satisfying.

There is one other aspect of this advisory function that the NAE performs that must be addressed. While study committee members serve pro bono, they are reimbursed for their expenses, which can be considerable, particularly when travel is required. Furthermore, staff support is necessary to guide the study process according to the exacting NRC processes that ensure independence, objectivity, and substantiation of all study results. Unfortunately, while many government leaders understand and value the advice from the academies' expert committees, it is increasingly evident that there are a number of issues for which that independent, objective, and nonpartisan advice would materially aid the development of public policy but is not requested or funded.

Donald C. Winter

Arguably the simplest way to address this is for the NAE to take the initiative and self-fund programs and consensus studies to address critical national issues. To do so requires discretionary funding, and this funding must come from donations. We are fortunate that a few significant donations in the past few months will enable us to proceed in this direction in a limited manner. More are needed. If you have donated previously, I encourage you to continue to do so and to consider increasing your level of support. If you have not done so, I ask you to reconsider your charitable donations and put the NAE Foundation at the top of your list.

Now, it is my pleasure to introduce NAE president **John Anderson** to deliver his address.

President's Address

John L. Anderson

Welcome to the National Academy of Engineering 2020 annual meeting. As president of the NAE, it is my honor to address this very distinguished gathering and celebrate the induction of our new members, the class of 2020.

Because of the covid-19 pandemic, our annual meeting this year is being held in virtual mode. This is an experiment for us. I want to thank our staff for their hard work in adjusting to the current conditions to make this a memorable meeting.

I'll begin with some background about the NAE and its sister academies.

President Abraham 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 in 2015 became the National Academy of Medicine—was established.

Two primary reasons for establishing the NAE were (1) to recognize the profession of engineering and its importance to society, and (2) to identify world-class experts in engineering to advise the government and public on technical matters. The first class of NAE members in 1964 had 25 members—56% from the business sector, 36% from universities, and 8% from national laboratories.

The National Research Council (NRC) was formed in 1916 "to bring into cooperation government, educational, industrial, and other research organizations" to advance science, aid the development of American industries, strengthen the national defense, and promote national security and welfare. The NRC is the operating arm of the overall organization, called 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, nor any congressional appropriation, as many may think. The vital work of the NAE and the institution as a whole depends on sponsors, donors, and volunteers. And I will be calling on all our members and friends to help with financial support of the National Academy of Engineering—we need your support to advance the mission of the NAE.

The mission of the National Academy of Engineering is to "advance the wellbeing 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 [and society] on matters involving engineering and technology."

This mission is accomplished through the work of NAE members in studies and activities of both the NRC and the NAE Program Office. To support our mission, we have reorganized the NAE Program Office consistent with what I call *the four 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

As examples, I offer a few NAE initiatives that support these objectives:

1. The publicized instances of police injustice inflicted on Black men and women over the past several months remind us of the continuous injustices suffered over centuries by minority populations in our country. In parallel with racial injustice is a stagnation or even decline in the percentage of minority students receiving degrees in engineering, thereby

resulting in lost talent to the engineering profession.

Several of our members wrote me and asked "What can we do about this situation?" In response, we created a Committee on Racial Justice and Equity, which is tasked to recommend actions that the engineering community and the NAE should take to further racial justice and equity for all our citizens. This committee aligns with our mission—to serve society, we must be *aware* of problems in society and potential *consequences* of our work. I believe engineering has much to offer in improving justice and equity for all our citizens, and the dedicated members of this committee will produce recommendations for action by the NAE.

2. The covid-19 pandemic has presented the world with its greatest challenge this century, and engineers, along with scientists and medical professionals, have worked together in the public and private sectors to address it. The contributions from engineering are apparent and numerous. To name a few:

   - the internet, Wifi, platforms like Zoom, computers, and microelectronics, which allow people to telework and communicate;
   - production of medical devices, diagnostics, and safety clothing;
   - development of robust supply chains of materials and chemical precursors; and
   - approaches to scale up the production and distribution of vaccines and therapeutics.

One very timely and dynamic initiative of the National Academy of Engineering in partnership with universities and others is the "Call to Action" against covid-19. Launched in April, it combines the imagination and talents of university engineering students in our Grand Challenges Scholars Program, midcareer professionals who have participated in our Frontiers of Engineering (FOE) program, and seasoned engineering veterans who are NAE members. It is truly *intergenerational*!

It works like this. Students and faculty members form teams and submit ideas to a technical review committee, composed of FOE alumni. The ideas judged to be most promising are forwarded to an NSF program called *I-Corps* that works with the inventors to develop "pitches" to attract investments toward commercialization. The top teams then make their pitches to the expert review committee, which is composed of NAE members.

The pitch sessions are fun to watch and inspiring. A few good ideas are being pursued as potential startup companies. These ideas may become tangible actions to address the covid-19 pandemic, but I think the greatest product of this initiative might be the intergenerational learning occurring in both directions between young and experienced engineers. The enthusiasm among all participants is contagious. I encourage you to watch the recordings of the pitch sessions; they're posted on the NAE website.

3. Another new initiative is *NAE Perspectives*, a series of short-form commentaries accessible to a wide range of audiences and published on the NAE website. The goal is to foster member and public engagement in technical topics of current relevance and interest to society. These commentaries may be supplemented with video, social media, and webinar dissemination.

   The first two perspectives were authored by NAE members of the class of 2020: **Charlie Bolden**, former NASA administrator and astronaut; and **Gwynne Shotwell**, president and COO of SpaceX.

   We are excited about this new series, which will highlight how engineers are contributing to progress in a variety of fields.

To strengthen the NAE Program Office, we have hired Dr. David Butler. David has been with the National Academies for 24 years and his expertise will help advance programs such as the NAE's new Cultural, Ethical, Social, and Environmental Responsibility (CESER) initiative, as well as National Academies studies related to engineering and environmental health topics.

David is the J. Herbert Hollomon Scholar. Dr. Hollomon was one of the founding members of the NAE. This position is made possible by the Hollomon Memorial Committee, chaired by David Roos, on the occasion of the NAE's 25th anniversary.

I now turn to the truly important part of the program: recognition of the NAE class of 2020.

Consider this a brief introduction of our new members—we will repeat this ceremony in person at the annual meeting in 2021, so that every member of the class of 2020 will have the opportunity to be properly introduced and walk across the stage of this auditorium to sign the Membership Rolls.

This year's election brings the total to 2271 members. The first class of NAE members in 1964 numbered 25. They were *all white males*! I'm happy to note that among this year's 86 newly elected members, 31% are women and 9% are from underrepresented minority groups. I congratulate the NAE members who served on our election committees and brought about this result.

The class of 2020 also includes 18 international members. They are from 13 countries, and one of them is the first member elected from his country. There are 5 women elected this year as international members—significantly more than the average of 2 women elected per year over the previous 4 years. This year's election brings the total to 279 international members.

A major goal of the NAE strategic plan adopted in 2015 was to increase the diversity of our membership in terms of gender, racial, and ethnic representation. Another goal was to increase the number of nominations and elected members from the business sector. The driving force behind these goals was to improve the talent of the NAE membership, and the strategy was to cast a wider net for nominations and search hard for outstanding candidates to nominate for membership.

Thanks to the hard work and commitment of our home secretaries, our section search committees, and our election committees, we have made good strides over the past 5 years. Over this period, 52% of our new members are from the business sector, 26% are women, and 8% are from underrepresented minorities.

While progress in diversification of our membership has not been fast, the data indicate we are moving in the right direction. Of course, it is imperative that we maintain our commitment to the diversity of the NAE, but our programs must also promote recruitment of women and underrepresented minorities into engineering education and careers. We need the talent if the engineering profession is to continue to flourish.

One thing has not changed over the years: election of NAE members is based on demonstrated achievement and impact of work. The selectivity is very high; only one of every 6 nominees was elected this year, and *all* nominees are highly accomplished.

Having said this, I want to make one point to the families of today's inductees. As accomplished as they are, the new members are still expected to take out the trash, clear the dinner table, and perform other chores they had *before* election to the NAE. Election does not relieve them of their domestic engineering responsibilities!

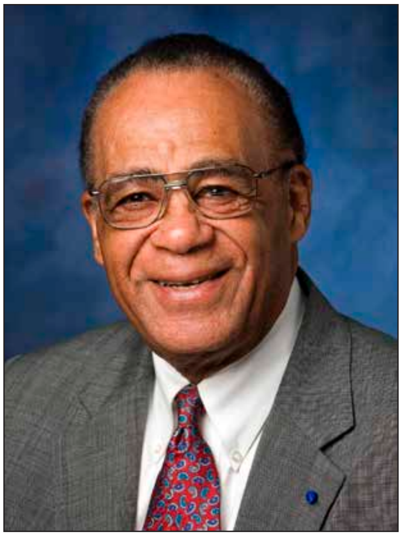
On a more serious note, I want to emphasize the expectation of <u>service</u> and <u>volunteerism</u> for NAE members. Keep in mind that *engineer* is a verb—implying action. It is a great honor to be elected to the NAE, but like a university commencement, it is just the beginning. We will be calling on you to help fulfill our mission of service to the nation. I look forward to working with you as we work together toward the betterment of this country, the world, and this organization. For that, I thank you in advance.

And I thank all the NAE staff who make our organization work so well. It is a wonderful group of individuals, and they make good things happen.

I would also like to acknowledge the great group of officers and councillors who govern the NAE. These individuals are elected by the members to serve the organization, and they do it very effectively.

I congratulate the class of 2020, and now introduce Dr. **Al Romig**, NAE executive officer, who will introduce the members and international members of the NAE class of 2020.

A Call to Action for Racial Justice and Equity in Engineering: 2020 NAE Annual Meeting Special Lecture



John Brooks Slaughter

I wish to express my appreciation to President **John Anderson** and to **Percy Pierre**, chair of the NAE's Racial Justice and Equity Committee, for inviting me to deliver the special lecture at this annual meeting. I also thank the committee members and staff for their assistance. I am honored and humbled to join you in this session.

It is certainly no secret to anyone participating in this virtual annual meeting that we are living in one of the most crucial periods in the history of our nation. And it is one of the most crucial periods in my lifetime.

I was born in the waning years of the Great Depression. I was too young at the time to fully understand World War II, although I remember certain aspects of it. I was born and raised in Topeka, Kansas, and attended one of the pre–*Brown vs. Board of Education* Black elementary schools. I endured the discrimination and exclusion faced by Black and Brown inhabitants of that city.

I have a vivid memory of the struggle for civil rights in this country, the tragic and violent deaths of Emmet Till, Medgar Evers, and Martin Luther King Jr., the Watts riots, the assassinations of the Kennedys, and the turmoil over the Vietnam War. I was a member of the commission chaired by Warren Christopher to investigate the use of force by the Los Angeles Police Department in the wake of the Rodney King beating, and I know the fear that Black people have when stopped and interrogated by police officers.

At this point in our history we are faced with many critical and potentially cataclysmic events and crises. There are three that come to my mind immediately.

The first is climate change, a global event that threatens the very survival and existence of our species and all other animal and plant species, as well as the air we breathe, the water that sustains us, and the Earth itself.

The second threat is the novel pandemics that have the power to imperil our lives and dramatically change the way we live, work, and interact with one another.

The third, and the one I wish to speak with you about today, is the one that jeopardizes our democracy, productivity, and wellbeing and calls into question whether we can all live together peaceably and harmoniously in a just and equitable American society. That is the crisis caused by the ignominious history of racism and anti-Blackness, the unwillingness to acknowledge and accept the humanity of Black people that has crippled our nation for 400 years.

A common thread that runs through each of these monstrous and intractable problems is the fact that engineers have a role to play in identifying and developing their solutions.

A Critical Moment in Our Nation's History

The broad, demonstrative, multiracial, multicultural reaction to the tragic and senseless killings of George Floyd, Breonna Taylor, and Eric Garner at the hands (and knee) of police officers and the murder of Ahmaud Arbery by armed vigilantes has led many institutions to pledge to work not only to identify and remove systemic and structural barriers to the inclusion and success of Black individuals in their organizations but also to strive to improve the circumstances of Black Americans in the larger society. The names of slaveowners have been removed from buildings at universities throughout the country. Statues of Confederate generals, the Stone Ghosts of the South as they were called by journalist Trymaine Lee, have been toppled. NFL players are displaying "End Racism" or "Black Lives Matter" on their helmets, shoes, and uniforms. Institutions that have expressed allegiance to the Black Lives Matter movement and have vowed support include professional engineering associations, honorary societies, and STEM-related organizations.

All of these are extremely encouraging developments because for far too long many of the organizations and institutions that are now on board have been on the periphery of racial justice movements and have, at most, provided rhetoric but little in the way of action to address the inequities, discrimination, and implicit biases that exist and persist in their midst. I believe that a cultural transformation is necessary in the profession of engineering and in many of its institutional arrangements and practices if we are to participate meaningfully in the efforts to create a more racially just and inclusive American society.

At this critical moment in our nation's history we need more than words that renounce racism and anti-Blackness, we need actions to abolish them. We must be mindful of the words of Martin Luther King Jr., "The arc of the moral universe is long, but it bends toward justice," and of the late Supreme Court justice Ruth Bader Ginsburg, who added "but only if there is a steadfast commitment to see the task through to completion."

The Need for Conversation and Understanding

When I was chancellor of the University of Maryland, College Park, I cotaught a class in the African American Studies Department. On the first day of the class, I went to the blackboard and wrote what I somewhat lightheartedly referred to as Slaughter's theorem: "Black Studies is for White students; math, physics, and chemistry are for Black students." There is no doubt that I could have been accused of hyperbole at the time, but I believed what I had written. I believe it even more today.

White Americans must come to understand and, hopefully, appreciate the lived experiences of Black Americans throughout the history of our presence in this country. From the egregious and repressive 245 years of slavery and its legacy that continues to haunt us all today, the Fugitive Slave Act, slave patrols, the aborted period of Reconstruction, the lynching of Black men and women for meaningless or nonexistent reasons, the bombing of the 16th Street Baptist Church in Birmingham, Alabama, that killed four little Black girls, and discriminatory practices in employment, education, health care, housing, and the criminal justice system, the story of Blacks in America needs to be known. The negative effects of the history of White supremacy are evident today in the covid-19 pandemic in which Black Americans are disproportionately affected medically and economically.

It is not hard to understand why the recent rise in the presence of White supremacists makes us fear for the lives of our children and grandchildren. No longer should any of us accept the excuse, "I didn't know." White Americans must understand the harm that White supremacy has on them just as it has on the Black people on whom it is targeted. In short, White Americans must come to understand what James Baldwin meant when he said, "To be Black in America is to be in constant rage." Fittingly, I believe it was Abraham Lincoln who declared, "Justice will not be served until the unaffected are as outraged as those who are affected."

So long as some behave as though they are unaffected by the systemic and structural racism embedded in the manner in which our society continues to operate, meaningful and difficult conversations—conversations not to assign guilt or blame but rather to find understanding and agreement—will not occur. But they must occur if we are to rid ourselves of the fear of the other, the yoke that prevents us from becoming a nation where everyone is treated with dignity and respect, with regard for the opinions of others. Engineers must be at the table where these conversations take place.

Diversity Drives Innovation

We are at a moment when this country can ill afford to ignore the talents that exist in those persons who have been historically underrepresented, underrecognized, and underappreciated in science, technology, and engineering. We must recognize that America cannot and will not maintain a prominent position in the STEM skills so long as anyone is prevented or impeded from the fullest possible opportunity to participate and contribute to our scientific, technological, and engineering activities and achievements. Our economy, productivity, and the welfare of our citizens depend on it.

Given the inevitability of future pandemics and the current and impending consequences of climate change, our very survival depends on preparing and marshalling all the talent we can possibly develop. We must, as NAE member **Nick Donofrio** puts it, make sure that opportunity is there to meet talent.

I have long contended that diversity drives innovation. Former NAE president **Bill Wulf** pointed out that "sans diversity, we limit the set of life experiences applied, and as a result we pay an opportunity cost—a cost in products not built, in designs not considered, in constraints not understood, in solutions not offered, in processes not invented." He went on to say that "Members of a diverse group each experience life differently and these differences in experience constitute the gene pool from which creativity springs." In the very same vein, his successor **Charles Vest** said, "A diverse technical workforce…is more likely to conceive, design, and develop products, processes, and systems that perform well in the marketplace." It is my belief that the discipline of engineering has to a large extent ignored these truths and failed to recognize or, perhaps, admit that diversity drives innovation.

But mere diversity is not enough. While diversity is necessary it is not sufficient to ensure that an institution practices equity and inclusion. As Stephanie Farrell, the 2018 president of ASEE, said, "Diversity is about counting heads; equity is about making heads count." We must commit ourselves to make engineering a professional discipline that is an example of equity and inclusion.

While the reality of what I have mentioned applies to all those who have been prevented, in one way or another, from the opportunities to fully participate and succeed in the STEM disciplines, the situation has been particularly acute for Black Americans. For 400 years, anti-Blackness and crippling policies and practices of structural and systemic racism, often sanctioned by local, state, and federal policies and laws, have prohibited them from being viewed as equals.

Most Americans are aware of the many significant contributions that Black Americans have made in fields such as music, art, literature, and poetry, but the same is not true for science and engineering. Too often their achievements in these areas have been unknown or unrecognized, or, if known, disregarded or denigrated. That was true for Benjamin Banneker (1731–1806), a self-taught mathematician, clock builder, almanac creator, and surveyor who assisted in surveying the original boundaries of Washington, DC, and whose astronomical observations and studies were devalued and discredited by Thomas Jefferson. And it was true for Norbert Rillieux (1804–96), one of the earliest chemical engineers and the inventor of the multiple-effect evaporator; Elijah McCoy (1844–1929), engineer and inventor of lubrication devices for steam locomotives; Lewis Latimer (1848–1928), who in 1881 was issued a patent for the process for developing the carbon filament for light bulbs before joining Thomas Edison in 1885 in the design and creation of the first incandescent bulb; and Garrett Morgan (1877–1963), inventor of the three-position traffic light.

How many members of the Academy know that **Mark Dean**, a coinventor of the personal computer, holds three of the nine original patents for the IBM PC, that **James West** invented the microphone technology on your cellphone, or that Black engineers **Gilda Barabino**, **Shirley Ann Jackson**, **Gary May**, **Darryll Pines**, and Gregory Washington are presidents of some of America's most highly regarded research universities?

Black Americans have been and are contributors to this country's might and capabilities in science, technology, and engineering. If we eliminated the systemic racial impediments that crush the aspirations and potential of so many Black Americans, our nation would not only be more just and equitable but it would also have an even greater capacity for innovation and productivity. We must let opportunity meet talent.

Grand Challenges and "Engineering Habits of Mind"

It is no secret that the field of engineering ranks well behind medicine, law, and other professions in terms of commitment to and practice of social justice activities. For the most part, engineering education has not afforded engineering students exposure to the liberal arts and social science courses that would prepare them to understand engineering in terms of its service to humanity.

I contend that the NAE's 14 Grand Challenges of Engineering will require more than science and mathematics to solve. They will require a profound understanding of matters such as the politics, economics, cultures, languages, religions, aspirations, fears, and histories of the societies and people who will be affected by and will use the technologies developed by engineers to address and solve those problems.

Speaking of the Grand Challenges, Racial Justice and Equity Committee member Gary May suggested that we add a 15th Grand Challenge for Engineering, "Achieving Diversity, Equity, and Inclusion." His suggestion was seconded by all.

Engineers must also have an appreciation for ethics and consider the questions of who benefits from and who is disadvantaged by the devices, machines, systems, processes, and organizations that we are responsible for creating. No longer should anyone tolerate the design of a highway, bridge, or light rail system that displaces a Black neighborhood or business community to advantage White suburbanites on their commutes to and from the central city. Engineers need to recognize our social responsibilities in helping to make health care more affordable and available for the poor and underserved, apply our critical thinking and problem-solving abilities to the inequities in performance and success of minority children in our public educational systems, and address the crucial problems of bias in our criminal justice systems. To do so we must employ the "engineering habits of mind" formulated by the NAE and NRC in 2009:

- being creative,
- working and negotiating in teams,
- adopting optimistic mindsets when problem solving and designing,
- thinking not only about individual technologies but also about how the systems in these technologies operate, and, importantly,
- considering the ethical nature of engineering and its products.

STEM, STEAM, and "STEEM" Education

A colleague at the University of Southern California, Professor Anthony Maddox, and I cofounded a center in the USC Rossier School of Education. The Center for Engineering in Education (which we refer to as CEE because we are both electrical engineers) was conceived in response to the fact that the Next Generation Science Standards, developed through a collaborative, state-led process, provide for the first time that engineering design be included in the science curriculum for all K-12 students. While we applaud the inclusion of engineering principles and concepts in elementary and secondary school science courses, we recognize that teachers in those settings are not likely to have the necessary background and preparation to teach engineering design. Therefore, one of the priorities of the center is the development of teacher education curricula that can prepare classroom teachers for this purpose.

We believe that personalized learning with the aid of the intelligent introduction and use of technology will be the principal way formal, nonformal, and informal learning will take place in the future.

We also support the idea of expanding STEM to STEAM, where the "A" is usually thought to refer to the arts. But we contend that the "A" could easily be interpreted as "anything" because of our belief that engineering thinking can inform and improve teaching and learning in every discipline and endeavor.

Considering the current emphasis on the need for addressing social justice and systemic racism, we have coined *STEEM*, where the additional *E* calls for *equity* to be included as an essential component of STEM education. The *E* could also stand for *empathy* or *ethics*, both of which are much-needed ingredients in our society today.

By the way, a few years ago the National Science Foundation reported that research had shown that a larger proportion of Black and Brown K-12 students aspire to become engineers than do their White peers. But another study revealed that only 4 percent of Black and Brown high school graduates have taken the requisite courses to enroll in engineering study in college. This is because many of these students have attended under-resourced schools in economically depressed areas, have lacked exposure to role models and mentors, and have faced discouragement from administrators, counselors, and teachers. I know this from experience because it happened to me and many like me in my generation. That it occurred back then could be considered shameful, the fact that it continues today borders on the criminal.

Corporate Responsibility

Corporate America has a major responsibility in ensuring that its structures and operations are free of discriminatory practices in hiring, promotion, and all employment procedures and policies. As a rule, the topics of diversity, equity, and inclusion have been absent from the board agendas of major corporations. This is particularly true for Silicon Valley and many other high-tech companies whose record of racial justice can only be described as failure. They must understand their obligations in the efforts to eliminate the digital divide as well as inequities inherent in the hardware and software they produce.

Corporations that employ engineers should provide substantial support to minority student organizations like the National Society of Black Engineers (NSBE), Society of Hispanic Professional Engineers (SHPE), and American Indian Science and Engineering Society (AISES). They should also provide scholarships, internships, and summer employment opportunities to needy Black and Brown undergraduate engineering students to address the high cost of education.

It is also important for corporations and industrial establishments to provide sustained support to minority-serving organizations such as the National Action Council for Minorities in Engineering (NACME), the largest private provider of scholarships for Black, Brown, and Indigenous engineering students; the National GEM Consortium, which enables qualified students from underrepresented communities to pursue graduate education in science and engineering; the Advancing Minorities' Interest in Engineering organization (AMIE) and the Career Communications Group's Black Engineer of the Year Award program and BEYA STEM Conference. Such actions would demonstrate their commitment to racial justice and inclusion.

A Perfect Storm for Higher Education

Higher education is in a perfect storm consisting of a pandemic likely to change forever the way colleges and universities operate, a society characterized by political partisanship, social and racial divisiveness, and the presence and impending threats of catastrophic climate change. How it responds to these "wicked" manifestations and the country's accelerating racial and ethnic demographic changes will determine how it teaches and educates the leaders and productive citizens of tomorrow and who will be the recipients of that education.

Although numerous encouraging transformations have taken place, I find many of the moralistic pronouncements by some of the most prestigious educational institutions, in the wake of the recent Black Lives Matter demonstrations, to be disingenuous and off-putting. A good friend of mine refers to them as *virtue signaling*. For too many years, these institutions have had the opportunity and the responsibility to address the structural racism that marginalizes Black Americans and deters them from the opportunities available to others, but they have failed to do so.

Given the increasing presence of Black and Brown students in the college-age population, the concomitant decline in the proportion of White students, and the potential decrease in international students due to the pandemic and changes in immigration policies, colleges and universities must diversify their undergraduate enrollees or ultimately close their doors. The same imperatives, regrettably, do not exist for graduate students and faculty.

The dearth of Black, Brown, and Indigenous persons on the faculties of major US research universities is higher education's Achilles heel and its shame. This is particularly true for the STEM disciplines. While the presence of Black tenured and tenure-track faculty in most large research universities hovers around 6 percent, it is 2 percent or less in science and engineering departments. Since in many engineering programs 75 percent or more of graduate students are nonresidents, these depressing figures are unlikely to improve. Our colleges and universities can and must do better. I hope they will develop the resolve to do so.

Steps Forward

Engineering schools can start by reaching out to historically black colleges and universities (HBCUs) and Hispanic-serving institutions (HSIs) to develop relationships with their faculties and students. They should be proactive in efforts to recruit more diverse faculty members rather than waiting for responses to ads in academic journals and newsletters. They should find ways to inform and encourage Black, Brown, and Indigenous engineering undergraduates to consider graduate study in preparation for an academic career. They must recognize the importance of removing structural impediments in their own organizations that discourage minority students and impair their ability to succeed. They must reevaluate their core values and become equity-minded rather than deficit-minded in their approach to ensuring a fair and equitable educational experience for all students. Importantly, they should focus less on being "elite" and instead strive to be excellent in the broadest sense of that word. Change must begin within.

An important first step was taken a few years ago when **Yannis Yortsos**, dean of the USC Viterbi School of Engineering, spearheaded an effort that led more than 200 engineering schools and colleges to sign a pledge to provide increased opportunity to engineering careers for underrepresented groups and to ensure educational experiences that are inclusive and prevent marginalization of any groups of people. They further affirmed the importance of these aims as a reflection of their core values and as a source of inspiration for drawing a generation to the call of improving the human condition.

NAE Involvement

What about the National Academy of Engineering? What must it do besides expressing its grave concerns about the treatment of Black Americans, addressing the structural racism that cripples the US economy and productivity, and proclaiming its intent and resolve to examine its own operations, policies, and procedures and to determine how it can improve the circumstances of underrepresented and marginalized persons in society?

The NAE has a long record of involvement in efforts to increase the presence of underrepresented minority students in engineering. At the behest of **Percy Pierre**, in 1973 the Academy hosted a conference, supported by the Sloan Foundation, that led to the creation of what came to be known as the Minority Engineering Effort and the founding of organizations such as NACME, GEM, and the Mathematics, Engineering, Science Achievement Program (MESA). This seminal event received strong support from the CEOs of corporations like General Electric, IBM, and DuPont, and the presidents of major universities such as Purdue, Notre Dame, and MIT. Sadly, the same levels of financial support and interest from these bodies occur only episodically now as attention to the topic of increasing minority representation in engineering has waxed and waned with changes in political administrations and economic fluctuations.

At the beginning of the Minority Engineering Effort the Academy formed the Committee on Minorities in Engineering, which spawned several important initiatives, some of which continue today. The NAE founded the Action Forum on the Engineering Workforce early in this century, and since then has supported a number of studies and research efforts that have been instrumental in illuminating the problems causing underrepresentation and has identified potential approaches to their solution.

The Racial Justice and Equity Committee has been asked to consider initiatives consistent with the NAE's mission, initiatives that will advance diversity, equity, and inclusion both within the Academy and in the larger community. It is the belief of the committee that a cultural transformation must take place in the engineering profession, including the NAE, if we are to provide a meaningful and sustainable contribution to the efforts to quell systemic and structural racism in engineering and in society. For this to happen we must all remember that the NAE is us, all 2250-plus members of the Academy. All of us must ask ourselves, "Am I doing enough to help make the discipline of engineering a just and inclusive profession? And am I making sure that my work does not add to the inequities and injustices that abide in society?"

Conclusion

The events of the past few months, where White supremacy and anti-Blackness have been on display in ways not previously seen in this century, have opened a window of opportunity that we cannot afford to allow to close without making major strides in guiding the discipline of engineering toward becoming a more diverse, pluralistic, and inclusive profession. And I feel a sense of urgency for us to do so. It is the kind of urgency represented by a "No Trespassing" sign in the Kansas countryside: "If you want to cross this field you better do it in 9.9 seconds; the bull can do it in 10 flat."

I conclude by simply saying that none of us can continue to hide behind the timeworn excuse of "I am too busy." Instead, we must adhere to Martin Luther King Jr.'s mandate: "We must use time creatively, in the knowledge that the time is always ripe to do right."

Thank you very much!

2020 Simon Ramo Founders Award Acceptance Remarks by Frances S. Ligler

The 2020 Simon Ramo Founders Award was presented to Frances S. Ligler, senior scientist (retired), Naval Research Laboratory; distinguished professor of biomedical engineering, Joint Department of Biomedical Engineering, North Carolina State University and UNC–Chapel Hill, "for the invention and development of portable optical biosensors, service to the nation and profession, and educating the next, more diverse generation of engineers."

Thank you for being here to celebrate with me. My first opportunity to serve the NAE was on the awards selection committee. I remember thinking that any normal person would require at least three lifetimes to accomplish as much as the nominees did in only one. So I am particularly humbled to be chosen for this year's Ramo Founders Award. I thank the awards committee for their generosity in selecting me; my nominator and references for their hard work in supporting my nomination; the

NAE members who have become my friends; and the mentors, colleagues, friends, and family who are a part of everything I do.

As I have listened to the NAE award lectures over the past 15 years, I have particularly enjoyed learning about each winner's unique life and how their backgrounds impacted their priorities. So I will try to entertain you with the history of my "evolution" to engineer.

I am a fifth-generation Kentuckian. My great-great-grandmother crossed through the Cumberland Gap with another relative, Daniel Boone. My wonderful grandmother Betty Smith was born in a log cabin in Cox's Creek, KY; after being widowed, she raised four kids by herself in an old cottage on the family farm with no electricity or running water. Consequently, Dad spent his career bringing electricity to the farmers of Kentucky.

Growing up, when I was not reading adventures of American pioneers, I spent my free time running around the woods with my hound dog, galloping my horse around my grandfather's farm, or on family fishing vacations. So while some of you may have been taking old radios apart, I was dissecting fish to figure out how they worked and what they had for lunch—sometimes I even got my worm back.

It was very natural for me to end up in biology and biochemistry as my education progressed. I was interested in being a cowgirl or a forest ranger. Then one summer my biology professor got me an internship at Oak Ridge where I isolated a secreted factor that controls growth in fish—and I was hooked on research forever.

That summer, I also got engaged to a young fellow who was headed to Oxford as a Rhodes Scholar. So I worked very hard to get a scholarship that could be used at Oxford and headed to England for the sake of true love.

After grad school I spent 5 years in medical schools doing research in biochemistry and immunology. The discrimination against women in science drove me out of academia to a terrific job in DuPont's Central Research and Development. I had an amazing degree of research freedom, promotion to head of cellular immunology, and the opportunity to take courses in project and personnel management that have served me well my entire life. But I am also part of a two-career family, and it was my turn to move for George's career—so in 1985 I became the youngest retiree in the history of DuPont.

In DC, I selected the weirdest of my job offers and went to the Naval Research Laboratory where Joel Schnur was starting a group to make new materials and systems based on self-assembly of biomolecules—a very odd concept at the time. It sounded like molecular tinker toys to me—great fun. Soon after I arrived, I realized how vulnerable the United States was to a biowarfare attack, so Richard Thompson and I successfully proposed to build a sensor for biothreat agents based on antibody recognition.

Now, according to the astrological charts I am a Gemini, born in June. All Gemini have split personalities, and it was time for the "scientist me" to develop the alter ego "engineer me."

To build a sensor system that could be used by real people I had to learn engineering, so I hired engineers of all types as postdoctoral fellows to teach me engineering and fill in the missing parts of our biosensor systems. I realized that I definitely think like an engineer; developing creative solutions became a habit. Finally, NRL gave me a wonderful opportunity to work on hard, really important problems and to build and contribute to cross-disciplinary teams of highly talented professionals.

Frances S. Ligler

In 2005 I truly "graduated" to the status of a real engineer: I was elected to the NAE. For the first time, I really saw myself as an engineer. I was amazed at the accomplishments of NAE members and thrilled at the opportunities to work with such incredible people to continue to serve my country. I learned so much, and my world grew a lot wider. It is really rewarding to be able to look back and know I helped make a difference.

So I conclude with thanking the NAE for this wonderful award—I am in amazing company. And I urge all of you to get involved with the NAE's mission and activities so that we really can be a positive force in improving life in our nation and around the world.

Thank you.

2020 Arthur M. Bueche Award Acceptance Remarks by Arden L. Bement Jr.

Arden L. Bement Jr.

The 2020 Arthur M. Bueche Award was presented to Arden L. Bement Jr., David A. Ross Distinguished Professor Emeritus of Nuclear Engineering and director, Global Policy Research Institute and Global Affairs Officer, Purdue University, "for contributions to science and technology advancement, international relationships, policy development, and Academies studies, from executive positions in government, industry, and academia."

I thank the Bueche family, the awards selection committee, and President Anderson, who notified me of my selection. This award is especially meaningful to me because it is named for a giant in scientific research, technology commercialization, and R&D policy, Arthur M. Bueche.

I worked at the GE Hanford Laboratories in Richland, Washington, from 1954 to 1964 when **Guy Suits** was director of the GE Research Laboratory. Although I did not meet Dr. Bueche during that time, I did sit next to him at a banquet shortly before his untimely death in 1981.

We spent part of this memorable dinner discussing the satisfaction of working in the space between discovery and application where innovations are seeded, the value of learning by doing and studying successful leaders, and the satisfactions that can come from traversing several learning curves during a career.

Our discussion encouraged me to continue my career of directing R&D programs within the Bueche triangle at the confluence of government, industry, and university R&D. These partnerships have included advanced energy technologies, advanced materials for space and defense systems, computer-integrated design and manufacturing, high-speed integrated circuits, high-temperature superconductors, and policy research and development.

My 37-year membership in the NAE has greatly reinforced this career path by offering many learning curves. It enabled me to serve on four NRC boards, chair the National Materials Advisory Board and the Commission on Engineering and Technical Systems, and participate in over 20 funded studies. Friendships and working relationships with members of the three academies have been of great value throughout my career.

Since the Rust Belt contraction of the 1960s and '70s, there have been major developments in the Bueche triangle. For example:

- Industries have increasingly located technology development centers and subsidiaries near universities and government labs both in the United States and abroad to facilitate R&D partnerships and enhance customer relationships.
- Some government-funded research centers at leading universities now involve multiple collaborating universities and foreign investigators.
- An increasing number of peer-reviewed journal publications by US researchers are coauthored with international collaborators.
- Research universities not only operate research parks but also provide innovation centers and foundries for their students to fast-prototype their inventions with computer modeling and additive manufacturing.
- A few leading research universities can now spawn up to 100 new startups per year.
- And some universities have established faculty and student exchanges with universities abroad in innovation and entrepreneurship. The partnership between MIT and the Skolkovo Institute of Science and Technology near Moscow is a prime example.

These developments and many more have substantially contributed to compressing the transition time from discovery to market to about half or less of what it was 50 years ago.

Arthur Bueche, who was a steadfast champion of building the nation's economy through the convergence of R&D in the Bueche triangle, would have been delighted with these outcomes.

In closing, I wish to thank the nominator and supporters for my award. My nominator was **Norman Augustine**, former CEO and chair of Lockheed Martin. My supporters were

- **Craig Barrett**, retired CEO and chair of Intel Corporation;
- **France Córdova**, president emerita of Purdue University and former director of NSF;
- **Edward Crawley**, Ford Professor of Engineering, MIT, and founding president of the Skolkovo Institute of Science and Technology;
- **Richard Meserve**, senior counsel, Covington and Burling LLP, former chair of the US Nuclear Regulatory Commission, and president emeritus of the Carnegie Institute for Science;
- **Hratch Semerjian**, former acting director and chief scientist of the National Institute of Standards and Technology; and
- **Henry Yang**, chancellor of the University of California, Santa Barbara.

My gratitude to these great leaders and my admiration for their impacts on our nation's research and development base run deep. I want to give special thanks to John Grundy of Purdue's College of Engineering who provided my nominator and supporters with needed information. And to all NAE members I give thanks for this wonderful award.

2020 J.C. Hunsaker Award in Aeronautical Engineering Acceptance Remarks by Alan C. Brown

The 2020 J.C. Hunsaker Award in Aeronautical Engineering was presented to Alan C. Brown, director of engineering (retired), Lockheed Corporation, "for innovative contributions to the design of commercial and military aircraft, and particularly leadership of the team that developed the F-117 Stealth Fighter."

It is a very great honor to receive the J.C. Hunsaker Award. My first reaction is to note that I worked at Lockheed with a very talented, hard-working group of engineers, and so have to comment that one has to be lucky as well as reasonably competent to have been chosen for this award.

The luck came in several forms. Lockheed was working on a new program in the Skunk Works, known as Have Blue. This was a very low observable research airplane headed up by **Dick Scherrer** and Leo Celniker. I had worked for Leo back in the 1960s in advanced design at Lockheed in charge of propulsion integration for new aircraft, and he asked me to come over and try to come up with a propulsion system that would have the required low radar cross section and still operate efficiently. The Skunk Works propulsion group had not been able to meet requirements—they were looking at SR-71 and D-21 variants—and Leo wanted a fresh look. He figured it would take me about 6 weeks—in fact I stayed at the Skunk Works for 14 years!

The next item of luck was good for me and bad for Dick Scherrer. Dick suffered a stroke and was sidelined for over a year, and I had to take his place on the design team as the integrator of aircraft design with low observability.

The third item of luck came after we had won the low observable competition with Northrop, at which point the US Air Force wanted to make a military airplane based on the new technology, which became

Alan C. Brown

the F-117A fighter (really, attack) aircraft. Colonel Jack Twigg wanted to be sure that the chief engineer was not the typical aerodynamics or structural person, but the person who had the most knowledge of integrating stealth into the aircraft design, and so insisted to Lockheed that I should be put in charge of the airplane design. Lockheed, in the form of **Ben Rich**, then head of the Skunk Works, agreed, and so I became chief engineer for the airplane.

I was fortunate to have two very experienced assistant project engineers in Bill Taylor (systems) and Ed Baldwin (structural design) assigned to the program, both of whom had long Skunk Works experience, and so we were able to produce an airplane—in 2½ years from receipt of go-ahead—that was essentially invisible to radar and infrared detection.

The fourth item, which demonstrated the aircraft very well, was the Gulf War in 1991. Here the F-117A showed its capability as an attack bomber, essentially for all the world to see, which wouldn't have happened otherwise.

In conclusion, I thank the National Academy for this award, which I regard as a great honor.

National Science, Technology, and Security Roundtable Established

The FY2020 National Defense Authorization Act called for a roundtable to bring together individuals from the research agencies, national intelligence, law enforcement, academic research, and business to explore critical issues related to protecting US national and economic security while ensuring the open exchange of ideas and the international talent required for American leadership in science and technology. The National Academies has created the National Science, Technology, and Security Roundtable to carry out Congress' direction.

Supported by the US Department of Defense and the National Institutes of Health, the roundtable will identify and consider security risks involving federally funded research and development, identify effective approaches for communicating risks to the academic and scientific communities, and share best practices for mitigating these risks. **Richard A. Meserve**, president emeritus, Carnegie Institution for Science, is cochairing the roundtable with Maria T. Zuber (NAS), MIT vice president for research, and John C. Gannon, adjunct professor in the graduate Security Studies Program at Georgetown University.

The NAE Transfers GCSP Network Office Operations to Consortium of Higher-Ed Institutions

After 6 years of nurturing and developing the Grand Challenges Scholars Program (GCSP) into the premiere undergraduate engineering initiative it is today, the NAE has determined that the time is right to transfer the day-to-day management and operations of the GCSP Network Office to a consortium of higher-education institutions.

This decision fulfills the original goal of the GCSP: a community-led endeavor to generate specific impacts in engineering education and professionalism. Universities and colleges around the world bring an expanded capability beyond what the NAE can offer, especially with the participants and beneficiaries themselves: students.

The NAE began officially transitioning the responsibilities of the GCSP Network to Arizona State University (ASU) on November 1; the transition is expected to be completed by March 31, 2022. Funding from the Kern Family Foundation to ASU will generously support this transition. The NAE expects the community-led endeavor initially under ASU leadership to be self-sustaining as the community assumes responsibility for the GCSP's programmatic management and development. After the full transition, the NAE commits to continue providing annual recognition to graduating GCSP scholars by working closely with the community-led GCSP network office.

Calendar of Meetings and Events

November 11	NAE FOCUS webinar on *Failure Management* by William Rouse (NAE): virtual book talk and conversation
December 8–9	NAE Committee on Membership meeting
2021	
January 1–31	2021 election of new NAE members and international members
January 1–April 1	NAE awards call for nominations
January 13–14	Promising Practices and Innovative Programs in the Responsible Conduct of Research: workshop
January 28	Workshop for chairs of 2022 election peer committees, search committees, and special nominating committees
February 4–5	NAE Membership Policy Committee meeting
February 9	Announcement of class of 2021 newly elected NAE members and international members
February 10	NAE Council meeting
February 11	NAE National Meeting
February 25–27	2020 US Frontiers of Engineering symposium (rescheduled) Beckman Center, Irvine, California
Late February–April 26	Call for new nominations for 2022 election cycle (from current members/international members only)
March 1–31	Election of NAE officers and councillors
March 18–20	German-American Frontiers of Engineering symposium Oak Ridge National Laboratory, Tennessee
March 25	NAE regional meeting Medtronic, Minneapolis
April 29	NAE regional meeting Amazon and University of Washington, Seattle

All meetings are held virtually unless otherwise noted.

In Memoriam

Jan D. Achenbach, 85, Distinguished McCormick School Professor Emeritus, Northwestern University, died August 22, 2020. Dr. Achenbach was elected in 1982 for leadership in making fundamental contributions to, and engineering applications of, the propagation of mechanical disturbances in solids.

Frank F. Aplan, 97, distinguished professor emeritus of metallurgy and mineral processing, Pennsylvania State University, died November 3, 2020. Dr. Aplan was elected in 1989 for contributions to education and research in the mineral industry through the integration of theory and practice covering metallic ores, industrial minerals, and coal.

Arthur Ashkin, 98, retired member of the technical staff, Bell Laboratories, Lucent Technologies, died September 21, 2020. Dr. Ashkin was elected in 1984 for contributions to quantum electronics, nonlinear optics, and seminal studies of optical levitation of small particles.

Charles R. Cutler, 83, distinguished adjunct professor of chemical and biomolecular engineering, University of Houston, died March 16, 2020. Dr. Cutler was elected in 2000 for invention, development, and commercial implementation of a new-generation digital process control technology.

B. John Garrick, 90, distinguished adjunct professor, B. John Garrick Institute for the Risk Sciences, University of California, Los Angeles, died November 1, 2020. Dr. Garrick was elected in 1993 for making quantitative risk assessment an applied science and a fundamental part of engineering design.

David B. Geselowitz, 90, professor emeritus of bioengineering and medicine, Pennsylvania State University, died August 22, 2020. Dr. Geselowitz was elected in 1989 for outstanding contributions of engineering theory and technology to electrocardiographic fundamentals and diagnoses.

Robert W. Gore, 83, W.L. Gore & Associates, Inc. (retired), died September 17, 2020. Dr. Gore was elected in 1995 for the invention and commercialization of high-technology products, including Goretex.

William J. Hall, 94, professor emeritus of civil engineering, University of Illinois at Urbana-Champaign, died June 9, 2020. Dr. Hall was elected in 1968 for contributions to structural engineering, structural mechanics, and soil dynamics.

David A. Landgrebe, 86, professor emeritus of electrical and computer engineering, Purdue University, died November 21, 2020. Dr. Landgrebe was elected in 2005 for contributions to the development of multispectral technology for remote Earth sensing.

Martin P. Lepselter, 90, president, BTL Fellows Inc., died May 8, 2020. Mr. Lepselter was elected in 1987 for invention and development of the beam lead contact for silicon devices and the platinum silicide Schottky barrier diode.

Eugene Litvinov, 70, chief technologist, Business Architecture and Technology, ISO New England, died September 25, 2020. Dr. Litvinov was elected in 2020 for development of optimization mathematics for new electricity markets and innovative applications for electric grid control, visualization, and planning.

Verne L. Lynn, 89, retired director, Defense Advanced Research Projects Agency, died May 23, 2020. Mr. Lynn was elected in 2006 for outstanding leadership and vision in the development and application of unmanned aerospace vehicles, sensors, and systems.

John D. Mackenzie, 94, professor emeritus, University of California, Los Angeles, died February 19, 2020. Dr. Mackenzie was elected in 1976 for contributions to glass technology through application of principles of chemistry and physics.

Robert J. McEliece, 76, Allen E. Puckett Professor and professor of electrical engineering, California Institute of Technology, died May 8, 2019. Dr. McEliece was elected in 1998 for error-correcting codes and cryptography.

Edward W. Merrill, 96, C.P. Dubbs Professor of Chemical Engineering Emeritus, Massachusetts Institute of Technology, died August 6, 2020. Dr. Merrill was elected in 2013 for contributions to biocompatible materials, biorheology, and biomedical engineering education.

Joseph H. Newman, 95, retired president and CEO, Tishman Research Corporation, died July 1, 2020. Mr. Newman was elected in 1973 for advancement of building science and technology by development of new construction concepts, systems, and procedures.

Eli Ruckenstein, 95, distinguished professor emeritus, Department of Chemical and Biological Engineering, State University of New York at Buffalo, died September 20, 2020. Dr. Ruckenstein was elected in 1990 for innovative research contributions using surface chemistry in chemical engineering applications ranging from separation science to catalysis.

Albert B. Schultz, 86, Vennema Professor Emeritus of Mechanical, Engineering, and Applied Mechanics, University of Michigan, died July 26, 2020. Dr. Schultz was elected in 1993 for contributions to the biomechanics of the spine, treatment of lower back pain, and understanding of falls in the elderly.

Mordecai Shelef, 89, retired corporate technical specialist, Ford Motor Company, died August 11, 2020. Dr. Shelef was elected in 2001 for contributions to the science and engineering of automotive exhaust catalysis.

Daniel I.C. Wang, 84, Institute Professor, Massachusetts Institute of Technology, died March 1, 2020. Dr. Wang was elected in 1986 for basic contributions to the field of biotechnology resulting in improved control of bioprocesses and recovery of biomaterials.

Watt W. Webb, 93, professor of applied physics and S.B. Eckert Professor in Engineering, Cornell University, died October 29, 2020. Dr. Webb was elected in 1993 for development of sensitive instrumentation for measuring molecular mechanisms of biophysical dynamics of living cells and of fluctuations in material properties.

Robert H. Wertheim, 97, retired senior vice president, science and engineering, Lockheed Corporation, died April 29, 2020. Admiral Wertheim was elected in 1977 for contributions to national strategic programs, particularly engineering leadership of naval ballistic missile systems.

Richard M. White, 90, professor and founding codirector, Sensor and Actuator Center, University of California, Berkeley, died August 14, 2020. Dr. White was elected in 1994 for contributions to surface-acoustic-wave devices, to microsensors and actuators, and to engineering education.

The
BRIDGE

(USPS 551-240)

National Academy of Engineering
2101 Constitution Avenue NW
Washington, DC 20418

Periodicals
Postage
Paid