

Spring 2024

THE US METALS INDUSTRY: LOOKING FORWARD

The

# BRIDGE

LINKING ENGINEERING AND SOCIETY

## **The Rise of the US Steel Industry**

*Raymond Monroe*

## **Current Challenges and Opportunities for the Aluminum Transformation Industry in the United States**

*Timothy J. Warner, Bill Allemon,  
Craig B. Lewis, and Guillaume Bes*

## **The Materials Genome Initiative and the Metals Industry**

*Jim Warren*

## **Harnessing the Power of AI in Materials Digital Transformation: A Synergistic Hybrid Approach**

*Jiadong Gong*

## **Concurrent Design of Materials and Systems**

*Charles Kuehmann*

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*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, agency officials, engineering deans, department heads, and faculty, and interested individuals all over the country and the world. Issues are freely accessible at [www.nae.edu/TheBridge](http://www.nae.edu/TheBridge).

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# A Word from The NAE Chair

## A Moment for Introspection



Donald C. Winter

As I write this, the week after New Year's Day, this time of year seems to be a moment for introspection, particularly this year as I approach the end of my tenure as NAE chair. I have joked that the last few years as chair are but another one of my failed retirements. My time as NAE chair, like my engagement as secretary of the navy, has afforded me the opportunity to give back to our nation and our engineering community in thanks for the many blessings that my family and I have received over the years. It has been what some have characterized as the "third act" in life.<sup>1</sup>

While I was educated as a physicist, I always worked as an engineer. I discovered late in my education that, while I enjoyed studying physics, I enjoyed doing engineering — creating something new. At the University of Michigan, I had the opportunity to do my dissertation research at the Willow Run Laboratories, a research organization that supported NASA and DoD efforts in remote sensing. That was at a time when the campus was consumed by protests against the war in Vietnam, and I was one of the last students to graduate before the university severed all ties with the laboratory. I view my time at Willow Run as a propitious start to my career, as it provided me insight into the impact that engineering could have on national security during a period when the existential challenge of the Cold War was very much with us.

After graduation, I took a position at TRW in Redondo Beach, California, where I met and was mentored by Si Ramo.<sup>2</sup> Si had a strong belief in the work that we did

and the value of systems engineering. I spent a little over three decades at TRW and Northrop,<sup>3</sup> working as a systems engineer, program manager, and corporate executive. Looking back at this period, I take great satisfaction in the organization's accomplishments; we took on some formidable challenges and had a significant impact on our nation's security. One major lesson learned during this period: without the systems engineering approach that Si Ramo promoted, it is doubtful that our efforts would have been successful.

My tenure as secretary of the navy gave me additional insight into the essential value of systems engineering. Unfortunately, the US Navy and Marine Corps had a number of major development programs that were in trouble; they were failing to meet performance expectations, invariably overrun, and well behind schedule. Particularly troublesome was the observation that many of the developmental challenges could have been avoided if a disciplined systems engineering process had been implemented from the start. The causes for the failure to implement an effective systems engineering effort were multifold, often with both navy and contractors complicit.

Perhaps that background helps explain my angst at our nation's response to the challenge of climate change, the latest existential challenge of our age. We, as a nation, will have to do our part to reduce greenhouse gas emissions and develop mechanisms to improve our and others' resilience to the inevitable changes in climate. Unfortunately,

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<sup>1</sup> Bronfman EM. 2002. *The Third Act*. New York: Putnam

<sup>2</sup> Si Ramo is one of the NAE founders and the "R" in TRW.

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<sup>3</sup> Northrop Grumman acquired TRW in 2002.

I believe that the magnitude of the costs (both financial and political) has not yet been recognized, leading to a failure to focus on and prioritize those societal changes and enabling technologies that will provide the greatest return on investment. Furthermore, no solution set to accomplish the Paris Agreement<sup>4</sup> goal of no greater than a 1.5 degree C global rise in temperature has yet been identified. This situation leaves us without a basis for an informed investment strategy that ensures that the limited funds available are focused on those efforts that provide the highest likelihood of impact on global temperature rise while limiting the undesirable collateral effects that often accompany such changes. Furthermore, much of our nation's response can best be described as multiple uncoordinated initiatives with limited aggregate impact. For example, shifting transportation to all electric vehicles while we are still highly dependent on coal-fueled generating plants risks near-term increases in CO<sub>2</sub> emissions. Such changes and investments need to be properly coordinated and managed using a disciplined systems engineering process.

Unfortunately, government's interest in initiating and following a systems engineering approach is limited. The

politics are simply too great to let go of the decision-making processes. We can still influence decision-making through National Academies studies,<sup>5</sup> but a sustained engagement, providing systems engineering and analyses directly in support of proposed and ongoing initiatives, could have a far greater impact.

It is unclear what role the National Academies should have in such an initiative. Not unlike the Systems Engineering and Technical Advisory (SETA) organizations employed by the DoD, this would require a full-time staff of exceptionally competent and experienced engineers, not an effort based on volunteer participation. We can, however, make a significant contribution through our many means of influence, as both an organization and as individual notable engineers. As I transition out of my role as NAE chair, I will continue to look for opportunities to advocate for a systems engineering perspective on our response to climate change. I ask each of you to consider doing the same. Without a more reasoned approach to our nation's response, we may well run out of the financial resources, social acceptance, and political support needed to address this crucial issue.

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<sup>4</sup> <https://unfccc.int/process-and-meetings/the-paris-agreement>

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<sup>5</sup> For example: <https://nap.nationalacademies.org/catalog/25931/accelerating-decarbonization-in-the-united-states-technology-policy-and-societal>

# Editor in Chief's Note

## The Materials Genome Initiative Grows



Ronald M. Latanision (NAE) is a senior fellow at Exponent and editor in chief of *The Bridge*.

Engineering systems of all kinds rely on the availability of materials of construction that meet design demands. From semiconductor photoelectrodes for use in water splitting to produce hydrogen to the materials of construction for hypersonic vehicles to materials for medical devices, the need for advanced materials that meet advanced design specifications is growing. In this issue of *The Bridge*, guest editors Greg Olson and Aziz Asphahani have assembled feature articles that demonstrate how computational materials science and engineering is leading the way in the deployment of metallic materials that meet increasingly advanced design specifications.

The Materials Genome Initiative (MGI) is mentioned often in this issue's articles. Whether it be the human genome or the materials genome, it is the chemistry and processing of materials broadly that determine their structure and, in turn, their properties and performance in service. In the case of humans, nature does the processing. In the case of engineering materials, humans take on that role. In either case, processing-structure-properties-performance relationships are key. MGI was launched by the White House Office of Science and Technology Policy in June of 2011, with the aim of increasing US global competitiveness by significantly accelerating the pace at which advanced materials are discovered, developed, and transitioned into manufactured products. The end goal of MGI is the deployment of new materials to address societal and national needs.<sup>1</sup> MGI

will be the focus of the fall 2025 issue of *The Bridge*, which will be guest edited by Amit Goyal (NAE 2018), SUNY Empire Innovation Professor and Distinguished Professor in SUNY-Buffalo's Department of Chemical and Biological Engineering.

I have had a long-standing interest and participation in the development of new materials for advanced engineering systems. Although I am not a computational materials science researcher, I recently co-chaired, along with Karin Rabe (NAS 2013), Board of Governors Professor of Physics in the Department of Physics and Astronomy at Rutgers University, a NASEM study of the National Science Foundation's role in the Materials Genome Initiative.<sup>2</sup> I refer in particular to the NSF program *Designing Materials to Revolutionize and Engineer Our Future* (DMREF). NSF has positioned itself as the MGI partner that, through DMREF, develops the fundamental science and computational and experimental tools for generating and managing data, and, through the students that DMREF supports at universities, develops the intellectual infrastructure and workforce that enable industry and government agencies to produce and deploy materials that meet societal and national needs. DMREF and MGI are arguably reshaping materials science and engineering in terms of education and practice.

The transition from discovery and development to deployment involves technology transitions and the partnerships that are required to make such transitions suc-

<sup>1</sup> The 2021 Strategic Plan for the MGI can be found at <https://www.mgi.gov/sites/default/files/documents/MGI-2021-Strategic-Plan.pdf>.

<sup>2</sup> The report can be found here: <https://nap.nationalacademies.org/catalog/26723/nsf-efforts-to-achieve-the-nations-vision-for-the-materials-genome-initiative>.

cessful. This is not without challenges. For example, the proprietary interests of a publicly traded company could lead to a reluctance to share research data that may have commercial potential. But such concerns can be managed as they have in the past. I believe that it is important for MGI to demonstrate to the public and to policymakers that the engineering community can identify materials needs and address them in order to serve societal interests and national priorities. As an example, mission-oriented national labs have taken a deliberate role in identifying such needs and then working alongside university faculty and US industry to respond.

I thank Aziz and Greg for assembling this issue.

In this issue we are also pleased to include an interview with celebrated novelist Andy Weir, known for his 2011 novel, *The Martian*, which was the basis for a 2015 film of the same name, as well as the 2021 novel, *Project Hail Mary*. With this interview, we add a new dimension to

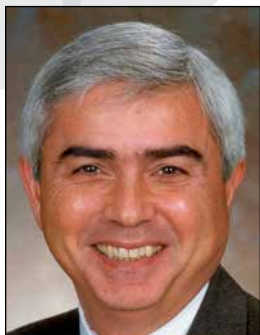
this feature: in addition to the print version of the interview that appears in this issue, a video of the interview will appear on the NAE website.

Finally, I'll conclude on a sad note, with the passing of Sam Florman, civil engineer, general contractor, and author. Sam died peacefully on February 4, 2024, at the age of 99. Sam was an advisor to Cameron Fletcher, former senior editor of *The Bridge*, and me as we launched the *Bridge* interview series in 2014. We began the interview series in large measure as a consequence of conversations we had with him. We traveled to Manhattan and interviewed him at his home for the winter 2015 issue. Always upbeat and insightful, his 2015 interview is as timely today as it was in 2014. I invite you to read it. Sam was my model for civility and grace, two attributes that are in short supply in the world today.

As always, I welcome your comments. Feel free to reach out to me at [RLatanision@exponent.com](mailto:RLatanision@exponent.com).

# Guest Editors' Note

## Challenges and Opportunities for the US Metals Industry



Aziz I. Asphahani



Gregory B. Olson

Aziz I. Asphahani (NAE) is chairman and CEO, QuesTek Innovations, and Gregory B. Olson (NAE) is professor of the practice, Department of Materials Science and Engineering, Massachusetts Institute of Technology.

It is widely recognized that US manufacturers must out-innovate their competitors and that, for key sectors, competitiveness will be defined by the ability to develop and deploy advanced materials.<sup>1</sup> Comparably, the importance of materials has been highlighted in Japan with the recognition that the “material industry of Japan, especially structural materials, has been the backbone of the whole Japanese industry.”<sup>2</sup> The US metals industry plays a similarly vital role in the ongoing restoration of domestic manufacturing.

In this short series of invited essays, most challenges confronting the metals supplier industry are illustrated by steel and aluminum, the highest volume sectors, while the opportunities to address these challenges are dependent on the metals user and design services industries, emphasizing innovative alloy sectors. By examining the Materials Genome Initiative (MGI), the leading national research initiative coordinated by the Department of Commerce, this issue explores the government’s role in enhancing ongoing metals innovation and broadens its scope beyond steel and aluminum (e.g., titanium, magnesium, nickel, cobalt, and niobium) and across other classes of materials (e.g., ceramics, polymers, and composites).

Raymond Monroe, executive vice president at the Steel Founders Society, recounts the history of the United

States’ steel production and emphasizes that construction steel is urgently needed to rebuild US infrastructure. Public policy, or the lack thereof, in conjunction with the globalization associated with the ill-fated concept of a “service economy,” has brought serious damage to this component of our industry. Despite steady improvements in steel production technology, the 1980s saw a severe flattening in the quantity of domestically produced steel, with an attendant increase in imports. In recent years, unfair competitive practices, supported by strategic investments, have enabled a historic dominance in steel production by China. Monroe calls for the enactment of policies that would assuage US financial institutions’ reluctance to invest in the steel industry and improve the investment climate for this important sector.

A more optimistic perspective on aluminum is provided by Scientific Director Timothy Warner and his colleagues at Constellium, a multinational corporation with a growing US presence. Motivated by the stricter sustainability requirements in Europe, a major focus of ongoing technology development is the comprehensive enhancement of energy efficiency and reduced carbon emissions in the production and use of aluminum products, with a significant focus on recyclability.

The globally acknowledged imperative of sustainability has brought attention to the underlying issues of materials technology. The time and cost of the traditional practice of trial-and-error empirical development have been major barriers to achieving the required pace of materials innovation to meet pressing needs related to sustainability and the environment. An especially promising role of

<sup>1</sup> US Council on Competitiveness. 2018. Leverage Phase II Sector Study: Aerospace (white paper). Washington, DC.

<sup>2</sup> Cross-ministerial Strategic Innovation Promotion Program. 2016. Structural Materials for Innovation. Department of Innovation Platform, Japan Science and Technology Agency. Chiyoda-ku, Tokyo, Japan.

government in meeting this challenge has been the development of MGI, as discussed by Jim Warren, director of the Materials Genome Program at NIST. Launched in 2011, this presidential initiative set the goal of building out the integration of computational methods and supporting materials science databases, mechanistic models, and efficient experimental validation, compressing the traditional ten-to-twenty-year materials development and deployment cycle by at least fifty percent and substantially reducing cost. The attention MGI garnered led to its swift adoption by leading corporations such as Apple, SpaceX, and Tesla. The cycle of materials development and deployment has already been compressed to two years or less. Ongoing MGI-related activities are broadening applications beyond the notable successes in metals to non-metallic materials and building the database infrastructure to expand beyond the core CALPHAD systems.

In the context of meeting MGI's goals, Jiadong Gong, CTO and CIO at QuesTek, a computational materials design company, overviews the significant achievements of efficient computational design grounded in the "genomic-level" CALPHAD data system, which has steadily grown in accuracy and scope in recent decades. Current interest in rapidly developing AI technology has fostered its integration into computational design. While raw AI methods have aided in the discovery of chemical compounds, the delivery of complex multiphase materials has seen its greatest success in the knowledge-based CALPHAD approach. There is currently an opportunity for hybrid approaches that integrate fundamental materials science knowledge with data-assisted AI techniques.

Echoing the importance of the new technology of computational materials design, Charles Kuehmann, vice president of materials engineering at SpaceX and Tesla, highlights the role of materials concurrency in radically accelerating materials-intensive manufacturing innovation. Kuehmann outlines a five-step process referred to as the Algorithm that has enabled this innovation. As a case study, the example of Tesla's now-famous aluminum gigacasting illustrates the rapid design of a novel alloy with the concurrent creation of a large-scale manufacturing system, making it possible for affordable aluminum car structures to be included in automotive electrification.

Fully realizing the opportunities outlined in this issue demands a substantial change in technical workforce development. A further side effect of the service economy was a shift in the nature of federal research support to favor the pursuit of novelty (i.e., discovery) at the expense of utility (i.e., designed and engineered products). Moreover, despite the power of computational engineering demonstrated by industry, many educators are still predominantly experimentalists, slowing the modernization of the materials curriculum by relying solely on their prior experience and know-how of the traditional trial-and-error approach. A 2019 National Academies review of materials research<sup>3</sup> not only recommended extending the MGI for a second decade but also strongly advocated for a return of support for the previously neglected "classical materials" of metals and ceramics. Such a return to utility is vital to the successful restoration of a domestic manufacturing economy.

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<sup>3</sup> National Academies of Sciences, Engineering, and Medicine. 2019. *Frontiers of Materials Research: A Decadal Survey*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25244>.

*While the use of steel in US manufacturing grew over the course of the twentieth century, current policies prevent the US steel industry from truly flourishing.*

# The Rise of the US Steel Industry



Raymond Monroe is executive vice president, Steel Founder's Society of America.

Raymond Monroe

**B**ridges have been made from stone and concrete since the beginning. Iron bridges, however, were not erected until the industrial age began. The first iron bridge crossing the River Severn in Shropshire was completed in 1779. This bridge is still standing and is open to foot traffic.<sup>1</sup> Larger bridges that have been made since the late eighteenth century are often dependent on steel for their construction and performance. There are five iconic bridges in the world that are made of steel: Sydney Harbour Bridge, Forth Bridge, Ikitsuki Bridge, Chaotianmen Bridge, and Akashi Kaikyō Bridge. Our infrastructure, exploiting the opportunities of the new technology for the production of steel available during the Industrial Revolution, made both skyscrapers and large bridges a reality. While the use of steel in US manufacturing grew over the course of the twentieth century, current US public policy prevents the steel industry from truly flourishing.

## **The Ascent of Steel in the United States**

The use of steel in the US economy has grown since the late nineteenth century, as shown in figure 1. The increase was due both to wider applications of steel from 1800 to the 1950s and the increase in population during that period and continuing until today. Today the per-capita use of steel in the United States is around 800 kg (1800 lb) per person.

<sup>1</sup> <https://www.english-heritage.org.uk/visit/places/iron-bridge/>

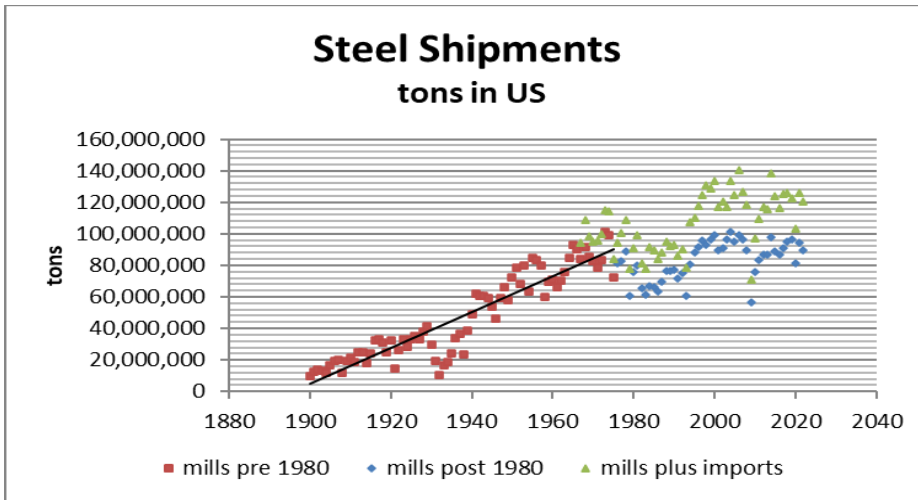


FIGURE 1 Shipments of steel produced in the United States as reported by AISI.



FIGURE 2 Value of steel mill products and construction materials from the PPI divided by the value of money. Source: BLS via FRED.

While the demand for steel has generally increased, there are notable peaks and valleys. It is useful to try to understand the variability of demand based on cost and availability. Figure 1 depicts a valley every thirty years, around 1930, 1950, 1980, and 2010. What is the explanation for these drops that are followed by rapid growth?

There appears to be a cyclical pattern for capital-intensive industries like steelmaking. This cyclical pattern is seen in figure 2. One way of understanding this is that when demand is high and customers and manufacturers

cannot get enough steel, the price goes up as individual purchasers are willing to pay more to get their needed steel on time. In bridge construction, the need to meet the schedule may force the fabricator to pay a premium to get the steel required. To ensure an adequate steel supply for their business, multiple orders are released by purchasers to different steel producers. To meet market demand, the producers begin to invest to increase capacity. Prices, production, and profits allow a capital investment cycle that creates the capacity for this peak demand and overshoots the post-boom need.

This is seen in the cycles captured in figure 2, which plots the value of steel and construction equipment. The price movement, as documented by the producer price index for these commodities, is divided by the gross domestic product implicit price deflator to give a relative value for the product. After World War II, the consumer economy invested to shift production from military needs to consumer products. The peak of the value of steel mills and construction materials was in the mid-1950s. After

that peak, incremental investments were made in capital investment with each three-to-five-year business cycle as commodity prices remained stable and producers tried to invest and gain quality and market share after each downturn. The cycle ended as this incremental reinvestment could not keep pace with the growth in population and increased usage. A new major investment cycle began in the 1970s. Increasing inflation and interest rates stimulated growing investments in capital-intensive industries and in basic infrastructure like bridges.

Contrary to normal economic theory, low interest rates and stable prices do not incentivize investment in capital-intensive industries. The lack of capacity that triggers increasing prices due to demand exceeding current capacity leads to rising inflation and interest rates. This drives new capital investment. In a time when capacity is inadequate, inflation makes the current purchases of capital equipment more valuable in the future and makes the money required to later repay the loans cheaper, so investment becomes a compelling decision. Rising inflation, interest rates, the growth of global demand, the idea that economic and national security depended on manufacturing, and the concerns triggered by the oil crisis about the limits of natural resources drove the capital investment boom from 1972 until 1981. This can be seen in figure 2. Much of our current infrastructure, including bridges, was produced during this time of investment, as seen in figure 3.

To control the inflationary pressures of the late 1970s, Paul Volker, who served as chairman of the Federal Reserve at the time, dramatically raised interest rates. This coincided with the peak at which capital investment created capacity for most steel segments that exceeded normal demand. The demand for steel fell sharply after 1980. Production of steel mill products that had exceeded 100 million tons in 1978 fell to less than 60 million tons in 1982.

The investment in steelmaking capacity continued after 1980. The change from integrated steelmaking, using blast furnaces that melt ore and convert iron to steel in basic oxygen furnaces and casting ingots for rolling to final products, to electric arc furnace (EAF) melting, which feeds continuous casting operations that directly produce the final mill product from liquid steel, is seen in figure 4. While declining integrated mills had other challenges and not all EAF steel production was in mini mills with continuous casting, these technologies were more economical and resulted in a revitalization of the steel industry.

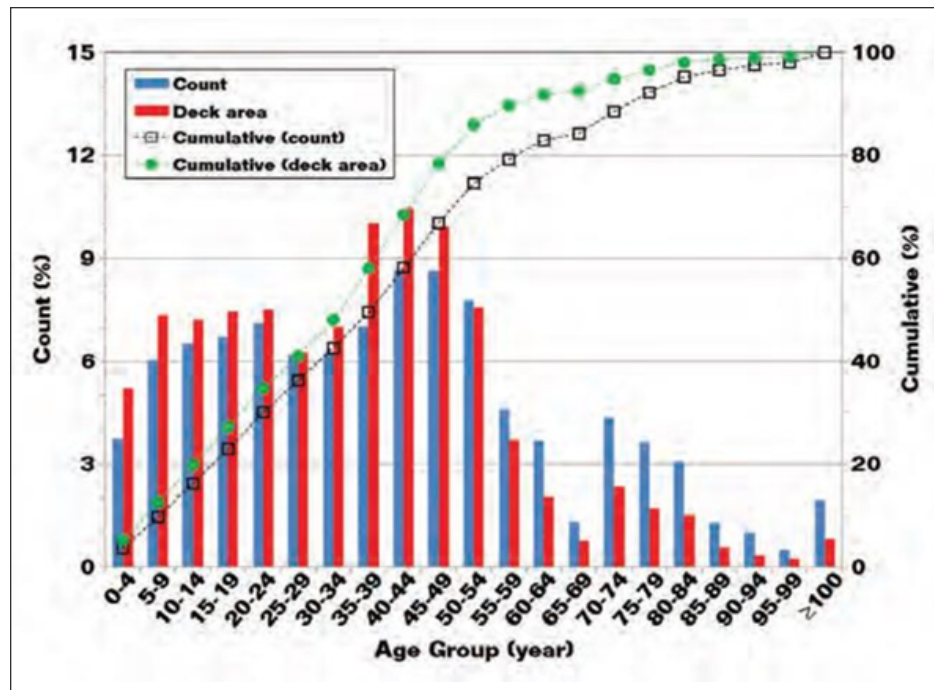


FIGURE 3 Age of bridges in the United States. Source: Toubia and Emami (2016).

The newer steel plants, using EAF or continuous casting for mill products, dramatically reduced the investment required and the cost of production. The significant reduction in the marketplace value of steel mill products from 1980 to 2000 was due to a combination of the reduction in the cost of production from new technology and the dramatic drop in demand as the economy had to absorb and eventually liquidate the excess capital investment stimulated by the economic boom of 1971-1981.

**Conditions of Limited Supply and Excess Capacity**

During times of economic expansion, when capacity is inadequate for the current market, prices rise as customers are willing to bid higher prices to secure the capacity and products they need. Since there are more willing buyers than capable suppliers, buyers bid for the last increment of available capacity. This market-clearing price is reflective of the value customers place on the product. Results of the conditions of limited supply include:

1. Prices increase to market value.
2. Production throughput becomes the critical measure of success.
3. Inventory, including spare parts, is an asset and increases in value.
4. Additional staff is valuable because downtime and production shortfalls are costly.

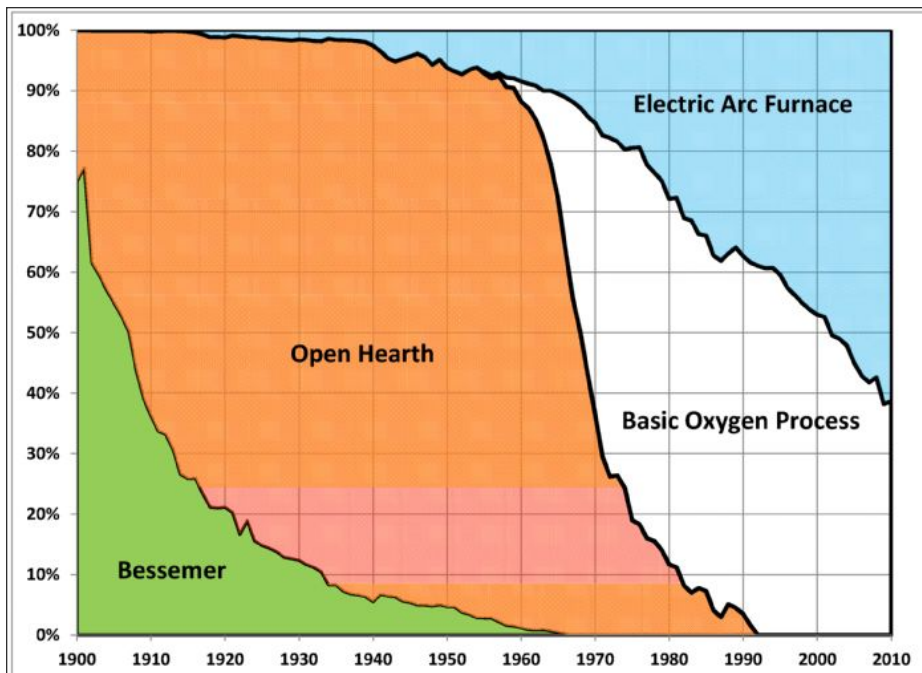


FIGURE 4 Shifting methods of steelmaking in modernity, including the recent shift to electric arc furnace steel production and continuous casting of mill products. Reprinted here from “A Brief History of Steelmaking,” by Daniel Schaeffler, published by *MetalForming Magazine*, August 31, 2020, a publication of PMA Services Inc. and the Precision Metalforming Association.

5. Purchasers are willing to consider and buy alternative products and try new processes.
6. Suppliers make and purchasers support adding capacity.
7. Increases in inventories, lead times, interest rates, and inflation are systematic.
8. Purchasers consider and invest in captive capability.

During the expansion, demand exceeds stable needs because the capital-intensive industries are not only producing the end products needed; they are also making the materials needed for the equipment and structures needed to increase capacity. When the peak of the boom occurs, the system is overbuilt with substantial in-process inventory and excess capacity. Prices drop as there are now more willing and capable suppliers than purchasers. The market price drops from the price of the product of the last willing supplier with capacity to the price of the product offered by the last willing purchaser with needs. This price is set not by the value of the product in service but by the cost of production. The conditions of excess capacity are:

1. Prices are stable or declining due to the cost of production.
2. Profitability is dependent on being a low-cost producer.
3. Inventory is a cost with a declining value.

4. Minimizing staff is necessary to minimize the cost of production.
5. Profitability is low, so investment is limited.
6. Capacity is liquidated with closures or restructuring.
7. There are low interest rates, inflation, inventories, and lead times.
8. Purchasers close captive operations to improve their ROI by making the “I” smaller.

In figure 2, the ten-year capital boom from 1971 to 1981 exhibited all the characteristics of limited supply. The twenty-year liquidation from 1981 to 2001 showed all the features of excess capacity.

The period after 1972 became more volatile. There was a shift to more macro-economic control with the abandonment of the gold standard and the institutionalization of inflation by the central bank, which was meant to manage the business cycle. These efforts plus continuing changes in the geopolitical system that included the increasing scope and cost of government policy did not reduce cyclical variability but exacerbated it.

It seemed reasonable to expect that the liquidation cycle for obsolete capital investment characteristic of the 1999–2003 recession would initiate a subsequent new capital boom. Growth in the world economy along with the removal of residual capacity in the United States could lead to limited supply, which would spark a new investment cycle like in 1971–1981. However, shifts in public policy to protect financial actors resulted in volatility and investments globally rather than a re-investment in the United States. From a public policy standpoint, globalization encouraged large original equipment manufacturers (OEMs) and government agencies to diversify their suppliers to exploit the lower costs from other countries. Many OEMs wanted to gain a market share in China, which was rapidly growing and promised to provide more growth and profitability than the relatively stagnant markets of the developed West.

### Challenges for the US Steel Industry

US steelmakers are the world leaders in making steel efficiently, using less energy and labor and fewer raw materials than competitors, and to the highest performance standards. The challenges for the industry are the costs of public policy and the exploitation of globalization by others to gain market dominance through nonmarket practices. In the US economy, goods-producing industries comprised 17.6% of the GDP in the first quarter of 2023, and services were 70.9%. Manufacturing is only 10.9% of the GDP (US Bureau of Economic Analysis 2024). Government spending is 38.5% of the GDP, twice the level of goods production.

In international trade, steel producers in the United States are at a fundamental disadvantage. Other countries view their steel industry as an essential tool for national and economic security. The United States, as the guarantor of global trade, negotiates trade agreements to strive for free and fair trade. Neither of these economic concepts are realized in our current arrangements. The United States has a stake in trade agreements that protect services like finance, entertainment, and software development. This outweighs any interest in ensuring steel production is treated fairly. Fair trade in trade agreements is not about reciprocity (e.g., I treat Canada the way Canada treats me); it is defined by evenhandedness (e.g., I treat China the way I treat Canada).

One major challenge of globalization was the failure to recognize the nonmarket nature of global trade. The economic justification for free trade is that market value should make the most efficient use of resources and secure the best economic outcome. The global challenge is that international trade is inevitably mercantilist and is not good at discovering market values.

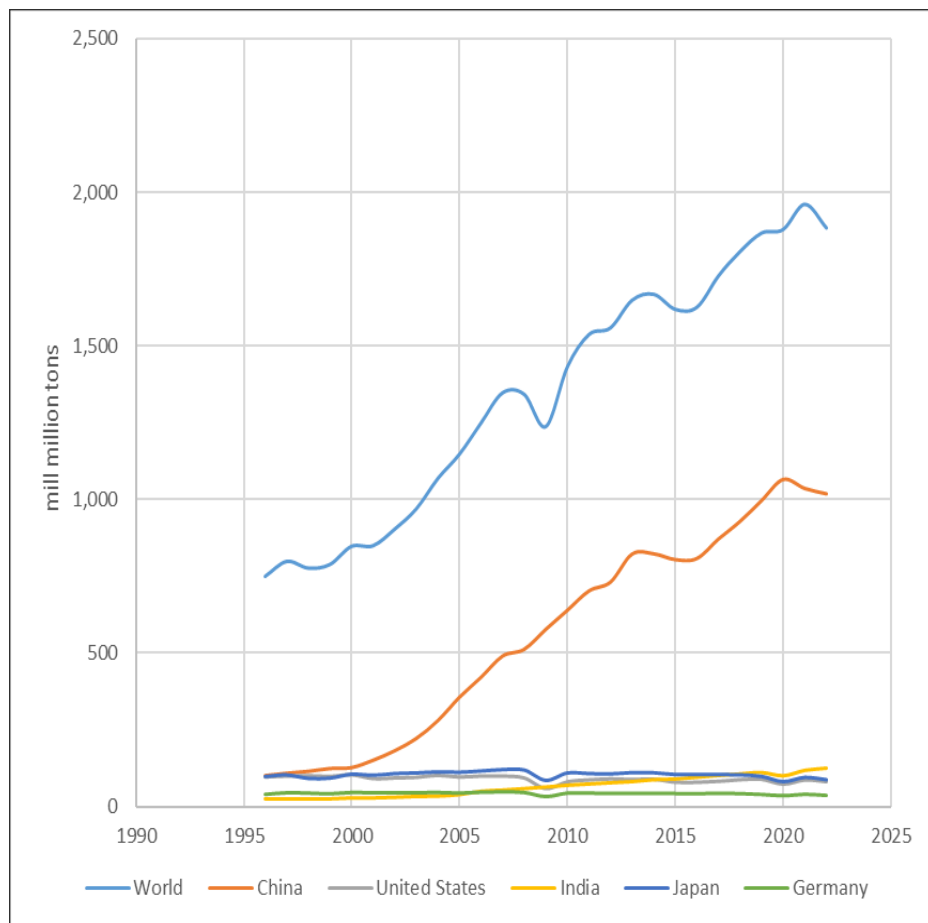


FIGURE 5 Historical production of steel around the world and by major steel-producing countries. Source: World Steel Association.

In particular, China has a strategy to dominate the world in steel production. With their ascension to the World Trade Organization in 2001, they pursued an effort to rapidly grow their steel production. As seen in figure 5, China went from parity with the major steel-producing countries to constituting more than half the world's production in twenty years. China has no resource or obvious economic advantage that would make them the lowest-cost or market-dominant producer. They have been clear in their intent to use public policy to establish dominance in most of the materials needed in a modern economy. This has been evident in lithium, pig iron, rare earths, etc.

Manufacturing is disadvantaged by tax policies like depreciation, regulatory costs, liabilities with no statute of limitations, and trade policies that allow other countries to violate and abuse our trade laws with no clear remedy for industries that are affected. In the wealthiest economy in the world, domestic investors are not attracted

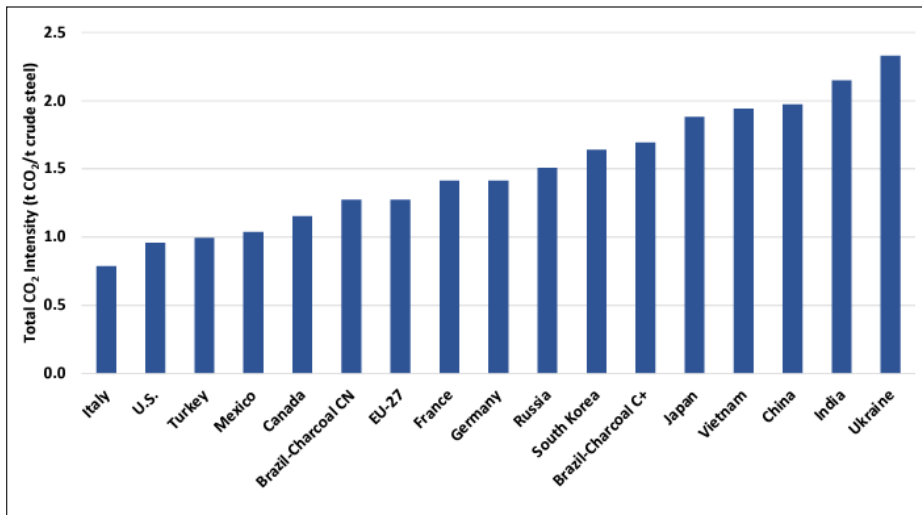


FIGURE 6 Carbon intensity of major steel-producing countries. Source: Hasanbeigi (2022).

to capital-intensive industries like steel production. In 2022, the United States had a net-positive foreign direct investment of \$1,326 billion (\$6,581b out and \$5,255b in) for all categories except for primary metals, for which there was a net negative of -\$73 billion (\$45b out and \$118b in). It is clear from the flow of foreign direct investment that these policies need to be changed.

## ***Steel production is necessary for our national and economic security.***

### **Considerations for the Future of Steel**

The United States recognizes the need for the private sector to provide both the materials and the wealth required to support the economy and carry the public policy costs for the programs promised. To strike this balance, public policy is developed to extract as much public benefit from private manufacturers as possible beyond the economic and national security they must provide. This reduces the profitability of capital-intensive industries like steelmaking, limiting their ability to provide lower costs and higher-quality products. Unfortunately, our industrial policies are a legacy practice that makes manufacturing, especially capital-intensive manufacturing, an unattractive investment.

There is growing recognition that change is needed to make capital investment industries attractive and

profitable. The challenge is not that US producers are not competitive, but that the public policies for taxes, regulations, trade, and financing all weigh against profitability. It is encouraging that there is a growing recognition of the capabilities of our steelmaking industry, its leadership in technology, and its foundational role in national and economic security. Making domestic steel producers the low-cost, high-value suppliers to industries like bridge design and construction is both necessary and valuable for our future.

Even with all the trade challenges, legacy costs, and cultural misconceptions, the US steel industry is aggressively pursuing new technologies, new materials, and new processes. The US steel industry is competitive and capable of reducing the impact of steelmaking on the climate.

In figure 6, US steelmakers had a low carbon intensity compared to the other major steel-producing countries. China is the largest emitter of CO<sub>2</sub>, relying on non-EAF melting with twice the emissions per ton of steel produced, and the largest steel producer by a factor of ten (Hasanbeigi 2022).

Steel technology remains an opportunity to improve our lives by providing higher performance and supporting our needs for infrastructure like bridges and modern transportation systems. The Steel Founders' Society has worked with Congress and the defense industry to provide significant funding for the development of new alloys and new processes. As can be seen in figure 4, the steel industry has routinely and rapidly adopted new technology in melting and casting. New opportunities like additive manufacturing, ICME alloy development, and automation allow us to effectively work towards a strong place for steel in the future of our manufacturing needs.

Steel technology has great opportunities for innovation. Collaborating with public policy makers, designers, fabricators, users, and investors is essential for us to move forward. Recognizing that steel is fundamental to our national and economic security requires policies that allow the profitability needed to support investments for current and future needs. Investments in technology

need to be supported by programmatic strategies that recognize the importance of being the leader in technology and the production of the most advanced steels.

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*A major focus of ongoing technology development is enhancing energy efficiency and reducing carbon emissions in the production and use of aluminum products.*

# **Current Challenges and Opportunities for the Aluminum Transformation Industry in the United States**

Timothy J. Warner, Bill Allemon,  
Craig B. Lewis, and Guillaume Bes



Timothy J. Warner



Bill Allemon



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Guillaume Bes

**T**he major challenge for the metals industry today is responding to society's need to reduce its environmental impact, in particular by reducing greenhouse gas (GHG) emissions and by reducing the quantity of landfill waste as a result of missed recycling opportunities. Aluminum is intrinsically well adapted to this challenge: its combination of low density and good mechanical properties makes it possible to design and manufacture lightweight structures at costs acceptable for high-volume requirements such as automotive applications (Aluminum Association 2021a). In addition, the fact that aluminum alloys, appropriately segregated, can be fully recycled into themselves is an enabler for a circular economy, as evidenced by the recycling of aluminum beverage cans

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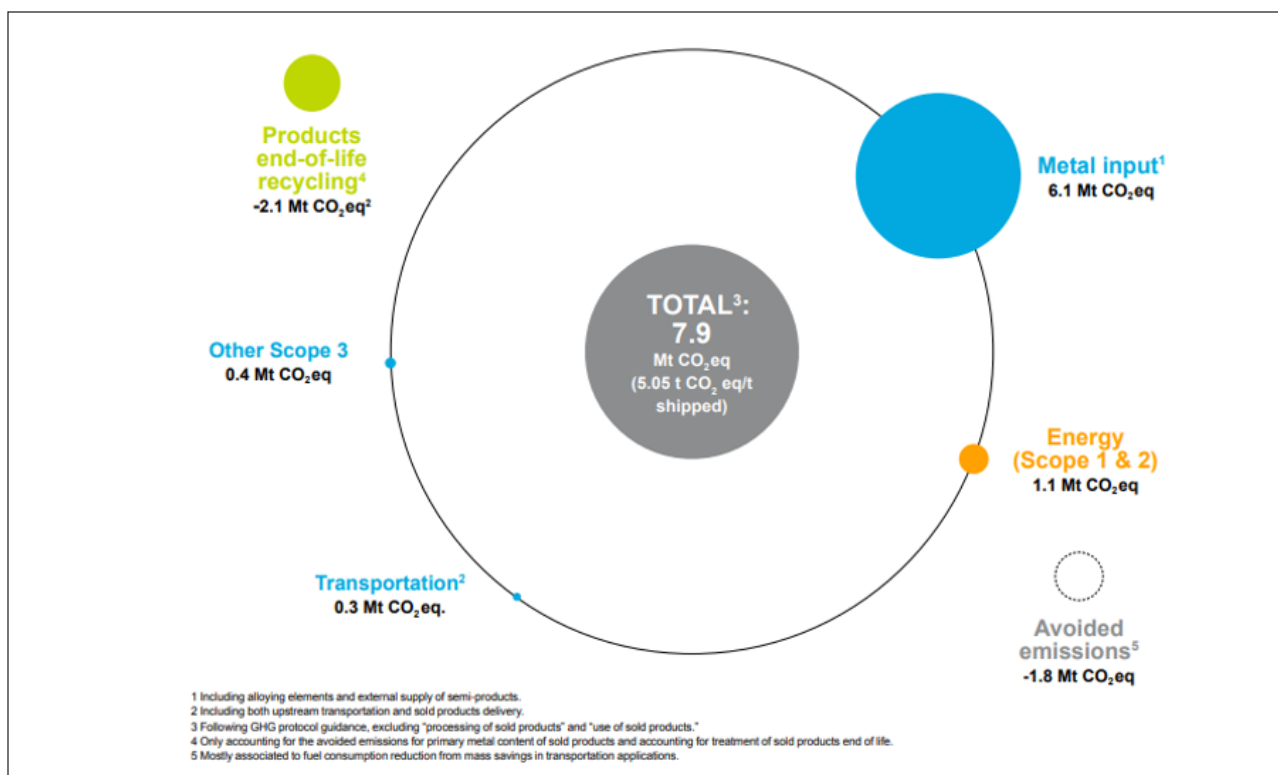


FIGURE 1 Simplified lifecycle analysis for Constellium’s transformation business. The largest source of GHGs is that embedded in the metal sourced from aluminum smelters (“Metal input”), which is more than 5 times that related to Constellium’s operations “Energy (Scope 1&2)”. Avoided emissions correspond to the impact of light weighting (image abstracted from Constellium 2021).

within the same application (Aluminum Association 2021b; Aluminum Association 2022).

A macroscopic life cycle analysis of a typical aluminum transformation<sup>1</sup> business today is presented in figure 1. Averaged over multiple applications, the data in figure 1 indicate that upstream primary metal production contributes the most to GHG emissions (i.e., bauxite refining to alumina [Al<sub>2</sub>O<sub>3</sub>], followed by smelting to produce commercially pure aluminum). This is due to the high energy consumption of both the smelting process and the production and consumption of carbon anodes used in the smelting process. The major smelters are actively working on both these fronts by ensuring that their energy sources emit as little GHG as possible (e.g., by preferring renewable or nuclear power to fossil-fuel power sources) but also by developing so-called inert anodes (Wang and Xiao 2013) that obviate the CO<sub>2</sub> emission due to consumption of the anode and the high energy requirement for

consumable carbon anode production.

The next highest contribution to the embedded GHG content of aluminum products comes from the transformation of the aluminum (i.e., the remelting and alloying of aluminum to produce solidified ingots or billets and their subsequent processing by rolling or extrusion to foil, sheet, plate, or profiles).

There are two GHG-emission-reducing contributions indicated in figure 1: 1) “Avoided emissions,” which represent the impact of light weighting of structures by replacing heavier structures, particularly in the transport industry, and 2) The impact of recycling of aluminum scrap, which is both intrinsically desirable to reduce levels of landfill and an enabler for a significant reduction in the energy cost (and thus the GHG emissions) of the metal input into the transformation process (see figure 2).

This article focuses on the challenges and opportunities in increasing recycling, reducing energy use during aluminum transformation, and light weighting of consumer products. The opportunities are both environmental and economic: increasing the rate of recycling reduces metal input costs, reducing energy use has a

<sup>1</sup> Aluminum transformation designates the remelting, rolling, or extrusion and thermo-mechanical treatment of aluminum. Upstream of this is the production of “primary aluminum,” from the mining of bauxite to the smelting of aluminum metal.

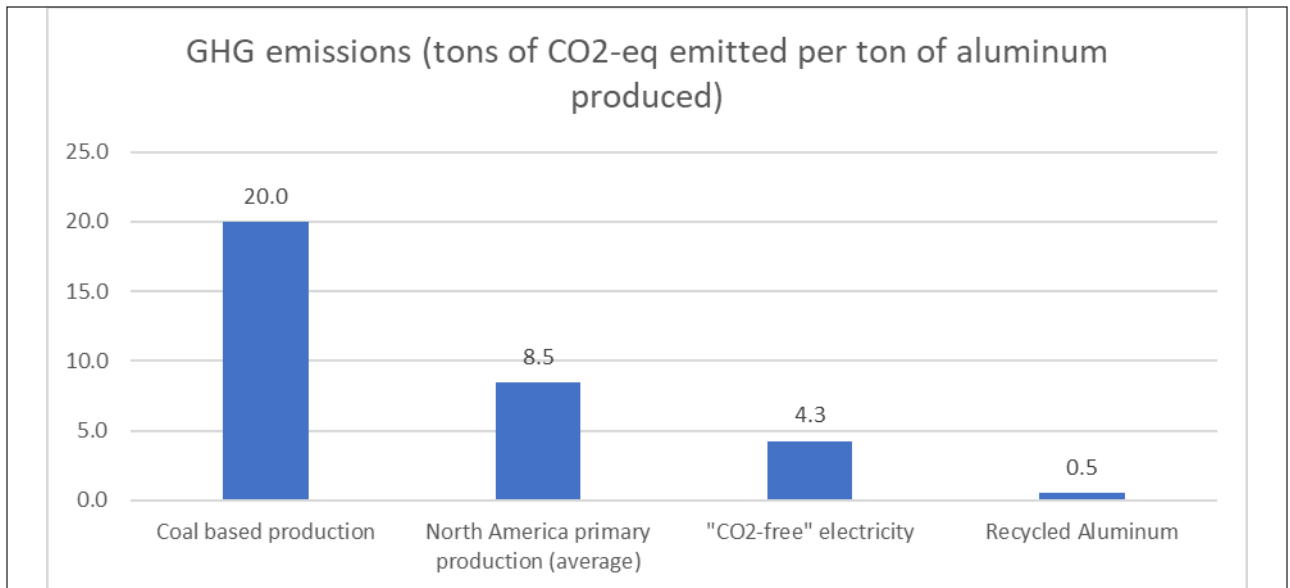


FIGURE 2 GHG emissions of primary aluminum production as a function of origin, compared with those of the recycling process (Aluminum Association 2022). Recycling generates roughly 95% less GHG emission than using primary aluminum today and remains less GHG intensive than even production with “CO2-free” electricity (for example using hydro-electric power but with a carbon anode).

direct financial impact on the bottom line of a plant, and light weighting reduces transport costs.

### Recycling

The US aluminum transformation industry already inputs roughly 50% of externally recycled scrap into its process (Aluminum Association 2022). Increasing this level is key to reducing the amount of aluminum that ends up in landfills (currently about 50% of the volume of aluminum transformed every year [Aluminum Association 2022]) and to reducing the industry’s overall level of GHG emissions. Improving the level of reuse within the same application (i.e., ensuring closed loops within the same alloy family) will also be necessary in order to ensure sustainable recycling loops.

A primary reason why aluminum ends up in landfills today is because it is mixed with different materials such as steel, plastics, and cardboard and, as a result, cannot easily be remelted to make new aluminum products. However, even if the aluminum were to be separated from the other materials, that would still not suffice to enable recycling in high-performance wrought alloy applications such as automotive or aerospace, because such applications require different property balances and therefore composition-processing combinations. Nearly 400 distinct wrought alloy compositions in eight different series corresponding to different major alloying additions are registered with the Aluminum Association (Aluminum

Association 2018), each with their own specific processing requirements and property balances. Separation and sorting of scrap, in many cases into exploitable alloy groupings, are therefore key for future volumes of recycling in the aluminum wrought industry.

Aluminum beverage cans demonstrate both the potential and some of the ongoing challenges of recycling in the United States. Used beverage cans (UBCs) are already recycled at extremely high rates in some states (e.g., 85% in Oregon) with the creation of well-developed circular scrap loops. However, at a national level (see figure 3), more than 50% of UBCs ended up in landfills in 2022. Although current UBC availability exceeds the recycling capacity of US rolling plants, planned domestic can stock recycling capacity increases will ensure that UBC demand will exceed supply within the next five years unless the rate of recovery of UBCs increases nationally.

The opportunities to increase the level of recycling are different for each major application of aluminum. In the aerospace market, given the level of machining required to make highly complex airframe parts, the largest recycling volumes and opportunities are in the so-called “pre-consumer scrap” generated by the aerospace machine shops. Aluminum scrap flows in the automotive market, currently low but building rapidly, trailing the recent substantial increases in aluminum alloy volume in auto body applications, are the object of industry and

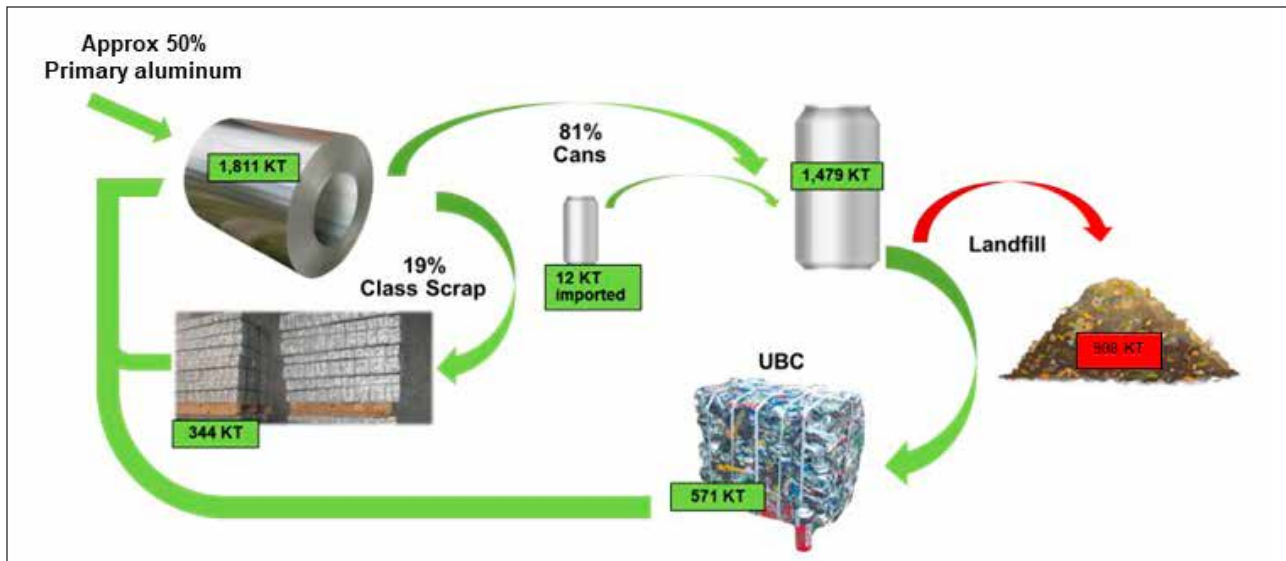


FIGURE 3 Recycling loop for beverage can sheet (data from Aluminum Association 2021b and internal Constellium estimates). As indicated, currently roughly 50% of the can sheet produced (903 kt of 1811 kt) ends up in landfills in the United States. The combination of pre- and post-consumer recovery (“class scrap” and “UBC”) is of approximately the same volume.

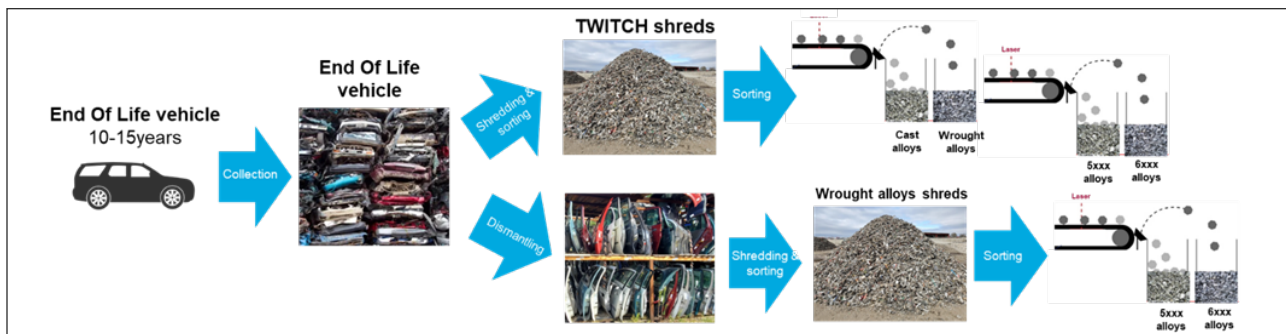


FIGURE 4 Illustration of two alternative routes to EOL recycling of automotive alloys: direct shredding or dismantling prior to shredding. See text for discussion.

academic studies to better predict and exploit the future scrap loops (Zhu et al. 2021).

Coming back to the beverage can example, different strategies could be used to keep the end-of-life (EOL) aluminum scrap in the beverage can life cycle:

- 1) **Selective collection:** depositing cans in dedicated recycling containers is the most efficient way to have high collection rates and a high quality of collection. This process only requires a simple sorting step, removing the remaining steel cans, as consumers have already made the effort to segregate aluminum cans from other waste.
- 2) **Global waste/scrap collection:** recyclable domestic food packaging (mixed cardboard, plastic bottles, plastic food packaging, cans, etc.) can be collected in the

same container. In this case, multiple high-efficiency sorting steps are needed to extract materials one by one. This path is easier for the consumer as there are not multiple collection bins, but it is more expensive. The quality of recovery is limited by the performance of the sorting technologies and by the joining technologies used (mechanical fastening, welding, hemming, etc.).

For automotive EOL recycling, there are two competing strategies to recover value from the mixed Al-Mg and Al-Si-Mg wrought aluminum alloys: full car shredding versus selective dismantling (Fick 2021). As a domestic car is a complex product where multiple materials are connected, current EOL recovery is dominated by auto shredder companies. Their main target is a high shredding rate, but the product generated (see figure 4) remains a

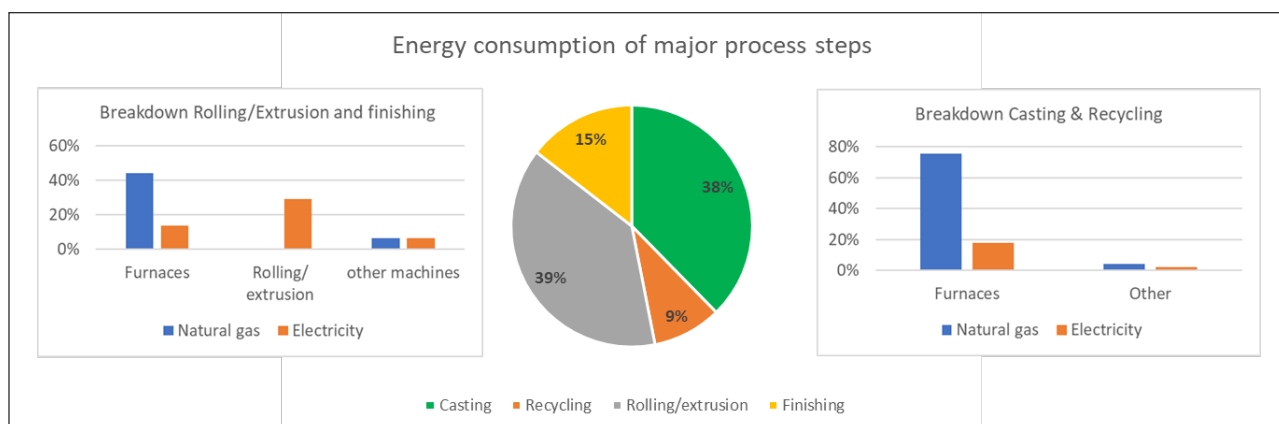


FIGURE 5 Illustration for a typical aluminum transformation plant of the principal areas of energy consumption (pie-chart) and the split between gas and electricity for major process steps (internal Constellium data). For this plant, 47% of energy consumption is in Casting or Recycling, within which more than 90% of consumption is in furnace heating. For the other major process steps most of the energy consumption corresponds to reheating in furnaces. Reheating steps are currently dominated by gas-fired furnaces.

mix of aluminum alloys that requires multiple high-speed sorting types of equipment, including x-ray transmission (XRT) and laser-induced breakdown spectrometry (LIBS). The current bottleneck of this strategy is the limited throughput of the sorting equipment (50-100t/h for a car shredder versus 1-10t/h for sorting machines). With the electrification of the automotive industry, more and more aluminum is being used in cars; new dismantling strategies, perhaps coupled with part design for recycling, could help to concentrate wrought alloy scrap. With such selective collection, cross-contamination between materials is limited, and the quality of wrought alloy recovery is improved. Though car dismantling is currently highly labor-intensive, its high potential ensures that it remains on the radar for EOL recycling.

### Energy Use during Transformation

Although the emissions associated with their primary aluminum content currently dominate in aluminum wrought products (for Constellium in 2021, these represented 77% of total GHG emissions per ton, see figure 1), many aluminum manufacturers have established CO<sub>2</sub> emission intensity reduction goals of 20%–30% for their own processes by 2030 (see, for example, Carbon Disclosure Project 2023), aligned with US manufacturers across other sectors.

With the largest contributor being the reheating of metal, including the melting and reheating of primary metals and scrap (“casting” and “recycling” in figure 5), the area of greatest focus is reducing the use of natural gas. This will be accomplished through near-term efficiency improvements and longer-term replacement with

alternative fuels and technology. The following discussion considers the available options with existing furnace technologies, such as electrification, alternative fuels, and overall process efficiency approaches.

### Existing Technologies

Starting with technology upgrades, a few common themes emerge. Price competition and CO<sub>2</sub> emission reduction demands have caused aluminum manufacturers to deploy commercially available technologies on their gas-fired furnaces, including improved burner technologies, magnetic stirring, and waste heat recovery.

One example is the use of regenerative furnaces. This design extracts heat from exhaust gases, storing the energy in a medium within each of two burners working alternately. While one burner is firing, the other burner captures energy from the furnace’s exhaust gases, which it then uses to pre-heat combustion air when it is that burner’s turn to fire. Each burner fires for approximately 2–3 minutes before the process is reversed. Regeneration can recover up to 85% of the energy that is typically lost as waste heat (Kermeli et al. 2016).

Non-contact stirring of the furnace melt charge increases melt rates and reduces cycle time, thereby increasing energy efficiency. The technology uses an electromagnetic device, permanent magnets, or a combination of both to improve flow within the melt. Easily retrofitted to existing furnaces, these devices improve furnace yield by 15% or more, while reducing natural gas consumption by approximately 5%. Other benefits include reduction of waste materials, elimination of melt surface burn, and homogeneity of the final product (Kermeli et al. 2016).

Generic waste heat recovery devices on furnace exhaust flues are a well-established technique to improve energy efficiency. The energy recovered may be used for heating in other industrial processes, such as pre-heating lubricants in nearby rolling mills or pre-heating and drying aluminum scrap, thereby reducing consumption of natural gas.

### *Electrification*

Electrification of industrial heating and other processes is currently much discussed (e.g., DOE 2022), primarily driven by government agencies, consultants, and technology solution providers.

Electric-powered solutions to all the major reheating operations in the aluminum transformation process are available and used in the industry. However, their applications have historically been limited by the high cost of electricity compared with the equivalent energy supplied as gas (see below) and by some scaling issues. For example, induction furnaces are used to remelt Al-Cu-Li alloys, for safety reasons in particular (Singh and Gokhale 2014). However, the maximum remelting furnace size commercially available today is roughly 20 tons, compared with more than 100 tons for a gas-fired furnace. Achieving the same production capacity would not only imply investments in many more furnaces but also a different workshop layout, with correspondingly high capital expenditure.

Although feasible in principle, substantial electrification would also raise questions around the net effect on carbon footprint, grid capacity, and reliability, as well as the cost effectiveness of technology conversion.

For example, with most electricity in the Midwest still generated from coal, the reduction in GHG emissions due to electrification at the aluminum manufacturers' facilities in this region would be more than offset by the increase in emissions at the utilities (Wang and Xiao 2013). In other parts of the country, such as the South and Southeast, where a higher percentage of power comes from carbon-free sources (hydropower and nuclear, respectively), the issue is the capacity of the local grid. Greatly increasing electrical demand would require investment in primary distribution, a financial burden on industrial and end-use customers.

The greater cost of electricity versus natural gas per equivalent energy unit is a fundamental challenge. Despite the rapid increase in solar power generation capacity, the continued fall in the price of photovoltaic generation (US Energy Information Administration 2023a), and

the continued maturation of utility-scale energy storage technologies (US Energy Information Administration 2023b), electricity still cannot compete with the price of natural gas at the time of writing. However, the future does look bright. The US Energy Information Administration estimates the levelized capital cost of photovoltaic electricity generation in 2028 to be \$24.08 per megawatt-hour, much lower than the future cost of modern coal-generated power at \$57.73 (Statista 2023).

### *Fuel Switching*

Replacing the use of natural gas with less carbon-intensive fuels is another logical step toward decarbonization. Trials are underway globally to evaluate reducing natural gas consumption by replacing air with oxygen in its combustion, as well as its complete replacement with hydrogen.

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***A primary reason why aluminum ends up in landfills today is because it is mixed with different materials such as steel, plastics, and cardboard and, as a result, cannot easily be remelted to make new aluminum products.***

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Oxygen enrichment in furnace applications is well established in the iron and steel foundry industry and is used to increase production throughput. The underlying principle of oxygen-fuel technologies is to reduce GHG emissions by displacing nitrogen in the furnace, greatly reducing NO<sub>x</sub> generation as well as reducing the quantity of natural gas used and therefore of CO<sub>2</sub> emitted. However, in an aluminum furnace, the use of oxygen requires precise control due to strict temperature requirements and to eliminate the potential for chemically damaging the production batch.

The use of hydrogen to fully replace natural gas is getting much press (Marocco et al. 2023; Deloitte 2023), primarily due to its reduction of GHGs, enabling the production of "green aluminum." Again, the reduction

of the overall carbon footprint rests solely on the emissions intensity (emissions factor) of the electricity used to produce the hydrogen.

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## ***The two principal challenges facing the aluminum industry today are reducing its own GHG emissions and increasing recycling rates.***

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We have identified three main challenges with hydrogen as a fuel for the aluminum industry (Hyinheat 2023). First, the safety aspect: due to the characteristics of hydrogen, the risk of leaks is greater than with natural gas, and the explosivity limit is higher. Secondly, the impact of moisture: after hydrogen combustion, the amount of water vapor in the exhaust fumes is very high. R&D activities are ongoing to determine the impact of this atmosphere on the quality of our products and on the lifetime of our infrastructure (furnaces, pipes, etc.). The last, but not least, challenge is the supply chain: as discussed previously, if the power used for hydrogen production is from a conventional carbon-intensive grid, the environmental footprint is worse. If power is supplied by carbon-free electricity, the discussion pivots in hydrogen's favor on an emissions-only basis. Depending on furnace configuration and application, the use of carbon-free generated hydrogen could reduce CO<sub>2</sub> emissions by up to 90% (LMA 2023). It should be noted that, as hydrogen gas is a much smaller molecule than natural gas, existing national infrastructure and plant-level distribution systems are not designed to safely transport the fuel.

### ***Energy Efficiency***

Regardless of the energy source and the carbon footprint of the electrical grid, energy-efficient production and usage continue to be a consistent area of focus. The trident of energy efficiency incorporates technology upgrades, best practice replication, and continuous improvement actions.

Industrial facilities have historically focused on individual capital project improvements for plant infrastructure such as compressed air, pumps, motors, fans, and

lighting. Some have conducted best practice sharing and opportunity identification workshops, such as the Energy Treasure Hunt process. However, these singular actions do not instill a comprehensive process of continuous improvement specific to energy efficiency and lowering emissions reductions.

Various standardization and best practice efforts provide guidance and encouragement to the industry to improve its practices holistically. Although more popular in Europe than in the United States, the ISO 50001 Energy Management Standard (ISO 2018) is gaining traction to help US manufacturers establish robust energy-specific continuous improvement programs.

To encourage the use of the standard, the DOE's Better Plants initiative created the 50001 Ready Program (DOE 2023), with a suite of tools and guides to supplement the succinct content found in ISO documentation. The DOE also provides both remote and onsite training to help implement 50001 and technical analytical tools developed by the agency.

In addition, the EPA's ENERGY STAR program, which predates ISO 50001, provides complimentary tools, training, and technical best practices for energy management programs (US Environmental Protection Agency 2023).

### **Avoiding GHG Emissions through Light Weighting: Past and Future Approaches**

Enabling weight reductions for transportation applications has long been a focus of the aluminum industry. Reduced weight in such applications translates directly into reduced energy consumption during the usage phase and, in general, into reduced GHG emissions.

Materials scientists can contribute to light-weighting structures by developing materials that meet the mechanical requirements of the application but have lower densities, as is the case with the Al-Cu-Li alloys developed over the last couple of decades and used especially in the aerospace industry (Lequeu et al. 2010; Warner 2006). In addition, increasing materials properties, such as strength, enables reductions in part thicknesses with concomitant weight reductions for the relevant component.

Structural light weighting in automotive applications will remain of interest even with the expected transition to battery electric vehicles (Hart et al. 2023). Largely because of range considerations, the aluminum content of today's battery electric vehicles is greater than their internal combustion engine counterparts of similar size and mission. Despite expected improvements in battery cost and storage density, aluminum light-weighting solu-

tions are expected to remain attractive, both from the point of view of their potential to reduce energy consumption and from an economic point of view, for at least the next decade.

There is currently strong interest in the additive manufacturing of aluminum parts, as additive manufacturing techniques enable the direct fabrication of parts that are of complex shapes. Comparisons between the CO<sub>2</sub> emissions of the fabrication of a given part via conventional or additive manufacturing are very unfavorable for additive manufacturing, largely because of the high energy intensity of additive processing (Ingarao et al. 2018). Nevertheless, the design freedom associated with additive manufacturing can result in significant part weight reductions and in very substantial reductions in the number of parts required for a given component (Faludi and Van Sice 2020). Particularly in applications whose use-phase emissions are very sensitive to weight reduction, such as aerospace, this can result in overall life cycle benefits for the additive manufacturing of some specific components, for example, small-scale but complex satellite components (Ingarao et al. 2018).

Another current trend with high potential is the concurrent optimization of materials, their processing, and part design. A recent example is Tesla's "megacasting" (Visnic 2020), which exploits the scrap available from the sheet metal used in a car assembly plant in a cast alloy part, in which the alloy, the process, and the design have been co-optimized.

As discussed above, historical aluminum alloy development for high-performance applications has resulted in the development of a large number of alloys with very tight compositional specifications and highly optimized processing conditions. As a result, the preferred approach to incorporating increased quantities of recycled metal is to separate and/or sort scrap for recycling in the same alloy. In many cases, a rationalization of the number of alloys used in the market would be beneficial. Where efficient separation and/or sorting is not possible or economically viable, the aluminum industry is looking into making optimum use of the corresponding mixed alloys (Aramburu et al. 2021; Raabe et al. 2022). Two main routes are being assessed: 1) The exploration of the new compositional spaces that are generated by mixing existing alloys, facilitated by innovative alloy design methods using either artificial intelligence techniques (Menou et al. 2019) or combinations of physics-based modelling approaches (Xiong and Olson 2015), or both, and 2) The exploration of alloy design and processing techniques

that are "impurity tolerant" (Raabe et al. 2022)(i.e., techniques that allow the incorporation of larger quantities of impurity elements by reducing their detrimental impacts). A third route, alloy purification in the liquid state, is the subject of active research, but no fully viable technology is available yet.

### Conclusions

The two principal challenges facing the aluminum industry today are reducing its own GHG emissions and increasing recycling rates. Much work has already been done on both fronts, but major opportunities remain.

Regarding the industry's direct emissions, energy efficiency initiatives are proving effective. Substantially lower-emission heating technologies exist or are in development, but to be effective in reducing overall GHG emissions, these will require concomitant investments in energy infrastructure.

The aluminum industry already has a strong track record of recycling. Given the intrinsically excellent recyclability of aluminum alloys, there are many opportunities to further extend and develop recycling, which the industry is addressing aggressively, but the engagement of other stakeholders will be critical to promoting full circularity (e.g., state and federal support to increase deposit rates by introducing deposit regulations and customers' and suppliers' engagement to recycle end-of-life vehicles).

The traditional light-weighting role of aluminum alloys will remain important going forward, but it will need to be achieved within the constraints of low GHG emissions and high recycled content.

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*The Materials Genome Initiative highlights the promising role of government in materials innovations.*

# The Materials Genome Initiative and the Metals Industry



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Jim Warren

In June 2011, during a speech at Carnegie Mellon University, President Barack Obama announced the Materials Genome Initiative (MGI).<sup>1</sup> The MGI is a multiagency effort to create a new era of policy, resources, and infrastructure that support US institutions in the endeavor to discover, manufacture, and deploy advanced materials twice as fast and at a fraction of the cost. The MGI is now twelve years old, but its roots go back a very long way, and the connection to the metals industry is especially strong.

The MGI was founded to accelerate materials deployment, and the mechanism that enables this is the so-called Materials Innovation Infrastructure (MII), which lies at the heart of the MGI, as is graphically depicted in figure 1. This simple-looking diagram is an attempt to articulate the tight integration of computation, experimentation, and data management that is essential to achieving the goals of the MGI. All of these concepts are not particularly profound, but the creation of the MII seeks to lower the barrier to applying advanced approaches to materials design and deployment, which, if successful, would have an enormous impact on manufacturing and the US economy.

In a very real sense, the MGI, building off a large number of prior studies (Glotzer et al. 2009; Jou et al. 2004; NRC 2004; NRC 2008), was about raising the profile of computational modeling within the materials R&D community to the same status as experimental approaches, as it was becoming clear that

<sup>1</sup> [www.mgi.gov](http://www.mgi.gov)

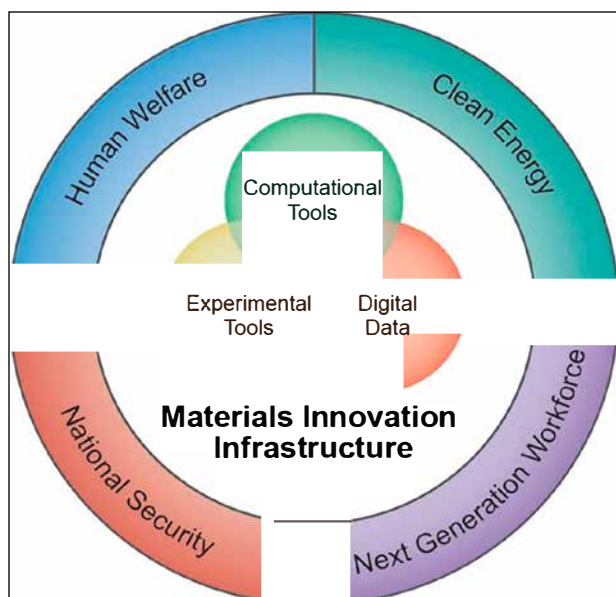


FIGURE 1 A simple Venn diagram detailing the components of the MGI and the associated integration needed for a materials innovation infrastructure to realize the aims detailed in the outer ring.

computation was at a place where it could substantively accelerate materials R&D, but it was not broadly adopted by industry. This was a central argument for the creation of the MII, which could make these approaches far more accessible and integrate modern techniques in materials modeling into industrial workflows.

There are a large number of technical approaches that fall under the MGI, all of which are united by the tight fusion of modeling, experimental approaches, and data management to accelerate materials R&D. One of the inspirations for the MGI was the Materials Genome Project at MIT, which has now graciously changed its name to the Materials Project to avoid confusion.<sup>2</sup> This effort, supported by the US Department of Energy, generates and makes available a vast trove of density functional theory calculations (quantum mechanical calculations) of materials properties for use by the materials R&D community. Another prominent MGI approach is integrated computational materials engineering (ICME) (NRC 2008). ICME has several decades of demonstrated use by industry to concurrently design materials for insertion in products, vastly reducing the time and cost and showing a near-order-of-magnitude return on investment.

Perhaps one of the most remarkable stories of the successful use of ICME comes from the small company

QuesTek Innovations. QuesTek has been using ICME techniques as its core technology to solve alloy development problems for a variety of industrial clients for several decades, and in 2012 QuesTek sold their technology to Apple while remaining in business for themselves. Apple subsequently used the QuesTek approaches to develop many of the metals found in their products, such as the Apple Watch and iPhone. In time, QuesTek-trained people migrated to SpaceX, where their approaches have allowed for massively accelerated alloy development to be deployed on their rockets. In support of the MGI, in 2016, the National Institute of Standards and Technology (NIST) supported several Quantitative Benchmark for Time to Market Framework case studies, one of which was the QuesTek alloy Ferrium M54,<sup>3</sup> which was developed in about six years from conception to deployment on a US Navy aircraft (far shorter than the usual fifteen to twenty years typical of alloy development and deployment times).

Another example of the power of these approaches can be found in what might seem an unlikely venue: money. In this case, NIST developed new coinage materials for the US Mint using MGI approaches and associated tools (Lass et al. 2018). Prototype alloys were designed in just eighteen months and validated by the US Mint in their 2022 Biennial Report to Congress (Alloy C99750T-M). The bill allowing the US Mint to use this alloy was re-introduced in the Senate in the spring of 2023.

Of course, beyond modeling it was broadly understood that materials data, whether from trusted models or experiments, was a poorly managed resource. In the case of industry, data will only be shared where it is in the interest of the sharing entity. All data costs money to produce and often would be of considerable value to the broader R&D community if made widely available. At a minimum, the data is valuable to the researchers that generated it. And yet, most workflows for curating these data remain extremely crude, with little metadata captured that would make understanding and reusing the data far more tractable. As is a topic largely ignored in traditional materials research environments, the MGI has focused considerable energy on exploring and supporting work to address these challenges.

NIST has framed its support for the MGI around data. NIST and its predecessor, the National Bureau of Standards, have a 120-plus-year history of providing high-

<sup>2</sup> next-gen.materialsproject.org

<sup>3</sup> www.nist.gov/system/files/documents/2018/06/26/materials\_innovation\_case\_study\_qustek\_090616.pdf

quality data to the world (e.g., the US time standard<sup>4</sup> or the Chemistry WebBook<sup>5</sup>). For the MGI, NIST identified three principal thrusts: (i) enabling the exchange of materials data, (ii) ensuring the quality of materials data, and (iii) developing new methods and metrologies based on the broad availability of materials data (like data-driven materials R&D). More information on the NIST program and its numerous projects can be found on the NIST website.<sup>6</sup>

### The MGI at the Outset

One of the areas of greatest success in the application of modeling to accelerate the design of new materials is in metallic systems. There are a number of reasons for this, including (i) the millennia-long history of metallurgy and several centuries of more quantitative understandings, and (ii) the relative simplicity (compared to polymers and ceramics) of the chemistry of metals, which allows for the application of rigorous thermodynamic principles to these systems. Starting in the 1970s, the technique known as CALPHAD (CALculation of PHAase Diagrams is the origin of the acronym, although the meaning is now broader) was developed to allow a database of measured properties to be assembled, and these databases became the basic inputs in predictive models of the processing-structure-property models that enable materials designers to create new alloys with targeted properties.

This predictive power is the essence of MGI approaches, allowing materials R&D efforts to feed experimental results into models, design new alloys, and iterate to converge rapidly to the desired combination of properties. However, making approaches like these more broadly available entails more than encouraging the use of certain software packages. It requires a host of associated additional considerations. It was in this light that the National Science and Technology Council (NSTC) subcommittee on the MGI rolled out a strategy in 2014. This strategy contained four goals:

1. Leading a culture shift in materials-science research to encourage and facilitate an integrated team approach.
2. Integrating experiment, computation, and theory and equipping the materials community with advanced tools and techniques.
3. Making digital data accessible.

4. Creating a world-class materials-science and engineering workforce that is trained for careers in academia or industry.

As can be seen from this list, the lead goal was not a technical issue but instead revolved around a culture shift in the conduct of materials research. This requirement was essential to achieving the goals of the MGI, which otherwise focuses on developing the MII, specific issues around data that had largely been left unexplored within the materials R&D community, and the ever-present need for training in state-of-the-art methods. As the MGI evolved, the culture shift began to take hold. And as the MGI approached its first decade, it was time for a fresh look at the materials research landscape, its requirements, and new opportunities.

### The MGI Today

As the MGI was taking hold across academia, translating these ideas into industrial practice became ever more pressing, as the adoption of MGI approaches was uneven. The economic arguments for widespread adoption seem irrefutable. In 2018, NIST supported a prospective study including an economic analysis and interviews with more than 120 industry experts on their needs for new technological infrastructure supporting advanced materials innovation and the potential economic impacts of meeting those needs. It was concluded that an improved MII (and its adoption) would deliver between \$123 billion and \$270 billion in value annually.<sup>7</sup>

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***One of the areas of greatest success in the application of modeling to accelerate the design of new materials is in metallic systems.***

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The reasons for lack of adoption were, and remain, complex, but the tide is beginning to turn. Certainly, the metals industry was far ahead of other sectors in their adoption of MGI approaches, but even there, significant impediments remain. Most of these barriers will fall away as the costs of adoption are lowered and the success stories become more broadly appreciated. One of the most promising areas that has arisen is the

<sup>4</sup> [www.time.gov](http://www.time.gov)

<sup>5</sup> [webbook.nist.gov/chemistry](http://webbook.nist.gov/chemistry)

<sup>6</sup> [mgi.nist.gov](http://mgi.nist.gov)

application of artificial intelligence (AI) approaches to materials R&D.

When NIST rolled out its strategy to support the MGI, as discussed above, the third element was the development of new methods and metrologies enabled by the broad availability of materials data (like data-driven materials R&D). Data-driven materials R&D is, of course, an accurate characterization of AI, although all data-driven approaches are not AI. Thus, NIST was extremely well situated when the AI revolution (as far as the application to materials is concerned) began around 2016 and continues to accelerate today.

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## ***The current importance of AI to the MGI is hard to overstate.***

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While the need for high-quality data and careful experimentation informed by physical models is never going away, the current importance of AI to the MGI is hard to overstate. Indeed, there are substantial reasons to be cautious with the applications of these techniques, as they can deceive the practitioner if used improperly. However, the potential benefits are readily apparent. With the ability to detect patterns in a manner that used to be strictly the provenance of humans, the process of microstructural characterization has become easier, faster, cheaper, and more accurate. Combining these approaches with robotics and mathematical inference models, autonomous (self-driving) materials R&D laboratories are becoming a reality, with groundbreaking demonstrations being reported ever more frequently. All of these developments are, of course, precisely in the wheelhouse of the MGI, as AI is a computational model and slots into the MGI paradigm with no need for modification. The success of these approaches, their relative low cost, and ease of deployment should effectively increase the adoption of MGI approaches.

In light of these developments, the subcommittee on the MGI realized it was time for a new strategy, and in 2021 they released an updated strategic plan.<sup>1</sup> The plan consisted of three goals:

1. Unify the Materials Innovation Infrastructure.
2. Harness the power of materials data and accelerate materials R&D through the application of AI.
3. Educate, train, and connect the materials R&D workforce.

The observant reader will note the absence of anything like a culture shift goal, as it is now clear to most of the MGI stakeholders that these approaches to materials R&D are clearly effective. The remaining goals are natural evolutions of the original goals. The MII is and always will be a work in progress. So, much of the effort must be on unifying otherwise disparate pieces to enable more effective R&D. The second goal has moved from a data-centric view of materials R&D to an AI-focused goal, with data as the enabling technology, while the third goal is an updated version of the education and training goal found in the original plan, taking into account the new approaches and technologies that have come to the fore since the original strategy was crafted. Indeed, the federal agencies supporting the MGI are all working aggressively to execute on this strategy in a rapidly evolving landscape. For example, generative AI models (e.g., Stable Diffusion and ChatGPT) have all risen to prominence in the less than two years since the strategy was released, and these models seem to have extraordinary potential for applications in the MGI space (as well as across much of science and other disciplines.)

It is worth drawing attention to one of the major objectives under the first goal: accelerate the adoption of the MII through the National Grand Challenges. This objective has the benefit of rallying the community around pressing national and worldwide challenges while simultaneously defining and accelerating the development of MGI approaches crucial for the long-term success of the MGI. The grand challenges could be any of the pressing environmental or social issues that occupy much of our attention, but the technical solutions to these challenges are undergirded by MGI approaches. In the metals arena, all of the areas articulated in the strategy are relevant, including issues around climate change, environmental degradation, energy storage, renewable power generation, critical materials substitution, advanced healthcare technologies that rely on new biocompatible materials, new manufacturing capabilities that address the lack of resilience in existing systems, and improved materials to rebuild an aging physical infrastructure.

### **The Metals Industry and the Way Forward**

The metals industry and, more generally, the technologies that make the design of new metal alloys possible using the techniques and data made available through the MII have been touchstones for the MGI. The metals industry has led the charge towards demonstration

of the high return on investment for MGI approaches while also exposing the various gaps in methods, data, and knowledge that must be filled for even more widespread adoption of these techniques. Indeed, there are some fascinating issues around the generalization of MGI approaches that use the phase diagrams that are successful for metallic systems for polymer systems. A great deal of the thinking around those ideas has been explored in the Polymer Properties Predictor Database (PPPDB) effort based at the Center for Hierarchical Materials Design in Chicago.<sup>7</sup> While such approaches are not inherently the best way to proceed for industrially relevant model of polymer systems, it is certainly the case that the more the successes in metals systems can be leveraged, the better it will serve the broader materials R&D community.

Ultimately, the MGI and the concepts it encompasses are the only way forward for materials R&D, and for the metals industry's goal of designing new alloys with tailored properties. While there are many other issues, both social and technical, that complicate the insertion of MGI approaches into industrial practice, the ultimate realization of the goals of the MGI has and will continue to pave the way for a nimbler and more cost-effective industrial base and increasingly impactful metallic systems.

#### Disclaimer

Certain commercial entities are identified in this paper in order to clearly elucidate the landscape of materials R&D. Such identification does not imply recommendation or endorsement of any product or service by NIST, nor does it imply that the entities identified are necessarily the best available for the purpose.

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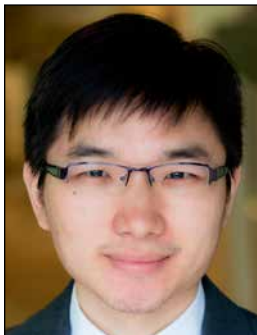
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<sup>7</sup> [pppdb.uchicago.edu](http://pppdb.uchicago.edu)

*The synergy between AI and materials science holds immense promise for the future of materials engineering.*

# Harnessing the Power of AI in Materials Digital Transformation: A Synergistic Hybrid Approach



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## Jiadong Gong

The quest for novel materials, alongside their optimization and adoption, has perennially fueled the engine of innovation. Traditionally, the development of materials relied heavily on a trial-and-error approach, characterized by extensive experimentation. However, this method often proved to be lengthy, arduous, and costly. That narrative began to shift with the emergence of computational methods and tools like computational thermodynamics (CALPHAD) (Saunders 1998) and density functional theory (DFT) (Kohn 1999), ushering in the era of computational materials design. Greg Olson pioneered this approach in a seminal paper (Olson 1997), setting the stage for a new paradigm in materials design and development. The value of the CALPHAD-grounded approach, trademarked as Materials by Design®, is that it allows us to use our existing predictive mechanistic knowledge in a quantitative and system-specific way (Olson et al. 2014). The efficacy of this approach was subsequently underscored by the accomplishments of companies such as QuesTek Innovations, SpaceX, Tesla, and Apple across diverse sectors including energy, aerospace, automotive, and electronics (Kuehmann 2024; Warren 2024).

The early triumphs of computational methodologies in expediting material innovation captured the attention of the US government, culminating in the inception of the Materials Genome Initiative in 2011. This ambitious venture aimed to halve the time and cost of the conventional ten-to-twenty-year cycle of material creation and deployment by funding and developing foundational

databases and computational tools. As the academic and industrial realms increasingly embraced this initiative, a plethora of tools emerged, including various science-based modeling tools across various time and length scales. This proliferation led to the widespread adoption of integrated computational materials engineering (ICME), a concept that was broached and demonstrated in an earlier NRC study and the DARPA-AIM program (NRC NMAB 2004, NRC NMAB 2008). In the hands of leading corporations, this technology has now reduced the full materials design and deployment cycle to under two years.

In tandem with the expansion of computational tools and databases came a surge in computational power that is ready for use. This prompted the proposition of a “digital twin” for materials, envisioned to obviate the necessity for physical trial-and-error experiments. The concept posited that all such experiments could be conducted in a digital realm, aligning with the broader narrative of digital transformation in materials engineering. The ascendancy of artificial intelligence and machine learning (AI/ML), epitomized by advancements in language processing, computer vision, optimization, and forecasting, has propelled this idea further (Choudhary et al. 2022; Gomes et al. 2019). The recent emergence of GPT (Vaswani et al. 2017), a large language model (LLM) from OpenAI, captured significant attention from both the research and business communities, marking a pivotal moment in the advent of generative AI (GenAI). This new wave of AI holds promises in promoting the generation of new materials, although the reports surrounding fully AI-created materials remain nascent and challenges abound.

### **Examining the Challenges**

The anticipation of AI as a catalyst for materials innovation is indeed burgeoning. A few have spotlighted promising outcomes in the domain of robotic and autonomous experimentation (Pyzer-Knapp et al. 2022). Particularly, self-driving laboratories have made strides in new thin-film discoveries (MacLeod et al. 2020), hinting at the burgeoning potential of AI in revolutionizing the materials engineering landscape. Notably, researchers have been delving into “materials discovery” (Gomes et al. 2019; Merchant et al. 2023), allowing algorithms to traverse the expansive space of material compositions, with hopes of “discovering” new materials with coveted properties. However, the fruits of these endeavors haven’t quite lived up to the initial expectations. Several factors underpin this shortfall, and below are some notable challenges:

#### *1. Data Deficiency: Quantity and Quality Matters*

The march towards an AI-first or data-driven approach in materials engineering has been championed by many, thanks to the growth in computing power and the emergence of sophisticated AI/ML algorithms (Chollet 2019). Unlike domains such as social economic studies or digital media, where data is abundant, materials engineering often grapples with data scarcity and sparsity (Wang et al. 2020). The available data needed for direct training of comprehensive material models is just not adequate. Complicating matters further, a significant chunk of valuable data resides as proprietary within the private sector. Moreover, the available data often comes with various errors and outliers. In addition, a well-trained AI/ML model promises efficiency after deployment, but the preparatory steps, from data acquisition, cleaning, and curation to training and validation, often make this approach much slower and inefficient than science-based modeling.

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***This new wave of AI holds promises in promoting the generation of new materials, although the reports surrounding fully AI-created materials remain nascent and challenges abound.***

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#### *2. Algorithmic Problem: Navigating the Black Box*

The quality of data and inherent biases within AI/ML algorithms markedly influence their performance and reliability. The usual black-box nature of most AI algorithms poses more challenges in understanding their modeling processes. This understanding is critical for validation and trust, especially in the context of materials engineering, where erroneous predictions can have substantial consequences. A striking illustration is the comparison between the interpolation-centric nature of AI models versus the extrapolation capabilities of physics-based models. AI models may falter, generating unrealistic predictions like negative strength values for materials, underscoring the necessity for particular accuracy and reliability in modeling outcomes.

### 3. Complexity of Materials: Hierarchical Systems

Applied engineering materials are usually complicated systems with various subsystems at different length scales; they aren't merely waiting to be discovered. Apart from some success in unearthing new chemical compounds, the creation of new materials necessitates deliberate designs. Practical material applications exhibit complex interlinks among process, structure, properties, and performance (PSPP), resulting in a hierarchical structure of multiscale systems, with a mixed state of stable or metastable, equilibrium or non-equilibrium. This complexity underscores the indispensable role of domain expertise in developing and deploying meaningful AI solutions in this field.

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***Despite the challenges of direct applications, there are potential opportunities for the role of AI in materials engineering, especially within the context of digital transformation.***

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Certain computational methods, like DFT, are suitable for ML techniques for synthetic data generation and exploring specific chemical compound spaces (CCS). DFT-based ML models have shown promise in efficiency and scalability (Huang et al. 2023), hinting at the potential for experimental planning within self-driving laboratories. Yet, the success in identifying suitable compounds for certain property combinations hasn't translated to broader material development applications. The crux lies in the multimode, multi-structured nature of almost all practical engineering materials, which is one key difference between materials development and chemical engineering.

#### **Where are the Opportunities?**

While raw data-driven AI techniques have had success in identifying new chemical compounds, far more success has been found in the direct application of mechanistic knowledge in the efficient parametric design of complex multiphase materials, aided by "genomic-level" funda-

mental CALPHAD databases. Notably, this has taken "clean sheet" designs of aircraft landing gear steels all the way to flight qualification (NIST 2016; NRC 2012). We next explore the opportunity of hybrid approaches within the framework of "structured hybrid modelling" (Bhutani 2006), which efficiently integrates mechanistic and empirical modeling.

Despite the challenges of direct applications, there are potential opportunities for the role of AI in materials engineering, especially within the context of digital transformation. As previously noted, the lack of domain-specific data and materials science expertise has resulted in significant gaps in the AI-centric approaches discussed in the preceding section. Moreover, this deficit in domain knowledge underscores why AI approaches, when purely data-driven and devoid of underlying scientific comprehension, demand a high volume of quality data and further exacerbate the data need. Overcoming this hurdle could markedly accelerate our journey towards a new era of engineering materials design and deployment.

Leveraging well-established science-based models can drastically trim the data requirement. A handful of critical calibration data points can yield highly accurate outcomes. These models are predominantly mechanistic and in analytic forms, with superior speed and efficiency in predicting PSPP relationships, without the cumbersome process of data collection and training.

Yet, some science-based models are stochastic or necessitate extensive simulation. While these models excel in prediction with scientific soundness, integrating them with AI/ML into hybrid models could potentially bring improved efficiency. The principles of ICME require the interconnection of models across various length and time scales, compelling materials modelers or designers to judiciously select model combinations that optimize overall efficiency. For example, atomistic simulations for materials are very powerful and accurate with high-fidelity atomic interactions; however, they are greatly limited by the large computational cost. Recent advancements in machine-learning interatomic potentials (MLIAP) have given access to atomistic simulations that reach similar accuracy levels but are orders of magnitude faster, thus dramatically widening the spectrum of materials systems that can be simulated with high physical fidelity (Deringer et al. 2019). Additionally, in scenarios where linkages within a particular PSPP system remain elusive and well-established scientific models are absent, AI/ML models could serve as valuable additions to bridge these gaps.

We have already recognized the success of AI in discovering new compounds within expansive CCS, as highlighted by the recent work by Google DeepMind (Merchant et al. 2023). However, the intricacy of engineering materials, underscored by their multiscale structures, renders the discovery of new materials via AI a challenging task. Nonetheless, the compounds discovered through AI could be promising candidates for constituents at different structural levels, enabling ambitious designs. In a multiscale materials system, a series of design choices exist for employing particular phases for diverse purposes, such as strengthening precipitates, grain-pinning particles, and inoculants, among others. Employing AI to fill the gaps in missing models of the PSPP linkage and to identify coveted microstructure constituents in the ICME design chart could significantly enhance overall materials design. Furthermore, the deployment of well-established AI algorithms for smart search and optimization could further fine-tune this process's efficiency. Below are two case studies to demonstrate some of these aspects.

#### *Case Study 1: High-Temperature Nb Alloy Design*

The aspiration to deploy Nb-based alloys as a viable upgrade for Ni-based superalloys is rooted in their potential for superior performance in high-temperature applications, such as rocket nozzles and next-generation turbines. However, realizing this goal requires overcoming formidable design hurdles, including achieving high specific strength, creep resistance, and oxidation resistance at elevated temperatures while preserving ductility at lower temperatures. Additionally, the requirement for alloy coatings to ensure compatibility with coating materials further complicates the design space.

QuesTek Innovations has employed a blend of computational methodologies to address some of these challenges. One of the key tasks was to delineate a strengthening strategy for the new alloy. Beyond the conventional solid solution strengthening from alloy elements in the Nb matrix, two other potent mechanisms were explored: precipitation strengthening and grain refinement through dispersion. For effective high-temperature precipitation strengthening, the chosen precipitate should be coherent with the Nb matrix (i.e., low crystal mismatch) and demonstrate robust coarsening resistance at operating temperatures (i.e., high-temperature thermal stability). Typical coherent, ordered bcc-type precipitate systems include the B2 (stoichiometry AB) and L2<sub>1</sub> (stoichiometry A<sub>2</sub>BC) structures. Similarly, the design of a fine grain

size is achieved through the formation of a small fraction of cubic MX (X=O, C, N) oxycarbide grain pinning dispersions. The strategy is to leverage the typical level of interstitial elements in Nb alloy to design a stable MX dispersion with suitable coarsening resistance and solvus temperature, ensuring refined grain size across various processing stages. However, employing commonly used phases to meet these stringent, sometimes conflicting constraints posed a significant challenge.

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***The integration of AI in engineering materials design heralds a new frontier of innovation, yet it could also bring along a spectrum of risks that may necessitate regulatory measures to ensure safe and responsible deployment.***

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A potential solution is the multicomponent concept—multiple substitutional elements within the same sublattice—to exploit the high entropy effect for phase stabilization. While seasoned materials designers could search available CALPHAD databases for well-assessed compound spaces, data pertaining to these multicomponent chemical spaces largely remained elusive. Employing hybrid machine learning and DFT approaches (Choudhary 2022) for a high-throughput search within a vast CCS, potent phases were identified that satisfied all constraints, specifically a multicomponent L2<sub>1</sub> strengthening precipitate and the MX oxycarbide grain pinner.

Low-temperature ductility, another crucial factor, hinges significantly on the precise design of the ductile-brittle transition temperature (DBTT). A traditional parametric DBTT model grounded in the “master curve” framework of Odette, employing a universal hardness dependence (Odette and Lucas 2001), could delineate contributions from different alloying elements for the solid solution of the niobium matrix. Yet, the endeavor to develop an accurate DBTT model within a high-

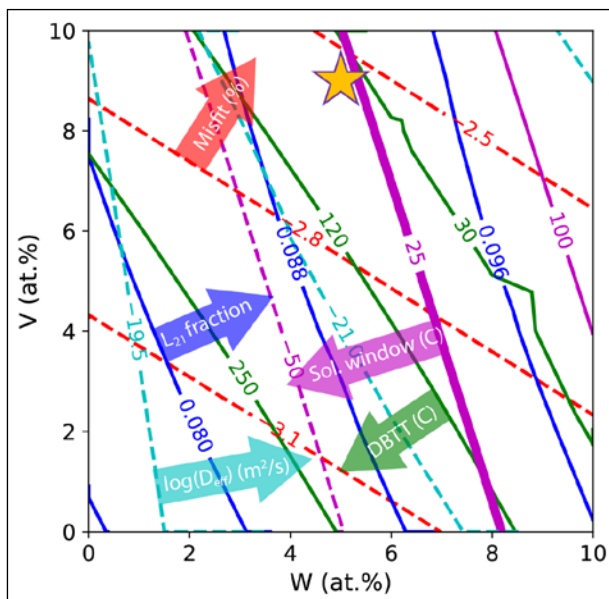


FIGURE 1 Example of computational parametric design of the Nb alloy by overlaying key processing and property constraints, which are indicated by lines labeled as: Solution window, Misfit percentage,  $L_{21}$  strengthening phase fraction, Logarithm of effective diffusivity, and DBTT. The star indicates one candidate optimal composition within varying V and W compositions. This modeling work and figure were generated using QuesTek ICMD® software.

dimensional multicomponent space was restricted by a dearth of relevant data for effective regression. QuesTek gathered a specific dataset encapsulating DBTT data for twenty-six multicomponent Nb alloys from available literature and internal datasets. Utilizing a statistical learning method, QuesTek was able to identify effective materials descriptors from possibly correlated feature spaces, enabling accurate DBTT prediction for multicomponent Nb alloys with very limited data.

With the proven Materials by Design® methodology under the ICME framework, QuesTek successfully engineered a novel Nb alloy that met the stringent design requirements. Some of the design highlights are illustrated in figure 1.

### Case Study 2: Shape-Memory Materials

Shape-memory materials, with their high functional potential, have been employed in a myriad of applications. The shape-memory effect primarily hinges on the martensitic transformations, which are diffusionless, displacive phase transitions and can yield significant engineering benefits such as hardening, toughening, and shape-memory properties across various material systems, from alloys to ceramics. The martensitic trans-

formation induces large strains, creating a complex issue as the transforming region coexisting with the surrounding untransformed matrix, thus leading to a considerable mismatch. In ceramic systems, this behavior is often associated with deleterious bond-breaking events reaching the material's elastic limit and the generation of transformation hysteresis. In what follows, a recent advancement in ceramics is examined to shed light on the transferable design methodology utilizing a combination of different modeling techniques.

Pang and colleagues (2022) utilized a multifaceted modeling approach, interlinking machine learning, computational thermodynamics, and lattice engineering to predict shape-memory characteristics of new ZrO<sub>2</sub>-based compositions (see figure 2). Zirconia ceramics exhibit a martensitic phase transformation permitting large strains, thus emerging as candidates for shape-memory and superelastic applications at high temperatures. Like other martensitic materials, the transformation strain can be engineered by alloying to yield a more commensurate transformation with reduced hysteresis. Yet, “lattice engineering” in zirconia is further complicated by additional physical constraints such as managing a large transformation volume change and achieving transformation temperatures high enough to evade kinetic barriers. Due to data scarcity for materials of interest, elements of data science, including supervised machine learning, were introduced to navigate a complex multidimensional search space. The multi-objective optimization outcomes directed targeted experiments, which subsequently led to a cracking-resistant polycrystalline martensitic zirconia ceramic with record low thermal hysteresis.

The outcome was a new zirconia composition with a low hysteresis of 15 K, showcasing about five times less than the best values reported thus far. This revelation implies that zirconia ceramics can exhibit hysteresis values comparable to those of widely deployed shape-memory alloys, thereby opening avenues for their application as high-temperature shape-memory materials. Compared to other reports of a pure data-driven AI approach for similar shape-memory designs (Treherm et al. 2022), the methodologies deployed herein that utilize different modes of models in both parallel and serial fashion can be readily transferred to the design of shape-memory alloys or other material systems upon careful modification and calibration.

### Smart Decision-Making Drives Innovations

A simplistic yet factual interpretation of decision-making activities can be seen in figure 3. Here, data in its myriad

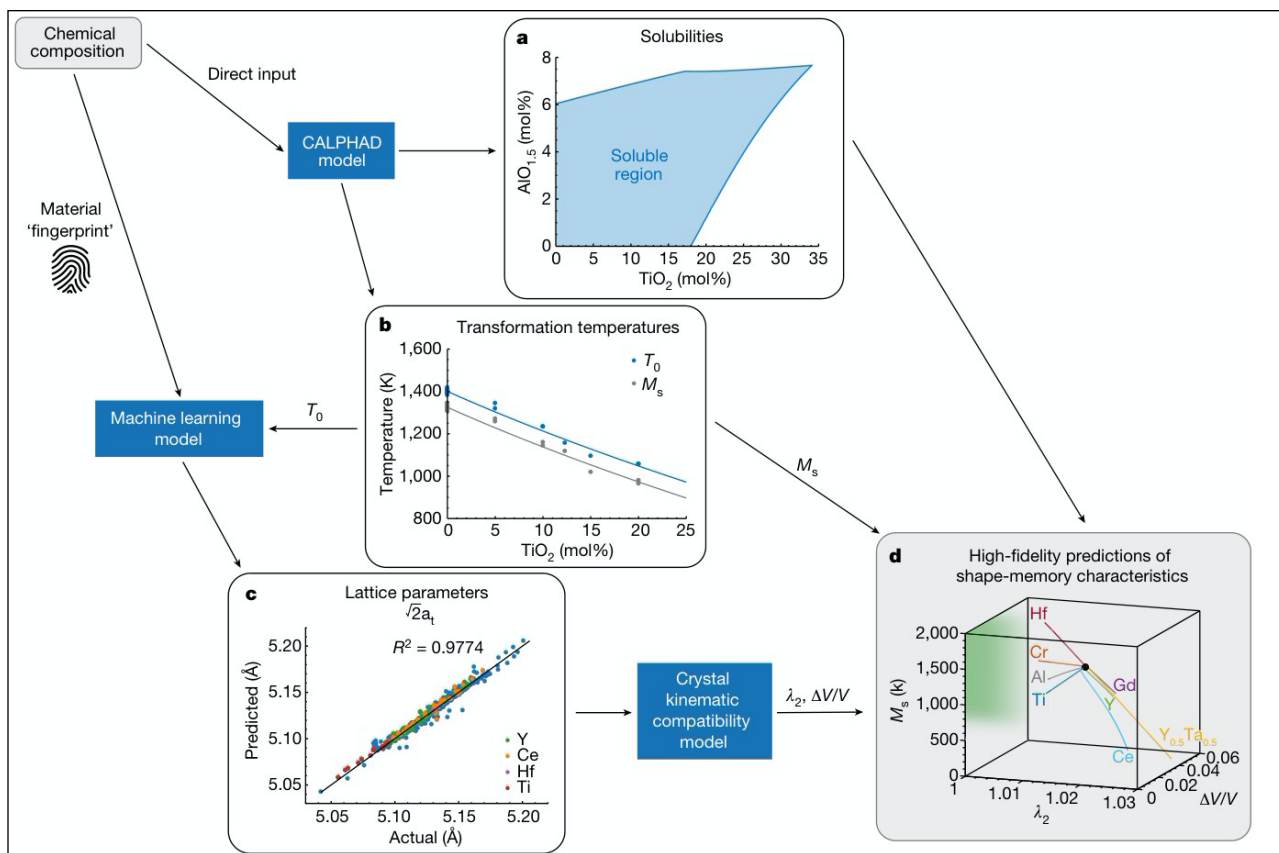


FIGURE 2 Multifaceted modelling approach combining machine learning, CALPHAD, and lattice engineering to predict shape-memory characteristics of new ZrO<sub>2</sub>-based compositions: a. Predicted single-phase soluble region in the ZrO<sub>2</sub>-TiO<sub>2</sub>-AlO<sub>1.5</sub> system, b. Comparison of experimental T<sub>0</sub> and M<sub>s</sub> values with CALPHAD predictions in the ZrO<sub>2</sub>-TiO<sub>2</sub> system, c. Comparison of experimental lattice parameters with predictions by machine learning model in various binary systems, d. Effect of various dopants on shape-memory characteristics in the binary systems for ZrO<sub>2</sub> ceramics (Pang 2022).

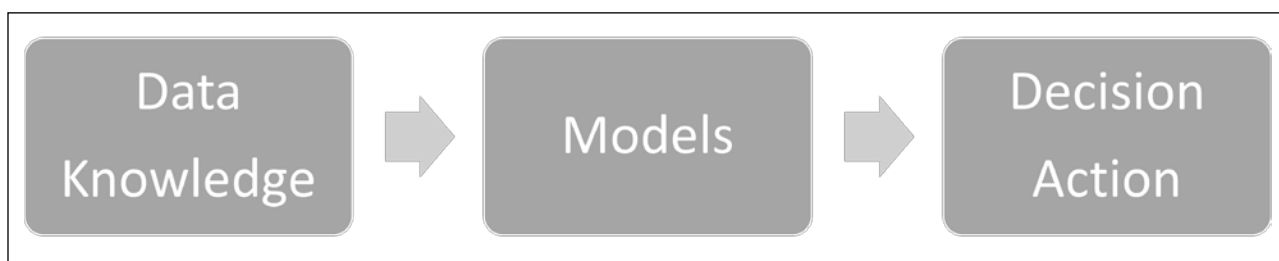


FIGURE 3 A schematic of the universal decision-making process.

forms—structured or unstructured, measured or synthesized, human-observed or sensor-derived—serves as the foundation. All terrestrial entities, whether humans or machines, process received data with prior knowledge through intrinsic models to generate decisions or actions. The essence of these models, their ability to generate the right decisions from the data, embodies the coveted trait of intelligence, be it artificial or natural.

The evolution of these models can be aptly segmented into four progressive categories: descriptive, predictive, prescriptive, and generative. The advent of large language models (LLMs) like ChatGPT has ignited substantial buzz around generative artificial intelligence (GenAI). Despite the appeal of a super GenAI tool capable of generating all kinds of recommendations and decisions, the importance of ensuring that models in

critical engineering applications accurately predict outcomes and recommend appropriate solutions remains paramount.

Presently, science-based models and simulations remain the workhorses in accelerating engineering innovations. Yet, as elucidated in previous sections, AI techniques can significantly enhance this decision-making process from all aspects across data, models, and materials domain knowledge. AI tools could essentially enable engineers from diverse fields to articulate intricate simulation needs in natural language and construct complex domain-specific materials models. Such simplification could potentially lower the domain expertise threshold significantly. A notable example is MIT researchers who, from mechanical engineering practice, combined ICME and machine learning techniques in a hybrid approach for the inverse design of additively manufacturable high-strength aluminum alloys, adeptly navigating a complex high-dimensional materials space while adhering to all constraints (Taheri-Mousavi et al. 2024). As emerging AI techniques mature and proliferate, anticipation surges around their potential to augment, automate, and optimize more facets of the decision-making process. Interweaving these advancements with science-based modeling and simulation could markedly elevate materials selection and design efficiency, reduce development and deployment time and cost, and nurture cross-disciplinary collaborations.

### **Risks and Regulatory Aspects**

The integration of AI in engineering materials design heralds a new frontier of innovation, yet it could also bring along a spectrum of risks that may necessitate regulatory measures to ensure safe and responsible deployment. The dependency on data, in particular, raises concerns regarding data privacy and security, especially when sensitive or proprietary information is involved. Ensuring the confidentiality and integrity of data is paramount to mitigate the risks associated with data breaches or misuse. The potential impact of biases and inaccuracies generated by lower-quality data can be disastrous for materials applications, and the black-box nature of AI algorithms poses additional challenges in validating and trusting their predictions. Determining accountability in cases of adverse outcomes resulting from AI-driven decisions in materials engineering could be a complex legal and ethical challenge. Clear liability frameworks are crucial to addressing potential disputes and to ensuring adherence to ethical standards.

The creation of innovative materials through AI is indeed the crown jewel of hopes, but it also poses questions regarding who owns intellectual property rights. Establishing clear guidelines on this issue of ownership is necessary to foster innovation while ensuring legal clarity. Developing standards and best practices can help harmonize the regulatory landscape and ensure the safe adoption of AI. Given the global nature of both AI and materials engineering, international collaboration is vital to address the associated risks and foster a conducive environment for leveraging the benefits of AI in materials engineering to address global issues, such as climate change and sustainability.

### **A Synergistic Future**

The narrative of a “digital twin” for materials, once a far-fetched notion, is gradually becoming a tangible reality, fueled by the relentless advancements in computational power and AI technologies. The integration of AI/ML with established ICME technologies presents a new frontier in the digital transformation of materials innovations, ushering in a synergistic hybrid approach. This combination expedites the quest for novel materials and optimization strategies, blending the rigor of scientific models with the adaptive capability of AI techniques. This synergy is poised to significantly reduce the time and resources conventionally required in the materials engineering domain, fostering a quicker transition from conceptualization to deployment. The examples illustrated in this article showcase the early tangible successes where a congruous integration can amplify the overall efficacy, and they also underscore the immense potential awaiting realization.

As we stand on the cusp of this juncture, the future beckons with the promise of accelerated advancements, rendering previously insurmountable challenges surmountable. The maturation of AI techniques, coupled with a growing understanding and adoption of a hybrid approach, could potentially redefine the landscape of materials engineering. The journey ahead, though laden with challenges, emanates a beacon of promise for a future where the synergy between AI and materials science catalyzes a new era of materials innovation, driving global progress in myriad applications.

### **Acknowledgement**

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*Materials concurrency has the potential to radically accelerate innovations in materials-intensive manufacturing.*

# Concurrent Design of Materials and Systems



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## Charles Kuehmann

Computational materials design and integrated computational materials engineering (ICME) have revolutionized new materials development, accelerating the introduction of new materials and expanding the scope of the materials engineering enterprise. Materials development timelines have been compressed from decades to as short as a few years, and the fundamental understanding and the systems engineering of materials have introduced robust and manufacturable solutions (NRC 2008). This leap was enabled by the deconstruction of the conventional materials tetrahedron into the systems engineering framework employing a linear process-structure-properties-performance concept (Kuehmann and Olson 2009; Olson 1997), as well as the development of modeling strategies to compute the process-structure and structure-property links the framework provides. Metals have led the way (Olson and Liu 2023) with well-developed examples (Kuehmann and Olson 1995), but polymers, ceramics, and composites are making strides, especially within the Materials Genome Initiative (MGI) (Office of Science and Technology Policy 2011).

In particular, NIST has championed progress across many broad classes of materials, as exemplified by the Center for Hierarchical Materials Design (CHIMaD), a Chicago-based consortium with efforts in thermoelectrics, polymers, and composites (de Pablo et al. 2019). However, computational materials design and development have continued to be relatively isolated endeavors, operating independently of engineering design and impacting new systems

only after the materials development process is largely complete.

While accelerated within the computational domain, the process of materials development has largely remained unchanged, progressing through stages of prototyping, scale-up, and qualification before being handed off to the design community for implementation. Traditionally, the barrier to the integration of materials development into hardware design and development existed due to the significant mismatch in the time scales of these activities. Hardware systems could be designed and iterated within a few years, and thus they could not wait for the introduction of a new material with advantageous new properties that might take ten to twenty years to reach the market while carrying significant risks (NRC 2008). The 2008 NRC study identified the need for ICME to accelerate the qualification and validation of computationally designed materials but also identified the technical gaps and benefits of integrating computational materials models into traditional engineering design and simulation tools utilized in product design. However, this by itself is insufficient to enable true concurrent engineering of materials and systems.

### **Concurrent Engineering and Computational Materials Engineering**

The systems engineering embedded in the computational materials engineering approach provides the connection of key materials properties to system-level performance and identifies the processing steps that determine cost and manufacturing complexity. Process-structure and structure-property models add the capability to employ fundamental relationships into the materials trades for candidate materials, allowing them to be included in the overall design strategy and solution. Further leverage is obtained by the inherent capacity of the approach to estimate the impact of process variability and stochastic property responses on the distribution of final properties (Xiong and Olson 2016). Because these distributions impact design choices, and minimum material properties are often controlling in design, the ability to predict them from fundamentals could accelerate the incorporation of new materials into designs, in the same manner that dynamic crash simulations have expedited new automotive structural design. Computational materials design and the validation and qualification framework that ICME provides compose the toolbox that enables concurrent materials and product design, but they are not the only requirements.

The design of any hardware system in the broadest sense is the selection of a set of design variables to satisfy a set of objectives. The objectives are delineated in a set of system requirements by which all proposed design solutions are measured. In most modern complex systems, the design problem is broken down into manageable subsystems, with design requirements established at the subsystem level to allow work to proceed on each without the need for much interaction across the whole. If this occurs within a new organization, such as a startup, teams can be organized around a logical classification driven by the design. The teams are generally small, and communication between them is fluid; thus design trades across teams are possible. Negotiation of requirements from one subsystem impacting another can be achieved, thereby ensuring a significant level of global optimization. In mature organizations, however, this becomes more difficult. Established department structures are not likely optimal for the new design challenge at hand, and thus the division of the problem into subsystems is driven by organizational history rather than the best engineering approach. This leads to suboptimal designs that reflect the organizational structure rather than an innovative solution borne of understanding the fundamentals and exploring creative solutions.

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***Computational materials design and development have continued to be relatively isolated endeavors, operating independently of engineering design and impacting new systems only after the materials development process is largely complete.***

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In the automotive sphere, for example, most established companies organize engineering teams around body, chassis, drivetrain, interiors, closures, electronics, and, increasingly, software. Unsurprisingly, automotive factories, or even tier 1 suppliers, are generally organized

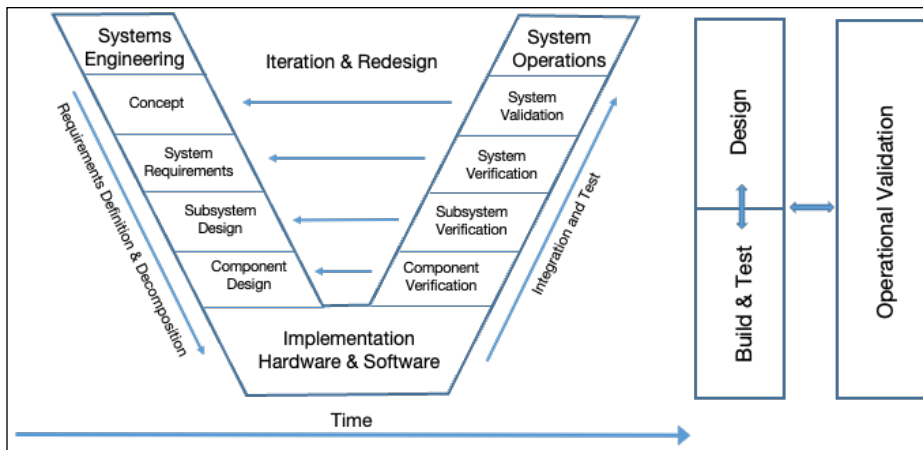


FIGURE 1 The traditional V&V process of development (adapted from Allouis et al. 2013) as compared to the concurrent build and test process with operational validation employed at SpaceX.

around similar scopes. Each of these divisions strives to optimize their specific scope based on relatively fixed requirements for their deliverable. As this situation has existed for many decades, the opportunity for significant and fast innovation is small.

Thus, in established industries, both the designs and the manufacturing method begin to be dictated by the organizational structure rather than the other way around. In addition, since communication is weakest across these boundaries, the product and the manufacturing system are also weakest across them. This organizational inertia results in design solutions that represent local optima and limits the opportunity for true innovation around a new global solution. This disruption is further heightened in the sphere of materials engineering, where traditional methods of development are far out of sync on a time basis with established product development timelines. Product design very rarely incorporates new materials as a design variable used in overall design trades, unless the new material has been fully developed prior to the design exercise. While computational materials design methods have now demonstrated that new materials for specific applications can be developed on timelines equivalent to product development efforts, historical organizational barriers mean few teams and engineers have the skills and experience to integrate new materials into the design landscape of their projects. This greatly limits the design space that can be considered when developing innovative design solutions. In addition, the lack of interaction between materials and product engineers restricts the scope of learning both groups experience. Concurrent

engineering of both materials and products creates the opportunity to drive better innovative solutions to problems but also creates better engineers to solve the future problems we will encounter.

To successfully execute concurrent materials and systems engineering, we also need a revolution in the building-block approach to systems engineering itself. The legacy of systems engineering, breaking down a design problem into subsystems and components and

integrating these into a sequential process of design, implementation, and verification, further slows and limits the ability to quickly execute on new design solutions (figure 1). In this model, a system is deconstructed into its subsystems and components, decomposing the requirements at each level before implementing it in hardware and software. Then validation is accomplished in reverse across components, subsystems, and finally the full system. This approach delays many failures until late in the process, and thus drives significant redesign, implementation, and test rework. Critically, by delaying this learning cycle until very late in the process, and since failure drives important learning, a traditional approach hampers the ability to use feedback early in the concept stage of design, where the most impact can be made. In a concurrent approach, design, build, and test are accomplished in sync with each other, where failures in both manufacturing and performance can be assessed readily and quickly and incorporated into better design solutions. Operational validation can also accelerate the pace of development of the hardware and its capabilities, further providing feedback quickly into the overall process. The operational envelope, if initially limited to let the hardware and design mature, can expand the operational characteristics to match a higher level of confidence as the full design goals are achieved. Operational validation is a gold standard, as validation testing often doesn't fully represent the operational environment, and if pushed late in the process, it risks costly and disruptive failures, as seen in the 737Max program (Sgobba 2019) and others.

## The Algorithm

Concurrent engineering, utilizing computational materials design and a development approach that integrates design, build, and test with early operational validation, is a powerful tool to accelerate development, but it is not sufficient to achieve breakthrough solutions. To create optimal solutions to technical challenges, it is absolutely necessary to avoid our inherent complexity bias. By a factor of 3 to 1, engineers will add complexity to a system when solving a problem, even when the deletion or simplification of components in the system is an equally valid path. As engineers, we want to create, making something that didn't exist previously. It seems antithetical to many engineers that the most important task in engineering may actually be to take something that exists and delete it. To achieve true innovation in design and combat this inherent complexity bias, it's critical to apply a five-step process as developed by Elon Musk and known internally to SpaceX and Tesla as the Algorithm.

### Step 1 – Question all requirements

The first step in any development program is the listing of requirements for the system. These elucidate the performance characteristics, attributes, regulations, costs, and other factors that must be considered in the design. The process typically tries to identify everything that could possibly constrain the system. This is exactly the drawback of defining too many requirements: it limits the ability to consider a wide range of solutions. Any constraint that isn't a real constraint will impact the design and limit its ability to achieve the most important objectives. And often, requirements that are carried over from previous programs, while sounding prudent, may not be applicable in the context of the current effort. To achieve the smallest set of applicable requirements, they must be: 1) Based on fundamentals (i.e., driven by physics), 2) Defended by a specific person. A constraint imposed by a group, agency, or committee has no one accountable for its applicability, and 3) Tied to a single metric for success of the project. If the requirement has no impact on ultimate success, it must be suspect.

### Step 2 – Delete the part or process

The first goal of an engineer should be to determine how the system can be successful without the part or process for which they are accountable. Any work to optimize, build, and test a part or process that ultimately is not needed is unnecessary work and leads to unintended negative consequences.

### Step 3 – Simplify

If the part or process cannot be deleted, it is important to make it as simple as possible. Remove as many characteristics as possible while still achieving a result that allows the system to be successful.

### Step 4 – Accelerate

Primarily for manufacturing and processes, faster is better. A process at high speed inherently requires simplicity and reduces cost. It also allows faster iteration, learning, and feedback into the development process. Slow processes result in a long lag between any changes and the ability to determine the impact on the design.

### Step 5 – Automate

As a last resort, automation can be used to solve an engineering problem. Automation can respond to variations in operational parameters and manufacturing conditions to achieve success, but at a significant cost in complexity.

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**To create optimal solutions  
to technical challenges,  
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complexity bias.**

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The steps in the Algorithm appear intuitive when viewed in sequence, but many examples exist where engineering solutions are pursued in the opposite sequence with negative results. Automation is applied to control a process that is sensitive to input variables, then sped up to account for high fallout from poor quality and subsequently simplified to make it easier to manufacture, before it is deleted in its entirety when it is discovered the requirements that drove the design of the part aren't valid. If the Algorithm is always employed in the right sequence, all this unnecessary work is avoided.

### Gigacastings: An Example

Extremely large structural castings (gigacastings) in automobiles have made significant strides in advancing the manufacturing of automotive structural bodies. These ultra-large castings provide a significant section of the body structure in a single component, significantly

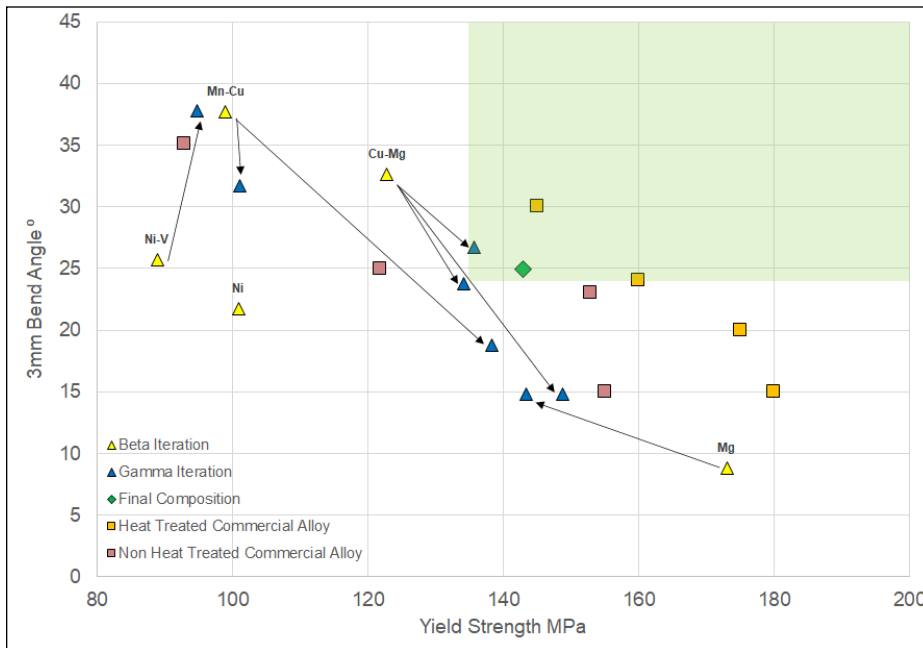


FIGURE 2 The primary property objective for un-heat-treated Al die casting alloys and the representative design box for the performance of structural automotive body applications (the square box in the upper right). While heat-treated alloys can easily meet these requirements, some un-heat-treated alloys can intersect the design criteria in the low left corner of the box (Stucki et al. 2023).

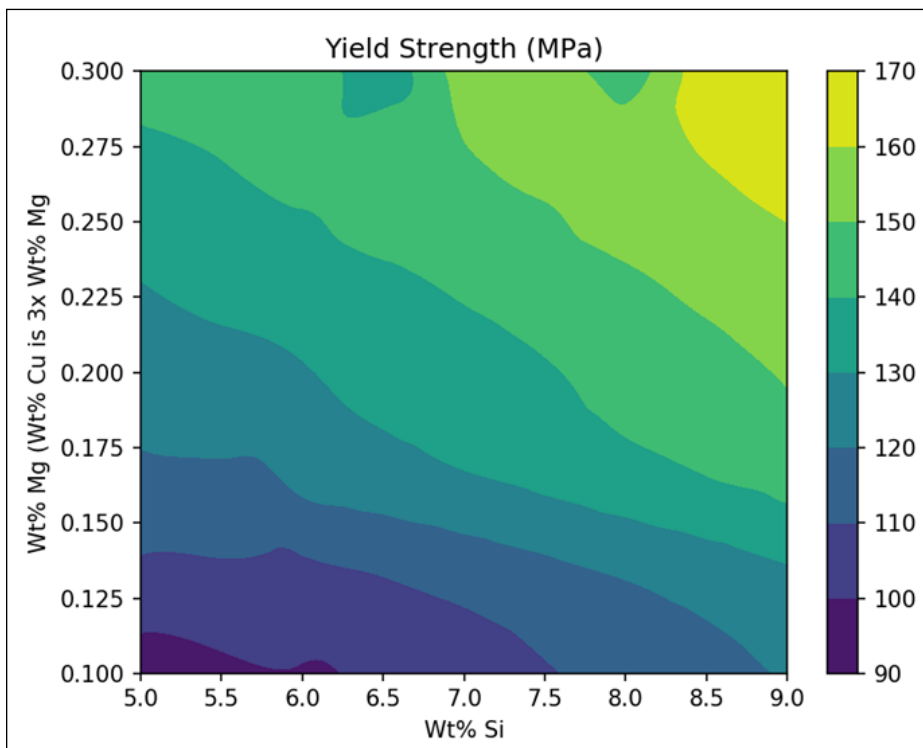


FIGURE 3 A computational alloy design model was employed to evaluate the influence of Mg, Cu (in a ratio of 3:1 with Mg), and Si content on the resulting yield strength of the die cast alloy. Along with other design considerations, this prediction allowed for the selection of promising alloy candidates that could meet the strength and ductility needed for large structural castings (Stucki et al. 2023).

lowering the cost, reducing weight, and simplifying the manufacturing complexity of vehicle structure. While high-pressure die castings have been used in car bodies previously, they have only been used for smaller nodes and backup structures due to their limited size, low ductility in crash events, and dimensional stability.

Employing the Algorithm for the development of gigacastings was essential to its success. In step one, requirements were challenged extensively to expand the functional capabilities of large castings. The current extent of the size of casting presses and dies was found to have no limitations based on fundamental physics, and thus large presses of more than 6000 tonnes were designed and commissioned. Existing structural aluminum high-pressure die-cast materials required post-casting heat treatment to achieve strength and ductility in structural applications (figure 2) but were not capable of meeting dimension tolerances after heat treating. Computational materials design methods expanded the strength and ductility envelope for non-heat-treated aluminum casting alloys, and creative part design, incorporating these new properties, allowed castings with up to two-meter flow lengths to be employed in the demanding components of vehicle crash structures (figure 3).

In step two of the Algorithm, the extent of

the casting was expanded iteratively by evaluating each part that was connected to the casting and determining if it could be incorporated into the casting with positive impacts on cost and performance while still maintaining manufacturability (figure 4).

In step three, the structure was further simplified by examining all the secondary attachments to the structure for interior components, harnesses, and other items. Attachment points that could be included in the casting were designed in, eliminating a clip, bolt, or other part and further reducing the part count. Quenching of the casting when ejected from the die was removed, further reducing distortion and eliminating a process step. Without heat treatment to burn off die lube, typically a cleaning process would be needed prior to the application of structural adhesives or e-coating of the car body. The development of a lube compatible with the structural adhesives and the e-coating process was accomplished, eliminating a secondary cleaning step. And finally, a large integrated structural casting would be difficult to repair in the case of a significant crash event, leading to a complex repair if even possible. Therefore, specific points in the casting were designed to allow the removal of the portion of the casting that absorbs crash energy, with a replacement service part then inserted to restore the structure. This significantly simplified post-crash repair.

In step four of the Algorithm, the casting process was significantly accelerated through the design of advanced cooling technologies within the die. Additive manufacturing allowed significant freedom in the design of the cooling loops in the die, and materials design for new additive and conventional die alloys has expanded their cooling characteristics while improving die life. Advanced but simple thermal backend systems allowed better control of flow and temperature conditions in the die.

Step five employed further automation in the process to reduce cycle time and control process variables. Metal delivery to the shot sleeve, application of die spray, and extraction of the part post-casting were all optimized and resulted in an over 60% reduction in cycle time of the process while improving yield.

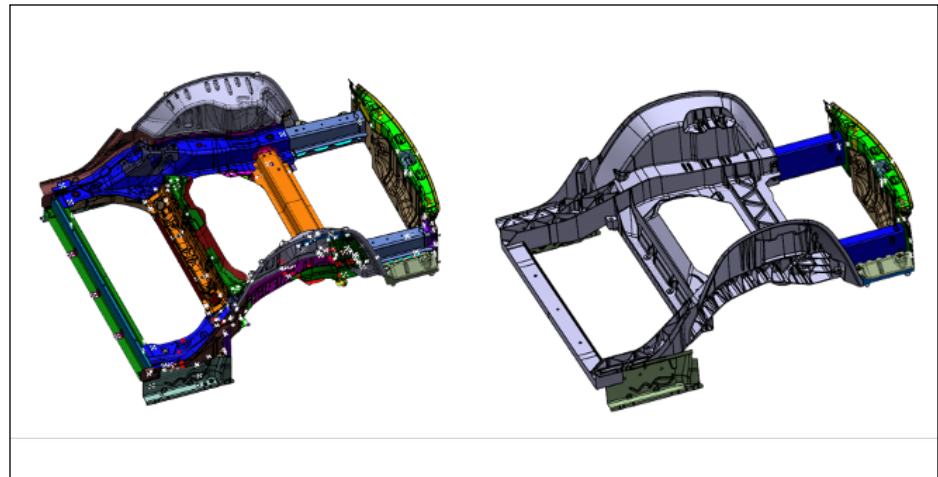


FIGURE 4 Comparison of a stamped rear underbody structure (left) in comparison to a structure incorporating a large structural aluminum casting (right). In the final design, over 80 parts were eliminated by adopting the cast structure design.

## Conclusions

Advances in computational materials design and their extension to ICME are essential to the concurrent design of systems and materials, opening new opportunities for engineering solutions to many challenging problems facing our society. In conjunction with a product development pathway that collapses design with build/test sequences, concurrent engineering of materials and systems can be achieved, accelerating the introduction of new innovations. The application of a design and manufacturing method called the Algorithm greatly streamlines the process of development, incorporating concurrent materials design and essentially determining not only what can be achieved but also what should be done to meet the ultimate objective. The benefits of doing so have been achieved in structural applications for metals but aren't inherently limited to them. Entrenched design processes and cultures, and even organizational structures, are significant barriers to achieving the accelerated feedback needed to allow concurrent engineering to succeed. Much work is still needed to expand the impact of concurrent design of materials and systems across wider sections of industry and materials classes, but the positive impact is clear.

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# An Interview with . . .

Andy Weir, *New York Times* bestselling author of *The Martian*, *Artemis*, *Project Hail Mary*, and *Cheshire Crossing*



**RONALD LATANISION (RML):** Today we are joined by technologist-writer Andy Weir. Andy, we're just delighted to have you with us.

**ANDY WEIR:** It's great to be here.

**RML:** To start, we'd love to hear about your upbringing, how you got into computer programming, and then how you transitioned from writing computer programs to writing science fiction novels.

**MR. WEIR:** I was born and raised in California. My father was a physicist and my mother was an electrical engineer, so I was pretty much doomed to be a nerd from the start. Although I should point out that my mom did the electrical engineering for the money. It wasn't her passion. My dad is genuinely a nerd. My mom is much more

into literature. I guess you could say that's how I came to be a half-literature, half-science nerd.

I grew up reading my father's science fiction collection. He had this bookshelf about six feet tall, three feet wide, and two feet deep that was jampacked full of paperbacks from his day. I grew up reading science fiction from the 50s and 60s. My holy trinity were Isaac Asimov, Robert Heinlein, and Arthur Clarke. That's the kind of work that colored me.

I've always been a space dork, but I also always wanted to be a writer. Even when I was a teenager, I was writing crappy short stories and stuff like that. And when the time came to go to college, I had to decide whether or not I wanted to go into creative writing or the fairly new field of computer science, because I'm that old.

I decided I liked regular meals, so I went into computer science. I attended UC San Diego's BS program for computer science for four years. And then I ran out of money and dropped out, so you are speaking to a high school graduate. That's my highest accreditation.

But at that time, in 1994, the software industry was just going crazy. They figured if you were clever enough to open the door, you were hired. I worked for various software companies. I enjoyed software and I liked writing programs and computer programming, in general. I'd been doing it since I was kid. I started on my little VIC-20 writing BASIC programs. Once I got into high school, I had an 8086 IBM computer with a 4 kHz processor, and I was writing C and assembly on that.

I worked for Sandia National Labs, which was a Department of Energy installation. They hired me as a sort of lab assistant. I was fifteen when they hired me.

**RML:** How did you manage to get hired at age fifteen? That's child labor, isn't it?

**MR. WEIR:** Well, there were child labor laws they had to follow. For instance, they weren't allowed to have me work more than twenty hours in a week. But it was a work experience program between my high school and the lab. I lived in Livermore, California, where the Lawrence Livermore Labs and Sandia National Labs employ the plurality of people.

Sandia did a lot of things with the community, one being a program where they'd hire teenagers with an interest in science to basically be lab assistants. That lab is actually where I started programming computers for real because they said, well, we don't really need a lab assistant. What we need is somebody to write software or to analyze the data that we're getting. So they gave me a book that said how to program in C, and there was a computer with a C compiler on it. They said, tell us when you've got that worked out, and then we'll tell you what we want you to make the computer do. And that's kind of where I got my start.

**RML:** How did you make the transition from computer programming to writing? Was it because of your interest in the novels that your dad had on his bookshelf?

**MR. WEIR:** I was always interested in both, I guess I would say. It's not like I suddenly became a writer. I was writing the whole time I was programming computers. I ended up being an engineer for twenty-five years total. But I was also always writing during that time: short stories, novels, web comics, et cetera. I posted them on my website once the internet became a thing. *The Martian* was just one of those things that I was writing, but it really took off. Once *The Martian* snowballed and became a book and a movie and everything, I found myself in a position where I could write full time. That's what I do now.

**KYLE GIPSON (KG):** Your journey is super fascinating, especially the fact that you were writing programs and fiction at the same time. Many people would think of writing programs and writing fiction as completely different, even as polar opposites. Are there ways that those two overlapped that might be surprising to people? For example, are there ways that your work in computer programming informed or inspired your writing?

**MR. WEIR:** Several ways. For starters, being a computer geek allowed me to write software to double check the math in my fiction. So all the orbital trajectories in *The Martian* are accurate. Also, while writing fiction, I do tons of spreadsheet work, because during my computer programming career I got pretty good at Excel. And working in computer programming gave me the technical skills to write very technically accurate prose.

Another thing is that my writing style is similar to my programming style. When I'm designing software, I come up with the top-level ideas: okay, we're going to have this class that does this, this class that does that, this layer that does this. I'll abstract that out and so on. While I'm

writing software, the code is when I go, okay, now we're going to get into the specifics of the design.

When I'm writing fiction it's pretty much the same thing. I have the top-level idea of the story, but it's while I'm actually writing the story that I come up with the detailed level. Oftentimes, same as in programming, when I'm implementing it, I realize there's a better way to do something, and then I delete what I've done and work on a different approach.

But I would say the main way that being an engineer has helped my writing is that I'm known for being extremely easy to work with. That's what you're used to as an engineer. I'm like, so here's a rev of the program, and then people say, well, here's like 150 bugs we found. You've got to fix them. Okay, I'll fix them. Here's the next round, and so on.

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## ***When you have an engineer's mindset and you enter the world of literature, you're used to turning in a project and then being given a list of bugs.***

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When you're working with people in the publishing world, and you give them your first draft and they give you a bunch of notes, the programmer mindset is to say, okay, I'll fix those bugs. And publishers are like, wow, that writer is really easy to deal with.

Because of my programming background, I also take deadlines very seriously. I'll admit, software engineers are not particularly famous for their people skills. But I never really had a problem with that. I really enjoy working on teams. In fact, that's what I miss the most about being a programmer. Writing is very solitary.

**RML:** You focus a lot of your writing, maybe most of it, on things related to space, lunar, Mars exploration, and survival. That must have taken a fair amount of homework on your part to be able to write a meaningful novel. *The Martian* is what I'm talking about, obviously. I've seen the movie twice.

**MR. WEIR:** Tons and tons of research, math, prep work, and so on. But that is the stuff that I enjoy, because being a space dork and geekery is my hobby. We're all good at doing the things that interest us. We're all knowledge-

able in our hobbies. If you're really into model railroads, you know all about model railroads. You know how to put together a landscape, you know how to make all the parts fit. If you really enjoy gardening, then you're going to know a lot about horticulture, even though you are not a professional. I'm really into space and space travel. I started off with much more than a layman's knowledge of those topics because it was my hobby, and I had enough knowledge that I knew how to google whatever I didn't know. And doing that research is fun for me. I really enjoy that stuff, so that's not even work at all. I really love the research and math parts of my books. It's that pesky writing that I have to do at some point that's unpleasant.

**RML:** But I mean, for example, I know that in *The Martian* you talk about producing water by essentially splitting hydrazine, using the catalyst iridium. How did you know that chemistry?

**MR. WEIR:** This is the fun part. When I'm doing my research is when I discover problems for Mark Watney (the protagonist of *The Martian*) that I didn't realize he would have. I didn't go into writing the novel with an idea of like, oh, he's going to need to make water. Initially, I was like, oh, well, this original mission was intended for six people, so it would definitely have some sort of water recycling system in play, and he wouldn't have a problem with drinkable water. But it was while I was researching that I discovered, okay, what do you need to make potatoes? You need, among other things, a certain minimum soil moisture percentage. I did the math on that, and I was like, wow, he's going to need like 600 liters of water, and there's no way they would have brought that much.

So he's going to be short on water. And I had to come up with a solution. How does he get the water? I scratched my head a bit. I started thinking, well, what does he have to work with? Bear in mind, I get to cheat a little bit because I'm the writer. So, I said, alright, I've decided that the Mars Descent Vehicle used hydrazine fuel, same



as the Apollo landers. And hydrazine fuel releases enormous amounts of hydrogen, so he can get some hydrogen from that. He gets the oxygen by just collecting CO<sub>2</sub> from Mars's atmosphere. But Mars's atmosphere is like 99 percent carbon dioxide, so he collects carbon dioxide from the atmosphere, runs that through the Hab's (the crew's manmade Martian habitat) oxygenator, which is made to turn exhaled carbon dioxide back into oxygen. He gets a bunch of oxygen that way and the hydrogen from the hydrazine, and he can mix them to make water.

That was an interesting little interlude in the book that I hadn't planned at all, which I included because of what I discovered while researching how to grow potatoes. Nobody would have given me any problems if I just hadn't had that scene at all. People would have said, okay, he brings soil in from outside and then he has potatoes. But I went down this whole rabbit hole of interesting problem solving.

**RML:** I'm just curious, what is NASA's reaction to that whole scenario? You need water to survive. The character in the book finds a means to survive by being clever enough to know that you could split hydrazine, and you could take the hydrogen and react it with oxygen to produce some water. Has NASA given any comments on that?

**MR. WEIR:** As an entity NASA didn't make an official comment on it, but many NASA engineers have talked to me about the book and how much they enjoyed it. Some

chemists pointed out, well, there were a few little issues here and there with that process. For starters, hydrazine is incredibly toxic. So being in an enclosed room with it would not be great for Mark. Second off, the process I describe by which he reduced the hydrazine to release the hydrogen is very exothermic, right? In fact, in the book, he has a little explosion while he's trying to do that. But, one guy did all the math and said, given the dimensions of the Hab, the internal pressure it has inside, et cetera, I can calculate how much the temperature inside the Hab would increase as a result of him doing this hydrazine reduction over the amount of time that you said he did it. And it would increase by like 300 degrees Celsius. He would have baked himself alive. I didn't know that. Had I known that at the time, I would say, well that's becoming a problem, so Mark turns off the heating elements so that the base is rapidly losing heat in Mars's extremely cold environment. There are ways that he could have done it. He could have reduced the hydrazine slower, and so on.

**RML:** The reason I'm so interested in hydrazine is that much of my work has been on water chemistry for nuclear power plants. And hydrazine is one of the chemicals that's often used in water chemistry control to remove oxygen. It's  $N_2H_4$ , a sort of ammonia derivative that has the effect of adjusting the pH and, at the same time, removing oxygen, so it's actually very useful in secondary water chemistry.

**KG:** One thing that I think is so fantastic about your work, speaking of *The Martian*, is that it can appeal to experts such as NASA engineers or Ron but also people like me, who have no idea about any of the science behind events in the book, but who find the experience of reading the book so enjoyable and the story utterly plausible. Going back to the research process, are you always trying to sort of track recent developments that you might incorporate into your science fiction?

**MR. WEIR:** Well, not compulsively, but that is an interest of mine. I'm always tracking recent developments in science because I'd like to hear about them. And sometimes they spur story ideas or subplot ideas.

**RML:** I'm curious, what will you work on next? You're obviously very interested in space travel. But what about AI and all the other evolving technologies?

**MR. WEIR:** I'm working on my next book now. AI plays a significant role in it. But I'm doing it my way, not writing a story about robots falling in love or anything. Writing a story that involves AI is kind of in my wheel-

house because I know how computers work. And I know more about machine learning than most fiction writers, I think. So yes, I'm having some fun with that. Although my writing process has been slowed down dramatically by the appearance of a child in my household who just keeps running around wanting my attention.

**RML:** That's wonderful! What is your general reaction to AI? It's evolving so quickly, at an almost-meteoric pace.

**MR. WEIR:** Yes. And there's a lot of doom-and-gloom talk about it. Or a lot of, oh my God, this is going to put so many people out of work. And I'm like, every new technology ends up putting a lot of people out of work. I think that AI will be no different. I think a lot of people are going to have these arguments like, oh, what about AIs that can now create art? The artists that they learn from—should those people get some sort of payment? I don't want to get a bunch of emails from angry artists, but I feel like human artists look at other artist's work to get better at what they do, and nobody expects the human to pay the artists who influenced them. Some comic book artist that was extremely influenced by Rob Liefeld doesn't have to then pay Rob Liefeld because he used Liefeld's works as a reference point for learning how to be a better artist, right? So why should AI technology be different? Well, because there's a limited number of humans on this planet, and it takes a long, long time to get really good at art. Whereas the AI art generator can generate entire work of bespoke art in a fraction of a second and on command. So it's going to affect a lot of things—in, for instance, advertising. Entities that need art and don't particularly care who it comes from or about the caliber or name recognition of the artist. It's going to be disruptive.

I also think people still dramatically underestimate how disruptive self-driving cars are going to be. And I mean disruptive in a good way. How much it's going to change our society. Something like fifteen to twenty percent of every major urban center is dedicated to parking. Imagine if that didn't have to be the case. Everything would get a little bit cheaper because there would be more real estate for other businesses to be in the city centers. Also, entire industries would disappear, like truck drivers and cabbies. But, at the same time, things would become cheaper. Goods being delivered across the country by truck will become cheaper. And probably about 50,000 people a year won't die from drunk driving accidents and other automobile accidents. Dying in a car crash will become as rare as dying in a plane crash. Also, it will start to become a question of, why should I own a car at all?

Why not just always use a car service? Some driverless car comes and picks me up and takes me where I need to go. I just type it into my phone.

And then you fast forward in time twenty or thirty years and the children of that era will be like, can you believe people used to have an entire huge room in their house dedicated to storing a car? A car you spent ninety-nine percent of your time not using? You spend most of your life not driving. But your garage is like 400 or 500 square feet of your house.

To get back to your question about AI, if you give me a hammer, I can build a house, or I can murder someone. The hammer itself is not the issue. It's the person who is using it. Someone could use AI to help cure cancer. Or someone could use AI to develop a custom virus that only attacks an ethnicity they don't like.




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***I consider all technology to be a tool. AI is no different. A tool is a tool. What matters is how people use it.***

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**RML:** To me, that's a good demonstration of the compromise we're dealing with in a technologically intense world. Just think about the internet. It was intended to be a platform to provide information throughout the globe. And it does that wonderfully well. But it's also been abused by people who wish to make it abusive by spewing misinformation.

**MR. WEIR:** I think the misinformation thing is overstated. I mean, yes, it's an issue, but I think the much worse stuff that people have misused the internet for is distributing child porn and scamming people. It used to be much harder to scam people before the internet.

Now they take advantage of elderly people. You can be in another country on the other side of the world scamming elderly Americans or Canadians. There's really no way of dealing with that within the legal system. A little bit of misinformation about a political party you don't like is the minor leagues compared to the bad things that happen on the internet.

That said, it's a tool. And I guess I'm a bit of a Pollyanna, but I think humanity is inherently good. For every one bad actor, there's 1000 good actors. Pick a technology that, overall, you feel has done more harm than good to humanity. Because it's very difficult to think of a technology that has done more harm than good. And the reason is because technology is a tool, and, I believe, humans are inherently good. And we have an inherent desire to, when you see a new tool, figure out how you can use that tool help people.

**RML:** I think that there's a very important message in what you're saying, Andy, and that is that science and technology should be used to help people.

**MR. WEIR:** It should be, absolutely. Try to name a technology that's done more harm than good. You say nuclear

bombs; I say nuclear power. How much coal dust is not in the air? How much pollution and emissions are not in the air because nuclear power plants exist? How many people did not die in coal mines over the past fifty years?

**RML:** How does a writer's mind work? How would you put what we've just been talking about into science fiction?

**MR. WEIR:** For starters, in science fiction, one of the most generic plots is to think of a new technology, then think of the bad actors and have them be the antagonists, and then have your protagonist out there trying to put a stop to them. You pick a technology and say, what could an organized group of bad people do with this technology? And what would the good people do to stop that?

In my stories, I tend to like person-versus-nature plots, where there is no bad guy. There are no bad actors at all. In *The Martian*, it's just all of humanity or a group of people working together to try to solve a problem, but there's no antagonist other than Mars. In *Project Hail Mary*, my latest book, a non-intelligent, monocellular pathogen is the main problem.

**RML:** And what is the origin of *Project Hail Mary*?

**MR. WEIR:** Well, it's kind of interesting. Between *The Martian* and *Artemus*, I had a contract to write a book for Random House. I was writing a book that was going to be called *Zhek*, and it was more of a soft science fiction book. At the time I started it I was like, this is going to be my magnum opus. *The Martian* is going to be seen as my entry into the world of literature. But this is going to be a book series consisting of five books, and it's going to be *Game of Thrones* level in terms of awesomeness.

I got 70,000 words into *Zhek*—for reference, *The Martian* is 100,000 words—and I realized it just wasn't good. The plot was too complicated. The characters were interesting, but everything was meandering around. I was still in the first act. I thought, this is going to be some giant 600-page tome that nobody wants to read.

I ended up bailing out of that project, asking Random House very nicely for an extension, and asking if I could write a completely different book instead. Then I went on to write *Artemus*. I'm really glad that I did.

But *Zhek* had in it a few really good ideas. It was like a big pile of garbage with a couple of diamonds in it. So I plucked those ideas out and I recycled them into *Project Hail Mary*, and one of them was mass-conversion-based fuel.

In *Project Hail Mary*, there is a technology called black matter, and what it does is absorb any electromagnetic radiation. That's why it's black, because it doesn't reflect anything. And it turns that energy into mass in the form of black matter. If

you had a little bit of black matter, you could get more and more. And then it could release that in the form of gamma rays whenever you wanted, and you could use that as propulsion because light can be used for propulsion if you have enough of it. And that's mass conversion as a fuel source. And I thought, that would be really cool. But what if modern-day people had this fuel? What if we invented black matter not in some distant, complicated future, but right now?

The first thing I thought was, wow, we could easily colonize the solar system. It's basically a perfect battery source. Life on Earth would get a lot better. Energy transportation would be easy. There would be no power grid issues. A developed nation like the United States could drop off a big package that could power a developing nation for years, their entire power grid. It would be a tremendous benefit.

And we could explore the solar system. We could colonize Mars, the Moon, everything, if we had this technology. But I didn't see any way that we could invent this technology in the modern day, and I didn't want to make the story take place like 300 years in the future because then I would have to explain all the shit that happened between now and then.

So how could I make this happen today? Alright, option number one: we find some black matter on an alien vessel or something that crashed on Earth millions of years ago. That might work. It's a little unsatisfying. It's sort of a bullshit way to introduce a technology. It's a trope, right? It's been done. What if scientists on Earth invent black matter? And I was like, even if I create a Dr. Emmett Brown-equivalent genius scientist, it's still too much for plausibility that one guy just comes up with this. And so I said, well, what if some black matter ended up in our solar system, not via an alien ship, but we just find some on the surface of a planet somewhere. We don't know where it comes from. Well, then everybody reading the book is going to want to know where it came from.

And I thought, what is black matter anyway? How does it even work? I was like, well, it takes energy and makes more of itself. That sounds like a lifeform. And I said, okay, what if I just make black matter a lifeform? It's a lifeform that collects enormous amounts of energy. Why? Because it's interstellar. It's basically mold that grows on the surface of stars and then spores out in all directions to try to reach other stars. It doesn't have an agenda or anything. It's literally just mold that spores. That's why it exists. That's why it has to store up so much energy, because it uses that light energy to travel from one star to another. Yes, I thought, this all makes sense. And let's say we acquired some of that and then we started using it as a fuel source. In the back

of my head I was like, oh, we'd have to make sure none of that got into the Sun because that would be disastrous. It would breed out of control. I thought, that's the story. The shit just shows up in our solar system, and it's breeding out of control on the Sun, and now humanity is like, well, what do we do now? And so that's how I stumbled into that plot – bit by bit, thinking about the details of *Astrophage*, which is the name of the star-eating bacteria.

**RML:** How do you plan your day when you're working? Do you work late at night or do you get up early and work in the morning? And what's your typical work schedule when you're writing?

**MR. WEIR:** Lately, it's very chaotic because of the toddler. But on a typical workday I get up in the morning and, after I've had my breakfast, I'll generally spend the morning hours dealing with non-writing work-related things, like answering fan mail. I always have multiple deals kind of floating in the air. So I answer email. I write work-related emails to my agent, my film agent, or emails directly to companies or about scheduling. I don't have a personal assistant or anything, so it's all just me. In the morning I'll do my maintenance work. And also research. I'll do some of that.

After lunch is when I try to do my writing. And when I'm working on a first draft, when I'm really nose to the grindstone, I give myself an objective of 1000 words per day into the draft. And I kind of self-enforce that by giving myself a list of things that I cannot do until I've achieved my word count. For example, I'm an amateur wood worker and metal machinist. That's one of my hobbies. I've got a workshop for all that. I am not allowed to do any of that fun stuff until I've written my words for the day.

I'm also not allowed to watch any form of video entertainment, no YouTube, no movies, no TV. And I'm not allowed to go to certain websites where I just zone out and waste my time. That sort of thing.

**KG:** To shift gears a little, *The Martian* was turned into a movie, which Ron and I are big fans of, starring Matt Damon. And, as I understand it, *Project Hail Mary* is slated to be turned into a movie starring Ryan Gosling. I'm wondering, what's it like seeing a book you wrote turned into a movie? What are some things you are hoping a movie gets right or that you're thinking about when a movie that's based on your book is made and goes out into the world?

**MR. WEIR:** Well, it depends on what role you have to play in the movie production. For *The Martian*, they just bought the rights and said, bye-bye. So my only job was to cash the check. I didn't have a say in anything. They chose to include me to get my input, but it was nonbinding.

They also used me as a technical expert. For instance, they'd say, could Mark Watney do this on the surface of Mars? And I'd say, no, that wouldn't work, but he could do this instead. I was consulted as a kind of advisor. But they definitely didn't have to pay attention to anything I said.

This meant that I got to read the screenplay in advance, so nothing was really a surprise to me. *The Martian* was also a very true adaptation. It follows the book very closely. There's a lot that got cut because the movie would be six hours long if everything that happened in the book happened in the movie. But the stuff that they cut is stuff that I would have cut if it had been up to me.

*Project Hail Mary* is a different matter. I'm actually a producer on that. The reason I'm a producer on it is because, when I put the rights up for sale, the book was selling very well. There was already one movie based on a book I wrote that made a lot of money, so studios were very interested.

And so, this time, I said that I wanted gross participation, which means I want a percentage of the money that the movie makes. Most of the studios said, we don't do that for writers. MGM said we don't do that for writers, but we do it for producers. We'll make you a producer so we can give you what you want, and we can get the rights to your book. And I said, that sounds great. I'll stay out of the way of the real producers who actually know what they're doing. So I am technically a producer on the movie based on *Project Hail Mary*, which means they had to get my approval to cast Ryan Gosling, which is funny. I was like, yes! So this time I do have a little bit of sway. I've seen the screenplays. They look very good to me. I'm pretty excited about how this is going to go.

**KG:** Is there a projected release date for the movie based on *Project Hail Mary*, or is that still up in the air?

**MR. WEIR:** The release of the *Project Hail Mary* movie will probably depend a lot on the 2025 movie season. Supposedly, we're going to start shooting in June of this year, so I would expect the movie to come out in 2025. When exactly it comes out will depend on what other films are coming out and when.

**KG:** That's very exciting.

**MR. WEIR:** It's pretty cool.

**RML:** I think has been a wonderful discussion, and I've enjoyed this tremendously. I can't thank you enough for joining us today.

**MR. WEIR:** Thanks for having me.

# NAE News and Notes

## Class of 2024 Elected

The National Academy of Engineering (NAE) has elected 114 new members and 21 international members. This brings the total US membership to 2,310 and the number of international members to 332.

Election to the National Academy of Engineering is among the highest professional distinctions accorded to an engineer. Academy membership honors those who have made outstanding contributions to “engineering research, practice, or education, including, where appropriate, significant contributions to the engineering literature” and to “the pioneering of new and developing fields of technology, making major advancements in traditional fields of engineering, or developing/implementing innovative approaches to engineering education.” Election of new NAE members is the culmination of a yearlong process. The ballot is set in December, and the final vote for membership occurs during January.

Individuals in the newly elected class will be formally inducted during the NAE’s annual meeting on September 29, 2024. A list of the new members and international members follows, with their primary affiliations at the time of election and a brief statement of their principal engineering accomplishments.

### New Members

**Nancy Lynn Allbritton**, Frank and Julie Jungers Endowed Dean, College of Engineering, University of Washington, Seattle. For innovation and commercialization of single-cell, analytical, and gut-on-chip technolo-

gies for drug screening and for engineering education.

**Martha C. Anderson**, research physical scientist, Agricultural Research Service, US Department of Agriculture, Beltsville, MD. For application of thermal satellite remote sensing in hydrology.

**Marc A. Baldo**, Dugald C. Jackson Professor in Electrical Engineering, Massachusetts Institute of Technology, Cambridge. For efficient light-emitting diodes for the modern display industry.

**Christian L. Belady**, distinguished engineer and vice president, Datacenter Advanced Development, Microsoft, Mercer Island, WA. For delivery of energy-efficient data centers and metrics to characterize their power utilization efficiency.

**Glenn R. Bell**, research civil engineer, Materials and Structural Systems Division, National Institute of Standards and Technology, Acton, MA. For creativity in building design, advancing forensic engineering, and innovation in engineering education.

**Carolyn R. Bertozzi**, professor of chemistry and T.Z. and Irmgard Chu Distinguished Professor of Chemistry, Stanford University, Stanford, CA. For engineering tools using bio-orthogonal chemistry for novel biomaterials, diagnostics, and drug delivery systems.

**Irene J. Beyerlein**, Mehrabian Interdisciplinary Professor, College of Engineering, University of California, Santa Barbara. For methodologies predicting the mechanics of complex engineering materials to improve their stability and strength.

**Alexandria B. Boehm**, professor and senior fellow, Civil and Environmental Engineering, Stanford University, Stanford, CA. For advances to protect public health from environmentally transmitted infectious disease.

**Shailendra V. Bordawekar**, vice president, Small Molecule Chemistry, Manufacturing and Controls Development, AbbVie Inc., Gurnee, IL. For leadership in the pharmaceutical industry, developing life-saving medicines, influencing regulations, and advocating for women in engineering.

**John R. Brophy**, engineering fellow, NASA Jet Propulsion Laboratory, Pasadena, CA. For technical leadership in development and flight implementation of electric propulsion in spacecraft systems.

**Jacopo Buongiorno**, Tokyo Electric Power Company Professor in Nuclear Engineering and director, Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge. For nuclear reactor safety, advanced nuclear power development, and community outreach.

**Hsiao-hua K. Burke**, principal staff, Air, Missile, and Maritime Defense Technology, MIT Lincoln Laboratory, Lexington, MA. For technology and leadership in remote sensing techniques and systems for ballistic missile defense and space systems.

**Pascale Carayon**, Leon and Elizabeth Janssen Professor, College of Engineering, University of Wisconsin, Madison. For application of human factors engineering

to health care systems to improve patient safety.

**Babu R. Chalamala**, senior scientist, Grid Modernization and Energy Storage, Sandia National Laboratories, Albuquerque, NM. For advancement of battery storage systems.

**Surajit Chaudhuri**, distinguished scientist, data systems, Microsoft Research, Redmond, WA. For automated database system tuning, database query optimization, and data cleaning.

**Jingguang Chen**, Thayer Lindsley Professor of Chemical Engineering, Columbia University, New York City. For discovering new catalysts and synchrotron techniques to connect catalytic and electrocatalytic mechanisms under reaction conditions.

**Zhangxing John Chen**, Natural Sciences and Engineering Research Council Energy Simulation Industrial Research Chair and professor, Chemical and Petroleum Engineering, University of Calgary, Canada. For modeling and simulation techniques for the recovery of hydrocarbon resources.

**Noel Thomas Clemens**, Clare Cockrell Williams Centennial Chair in Engineering, Aerospace Engineering and Engineering Mechanics, University of Texas, Austin. For laser-based measurements to understand and control high-speed reactive and nonreactive flows.

**Theodore Colbert III**, president and chief executive officer, Defense, Space, and Security, Boeing Co., Arlington, VA. For engineering leadership in advanced commercial and military air and space platforms.

**Antonio J. Conejo**, professor, Integrated Systems Engineering, The Ohio State University, Columbus. For power systems planning and electricity markets.

**Rory A. Cooper**, Distinguished Professor of Rehabilitation Science and Technology, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, PA. For wheelchair innovations that transformed the health, mobility, and inclusion of people with disabilities and older adults.

**Jingrong Jean Cui**, co-founder, president, and CEO, BlossomHill Therapeutics Inc., San Diego. For innovation of new medicines to fight cancers and solve urgent medical needs.

**Ruth S. DeFries**, professor, Department of Ecology, Evolution, and Environmental Biology, Columbia University, New York City. For elucidating anthropogenic land-use change impacts on environmental sustainability, and for providing science for policy decisions.

**Tejal A. Desai**, Sorensen Family Dean, School of Engineering, Brown University, Providence, RI. For nanofabricated materials to control biologics delivery, and leadership in the fields of nanotechnology and regenerative medicine.

**Dariush Divsalar**, principal scientist and JPL Fellow, NASA Jet Propulsion Laboratory, Pasadena, CA. For theory and practice of channel codes that impact deep-space communications.

**Elaine Jay Dorward-King**, independent non-executive director, Sibanye-Stillwater, Park City, UT. For promoting safety, biodiversity, sustainability, health, and environmental responsibility in the mining industry.

**Carolyn Duran**, senior director, Product Integrity, Apple Inc., Cupertino, CA. For holistic materials innovations in semiconductor manufacturing.

**Donald O. Dusenberry**, consulting principal (retired), Engineering Mechanics Division, Simpson Gumpertz & Heger Inc., Wakefield, MA. For national structural design load standards, and for standards covering blast, fire, and progressive collapse.

**Shanhui Fan**, Joseph and Hon Mai Goodman Professor of the School of Engineering, Electrical Engineering, Stanford University, Stanford, CA. For showing that “the coldness of space” relative to Earth can be a major energy source for humankind.

**Bruce Behruz Fardanesh**, vice president, System Planning and Analysis, The New York Power Authority, White Plains. For flexible operation and control of large-scale power systems.

**Gerhard Fettweis**, Vodafone Chair for Mobile Communications Systems and professor, Electrical and Computer Engineering, Technical University of Dresden, Germany. For wireless network innovations and entrepreneurship.

**Catherine E. French**, CSE Distinguished Professor, Civil, Environmental, and Geo-Engineering, University of Minnesota, Minneapolis. For design, safety, and construction of structural concrete buildings and bridges.

**Rong Fu**, director, Joint Institute for Regional Earth System Science and Engineering, University of California, Los Angeles. For methodologies that use satellite remote sensing to characterize and predict precipitation over land.

**Salvador García Muñoz**, executive director, Process Modeling and Simulation - Small Molecule Product Development, Eli Lilly and Co., Indianapolis. For modeling and data analysis for development of manufac-

turing processes for pharmaceutical products.

**James E. Gebhardt**, senior engineer (retired), FLSmith & Co., Salt Lake City, UT. For transforming mineral processing operations with online measurements, electrochemical sulfide flotation, and hydrometallurgical models.

**Dario Gil**, senior vice president and director of research, IBM Research, IBM, Yorktown Heights, NY. For advancement and practical use of artificial intelligence and quantum computing in industry and society.

**James R. Gosler**, senior fellow, Applied Physics Laboratory, Johns Hopkins University, Laurel, MD. For national leadership in cyber and information security.

**Martha R. Grabowski**, McDevitt Distinguished Chair in Information Systems, information systems program director, and professor of information systems, Madden College of Business and Economics, Le Moyne College, Syracuse, NY. For engineering information systems that promote transportation safety and for national leadership in marine transportation policy.

**Patrick R. Gruber**, chief executive officer and director, Gevo Inc., Englewood, CO. For renewable resource-based chemicals, plastics, and fuels, demonstrated by scalable, economically viable processes.

**John M. Guerra**, president and CEO, Nanoptek Corp., Concord, MA. For inventing and commercializing nano-optics to advance super-resolution microscopy and produce hydrogen directly with sunlight.

**Carlos Ernesto Guestrin**, professor, Computer Science, Stanford University, Stanford, CA. For scalable systems and algorithms enabling the broad application of machine learning in science and industry.

**Ashraf Habibullah**, founder, president, and CEO, Computers and Structures Inc., Walnut Creek, CA. For structural engineering software for use by engineers globally and for advocacy of the engineering profession.

**Kiruba Sivasubramaniam Haran**, Grainger Endowed Director's Chair Professor and director of the Grainger Center for Electric Machinery and Electromechanics, Electrical and Computer Engineering, University of Illinois, Urbana-Champaign. For high-power density electric and superconducting machinery technology and innovations in aircraft electric propulsion.

**Peter Hart**, founder and chairman emeritus, Ricoh Innovations Inc., Cupertino, CA. For pattern classification, information theory, computer vision, and robotics.

**Dennis Wayne Henneke**, consulting engineer, Probabilistic Risk Assessment, GE Hitachi Nuclear Energy, Wilmington, NC. For applying probabilistic risk assessment to enhance nuclear reactor safety.

**Mark Hersam**, Walter P. Murphy Professor of Materials Science and Engineering, Northwestern University, Evanston, IL. For the synthesis, purification, functionalization, and application of low-dimensional nanoelectronic materials.

**Vicki A. Hollub**, president and chief executive officer, Occidental Petroleum Corp., Houston. For leadership in energy company management and advocating for carbon management solutions.

**Arpad Horvath**, Lawrence E. Peirano Professor of Civil and Environmental Engineering, University of California, Berkeley. For environmental life cycle assessment of infrastructure systems.

**Jen-Hsun Huang**, co-founder, president, and chief executive officer, Nvidia Corp., Santa Clara, CA. For high-powered graphics processing units, fueling the artificial intelligence revolution.

**Charles Johnson-Bey**, senior vice president, Booz Allen Hamilton, Perry Hall, MD. For development of engineering innovations in support of national security.

**Farhad Khosravi**, chairman and CEO, Imperative Care Inc., Campbell, CA. For revolutionary ophthalmic, cardiovascular, and neurovascular interventions.

**Rob Knight**, professor, Pediatrics, Computer Science and Engineering, University of California, San Diego. For understanding microbiomes and their application to health-care and sustainability.

**Eugene Francis Kranz**, director (retired), Mission Operations, NASA Johnson Space Center, Dickinson, TX. For establishing the principles and mission control procedures for manned spaceflight operations.

**Sonia L. Kreidenweis**, University Distinguished Professor, Atmospheric Science, Colorado State University, Fort Collins. For elucidating the impact of aerosols on climate, linking chemical composition and cloud formation capacity.

**Kei May Lau**, chair professor, School of Engineering, The Hong Kong University of Science and Technology, Kowloon. For photonics and electronics based on III-V semiconductors on silicon.

**Eugene Lavretsky**, principal senior technical fellow, Boeing Research & Technology, Boeing Co., Los Angeles. For application of optimal and adaptive control theory to commercial and military aircraft systems.

**Chunqing Liu**, R&D senior fellow and senior manager, Green H2

Growth Vector Group, Honeywell, Des Plaines, IL. For polymer and membrane innovations for cost-effective natural gas and green hydrogen production and use.

**K.J. Ray Liu**, founder, chairman, and CTO, Origin AI, Rockville, MD. For signal processing for wireless sensing with communications.

**Bret Lizundia**, principal, Rutherford + Chekene, San Francisco. For seismic design through applied research, innovative practice, earthquake reconnaissance, and building code development.

**Timothy P. Lodge**, Regents Professor, Chemical Engineering and Materials Science, University of Minnesota, Minneapolis. For contributions to the understanding of the dynamic properties of multicomponent polymers and self-assembled structures.

**Michael K. Loose**, deputy chief of naval operations (retired), US Navy, Vienna, VA. For the planning, execution, and operation of worldwide capital asset programs to serve national security.

**Gargi Maheshwari**, vice president, Biologics Development, Bristol Myers Squibb, Blue Bell, PA. For industrial bioprocessing, leading to licensure of biologics and vaccines for human health.

**Pamela Gail Marrone**, co-founder and executive chair, Invasive Species Corp. and Invasive Species Research Institute, Davis, CA. For sustainable bioprotection products for agriculture and the environment.

**Duane K. Miller**, manager of engineering services and welding design consultant, Lincoln Electric Co., Middlefield, OH. For design, fabrication, and performance of welded structural steel connections and for contributions to welding education.

**Nicholas Wright Miller**, principal, HickoryLedge LLC, Delmar, NY. For reliable integration of wind and solar plants into electric power systems.

**Paul Christopher Damian Milly**, research hydrologist, US Geological Survey, Princeton, NJ. For advances in the understanding of global and continental hydrology and their interactions with a changing climate.

**Patricia L. Mokhtarian**, Clifford and William Greene Jr. Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta. For improved transportation systems planning and practice through quantifying human behavior.

**George Michael Morris**, founder and CEO (retired), Apollo Optical Systems LLC, West Henrietta, NY. For nanophotonic optical filters, super-resolution imaging, laser metrology and optical storage.

**Pandurang Nayak**, vice president of Search, Google LLC, Mountain View, CA. For web search ranking technology.

**Tina M. Nenoff**, senior scientist, Material, Physical, and Chemical Sciences, Sandia National Laboratories, Albuquerque, NM. For translating fundamental understanding of nanoporous materials into applications with societal and national security impact.

**Melissa E. Orme**, vice president, Additive Manufacturing, Boeing Co., El Segundo, CA. For industrialization of additive manufacturing for aerospace applications and research advancing 3D printing.

**Umit S. Ozkan**, distinguished university professor and distinguished professor of engineering, William G. Lowrie Department of Chemical and Biomolecular Engineering, The Ohio State University, Columbus. For research in electrocatalysis and

elucidation of mechanisms of oxidation catalysis.

**Sethuraman Panchanathan**, director, National Science Foundation, Alexandria, VA. For multimedia computing for assistive and rehabilitative applications and for leadership at the institutional and national levels.

**George J. Pappas**, UPS Foundation Professor and chair, Electrical and Systems Engineering, University of Pennsylvania, Philadelphia. For analysis, synthesis, and control of safety-critical cyber-physical systems.

**Seth L. Pearlman**, chief executive officer, Menard USA, Carnegie, PA. For ground improvement technologies, geotechnical design, and geotechnical construction techniques.

**Larry F. Pellett**, vice president, Special Programs, Lockheed Martin Corp., Palmdale, CA. For engineering development, transition, and operation of airborne system technologies for national security.

**Ravi Prasher**, chief technology officer, Bloom Energy, San Jose, CA. For development of thermal management technologies for microelectronics and the decarbonization of thermal energy systems.

**Robert K. Prud'homme**, professor emeritus of chemical and biological engineering, Chemical and Biological Engineering, Princeton University, Princeton, NJ. For mass manufacture of SARS-CoV-2 vaccines and other applications to improve human health.

**Peter J. Pupalaikis**, founding member and director of signal integrity, Nubis Communications, Ramsey, NJ. For digital signal processing for test and measurement instruments.

**Jeffery J. Puschell**, engineer, Northrop Grumman Corp., El Segundo, CA. For development of

optical, multispectral, and hyperspectral space-based remote sensing systems for Earth observation.

**Gamal Refai-Ahmed**, senior fellow and chief thermo-mechanical architect, Advanced Micro Devices Inc., San Jose, CA. For development of thermal-mechanical technologies for the thermal management of microelectronics.

**Maureen Fahey Reitman**, group vice president and principal engineer, Polymer Science and Materials Chemistry, Exponent Inc., Natick, MA. For understanding the selection, performance, and durability of polymeric materials in consumer, medical, and industrial applications.

**John Michael Richardson**, consultant, Briny Deep LLC, Alexandria, VA. For leadership in nuclear power and submarine engineering advances and national security.

**Susan D. Richardson**, Arthur Sease Williams Professor of Chemistry, Chemistry and Biochemistry, University of South Carolina, Columbia. For methods to measure disinfection byproducts and other contaminants in water and advancing their use in treatment and risk assessment.

**Jorge J. Rocca**, University Distinguished Professor, Electrical and Computer Engineering, Colorado State University, Fort Collins. For soft X-ray lasers and their applications to photolithography, microscopy, and chemical analysis.

**M. Taher A. Saif**, Edward William and Jane Marr Gutgsell Professor, Mechanical Science and Engineering, University of Illinois, Urbana-Champaign. For characterizing mechanical properties of materials at small scales, with applications in materials science and biology.

**Christine E. Schmidt**, distinguished professor and J. Crayton

Pruitt Family Endowed Chair, J. Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, Gainesville. For biomaterials and tissue engineering for neural regeneration and improved wound healing and for leadership in diversifying bioengineering.

**Jill E. Seebergh**, principal senior technical fellow, Boeing Research & Technology, Boeing Co., Seattle. For materials and coating processes that enable efficient and sustainable aircraft production, performance, and safety.

**David S. Sholl**, director, Transformational Decarbonization Initiative, Oak Ridge National Laboratory, Oak Ridge, TN. For addressing large-scale chemical separation challenges, including carbon dioxide capture, using quantitative materials modeling.

**Raj N. Singh**, Regents Professor of Materials Science and Engineering, Materials Science and Engineering, Oklahoma State University, Stillwater. For the science and technology of manufacturing fiber-reinforced ceramic matrix composites leading to their applications and commercialization.

**Metin Sitti**, president, Koç University, Stuttgart, Germany. For bio-inspired adhesives and small-scale mobile robotics.

**Matthias Steffen**, IBM Fellow and chief quantum architect, Quantum Computing, IBM, Yorktown Heights, NY. For quantum computing systems, from demonstration of Shor's algorithm to the first deployment of publicly available quantum computers.

**Jonathan P. Stewart**, professor, Civil and Environmental Engineering, University of California, Los Angeles. For improved understanding of soil-structure interaction,

earthquake ground motions, site response, and soil liquefaction.

**Ion Stoica**, professor, Electrical Engineering and Computer Sciences, University of California, Berkeley. For networked systems for large-scale data processing, analytics, and machine learning.

**Jose E. Tabora**, senior scientific director, Chemical Process Development, Bristol Myers Squibb, Princeton, NJ. For pharmaceutical process development through innovations in modeling, design of experiments, and data analysis.

**Charles A. Taylor Jr.**, founder and chief scientific officer, HeartFlow Inc., Mountain View, CA. For patient-specific computer modeling of blood flow and the noninvasive diagnosis of heart disease.

**Cristina Urdaneta Thomas**, 3M Global R&D Services Leader (retired), 3M Co., Stillwater, MN. For innovation, commercialization, and leadership in using polymeric materials for energy savings and traffic safety, and to ensure worker well-being.

**Dawn M. Tilbury**, Ronald D. and Regina C. McNeil Department Chair of Robotics and professor of robotics, University of Michigan, Ann Arbor. For advances in manufacturing network control and human-robot interaction and for engineering leadership.

**Hye Kyung Timken**, principal scientist and Chevron Fellow, Chevron Technical Center, Richmond, CA. For environmentally friendly processes for producing hydrocarbon fuels.

**James M. Tour**, T.T. and W.F. Chao Professor of Chemistry, Rice University, Houston. For synthesis, fabrication, properties, applications, and commercialization of novel forms of carbon and their composites and derivatives.

**Sven Treitel**, chief scientist, TriDekon Inc., Tulsa, OK. For the foundations of digital seismic exploration, for developing its applications, and for inspiring three generations of geoscientists.

**Bruce J. Tromberg**, director, National Institute of Biomedical Imaging and Bioengineering, National Institutes of Health, Bethesda, MD. For US diagnostics innovation initiatives, resulting in advanced SARS-CoV-2 testing capacity and performance.

**Rien van Genuchten**, associate scientist, Center for Environmental Studies, São Paulo State University, Rio de Janeiro, Brazil. For contributions to experimental analysis and modeling of flow and transport in saturated and unsaturated soil.

**Peter J. Vickery**, consultant, Peter J. Vickery Consulting PLLC, Raleigh, NC. For establishing hurricane risk in national standards, and modeling hurricane losses.

**Steven D. Weiner**, chief engineer (retired), Sikorsky Aircraft Corp., Lockheed Martin Corp., Orange, CT. For development and fielding of advanced high-speed VTOL aircraft.

**Scott Willoughby**, vice president and Northrop Grumman Aeronautics Systems Program Manager, James Webb Space Telescope Program, Northrop Grumman Corp., Redondo Beach, CA. For engineering leadership enabling the deployment of the James Webb Space Telescope.

**Jeannette M. Wing**, executive vice president for research, Columbia University, New York City. For formulation and advocacy of computational thinking, and for contributions to formal methods and trustworthy computing.

**Jack Harriman Winters**, fellow and principal member, Advanced

Radar Architecture, Lockheed Martin Corp., Middletown, NJ. For communications and signal processing techniques for multi-antenna wireless networks.

**Daniel Christopher Worledge**, distinguished research scientist and senior manager, Magnetic Random Access Memory, IBM, San Jose, CA. For development of magnetic random-access memory materials, devices, and technologies.

**Stephen J. Wright**, George B. Dantzig Professor of Computer Sciences, Computer Sciences, University of Wisconsin, Madison. For theory and design of optimization algorithms and their application in signal processing and machine learning.

**Tien H. Wu**, chief executive officer, Advanced Semiconductor Engineering Inc., Kaohsiung, Taiwan. For sustainable electronics manufacturing and advancements in the high-volume production of semiconductor packaging.

**Z. Cedric Xia**, distinguished engineer and director, Hardware Engineering, Apple Inc., Cupertino, CA. For advanced forming technologies in automotive and electronic products.

**Caroline Melkonian Ylitalo**, division scientist, Personal Safety Division, 3M Co., Maplewood, MN. For development of personal safety products, including for N95 respirators used during the pandemic.

**Howard Allan Zebker**, professor of electrical engineering and of geophysics, Electrical Engineering, Stanford University, Stanford, CA. For developing radar interferometry for space-borne sensors that measure meter-scale topography and millimeter-scale surface deformation.

## New International Members

**Marco Amabili**, professor, Mechanical Engineering, McGill University, Montreal, Canada. For dynamic analyses and fluid-structure interaction studies of composite plates and shells.

**Stephane Bancel**, chief executive officer, Moderna Inc., Cambridge, MA. For development and manufacturing of pharmaceutical products, including the COVID-19 vaccine.

**Pierre Bornard**, senior consultant, Counsel in Energy, BSDE Associates, Saint-Cyr-Sur-Mer, France. For control and protection technologies and structuring of electricity markets.

**Wonyong Choi**, director and distinguished professor, Institute for Environmental and Climate Technology, Korea Institute of Energy Technology, Naju, South Korea. For solar-based photoelectrocatalysis for water and air treatment.

**Anthony George Constantinides**, emeritus professor, Electrical and Electronic Engineering, Imperial College London, London, United Kingdom. For advancing digital signal processing and its applications.

**Juan Carlos De La Llera**, professor, Structural and Geotechnical Engineering, Pontificia Universidad Católica de Chile, Santiago, Chile. For contributions to seismic isolation and energy dissipation for improved earthquake performance and safety.

**Georgia Destouni**, professor, Physical Geography, Stockholm University, Stockholm, Sweden. For understanding anthropogenic and climate-driven shifts in Earth's freshwaters and for sustained community service.

**Alberto Guadagnini**, professor of hydraulic and water engineering and vice rector for research, Politecnico di Milano, Milan, Italy. For advances in stochastic hydrogeology and con-

taminant transport in subsurface aquifers leading to improved water supply and quality.

**Yidong Huang**, professor, Electronic Engineering, Tsinghua University, Beijing, China. For photonic sources and imagers and their translation to industry.

**Taeghwan Hyeon**, distinguished professor, School of Chemical and Biological Engineering, Seoul National University, Seoul, South Korea. For scalable synthesis of precisely controlled nanoparticles and design of inorganic nano-biomaterials.

**Tobias J. Kippenberg**, professor, Laboratory of Photonics and Quantum Measurements, Swiss Federal Institute of Technology Lausanne, Lausanne, Switzerland. For development and commercialization of chip-scale optical frequency combs.

**Alison Emslie Lewis**, dean, Faculty of Engineering and the Built Environment, University of Cape Town, Cape Town, South Africa. For contributions to crystallization processes for saline water treatment and

extraction metallurgy, and leadership in engineering education.

**Qinghuang Lin**, director, Lam Research Corp., Fremont, Calif. For electronic materials for the manufacturing of integrated circuit products.

**Tanya Monro**, chief defence scientist, Defence Science and Technology Group, Australian Department of Defence, Canberra, Australia. For contributions to optics engineering and advancing Australian national security.

**Daniel A. Nolasco**, founding partner and president, Nolasco & Associates, Buenos Aires, Argentina. For advancing wastewater treatment technologies and adapting treatment processes for climate change.

**Constantinos Pantelides**, managing director, Process Systems Enterprise Ltd., London, United Kingdom. For process modeling and optimization, and for pioneering modeling software.

**Thalappil Pradeep**, Deepak Parekh Institute Chair Professor and professor of chemistry, Indian Institute of Technology Madras,

Chennai, India. For contributions to cluster chemistry and the discovery and implementation of affordable drinking water solutions.

**Yvonne Rogers**, chair of interaction design, Computer Science, University College London, London, United Kingdom. For advancing human-centric computing through technical innovations and worldwide education.

**Derrick J. Rossi**, president and CEO, Convelo Therapeutics Inc., Cleveland, OH. For discoveries in stem cell biology and launching companies to translate them into health benefits.

**Vera Silva**, chief strategy and technology officer, Grid Solutions, General Electric Co., Paris, France. For grid integration of renewable energy.

**Yu-Pen Su**, consultant, Missile and Rocket Systems Research Division, National Chung-Shan Institute of Science and Technology, Pingtung, Taiwan. For development of aerospace propulsion and vehicle technologies for missiles and rockets.

## NAE Newsmakers

**Norman A. Abrahamson**, adjunct professor, Civil Engineering, University of California, Berkeley, has been chosen as the **2024 Harry Fielding Reid Medalist** by the Seismological Society of America. Dr. Abrahamson is recognized as a global leader in the field of probabilistic seismic hazard assessment, for his leadership in a series of Next Generation of Ground-Motion Attenuation Models projects, and for his outstanding contributions to expanding gender diversity in the earthquake engineering field.

**Robert O. Ambrose**, J. Mike Walker Chair in Mechanical Engineering and director for Space & Robotics Initiatives, Texas A&M University, is the 2023 recipient of ASME's **Charles Russ Richards Memorial Award**. Established in 1944 as a partnership with Pi Tau Sigma, the award recognizes an engineer who has demonstrated outstanding achievement in the two decades or more since graduating with their degree. Among Dr. Ambrose's many contributions to the field of engineering, working

to solve the challenges facing rovers on the Moon's surface and developing robots capable of safely working alongside humans are among the most impactful.

**John Edward Bowers**, director, Institute for Energy Efficiency, professor of electrical and computer engineering, and Fred Kavli Chair in Nanotechnology, University of California, Santa Barbara, has been selected to receive the prestigious **2024 Jun-ichi Nishizawa Prize** from the Institute of Electrical and Electronics Engineers. He was chosen for

his “contributions to photonic integrated circuit technologies.”

**Robert J Budnitz**, retired staff scientist, Energy Geosciences Division, Lawrence Berkeley National Laboratory, has been honored by the American Physical Society with the **2024 Leo Szilard Lectureship Award**. The award recognizes outstanding accomplishments by physicists in promoting the use of physics for the benefit of society in such areas as the environment, arms control, and science policy. Dr. Budnitz earned the award “for outstanding leadership in formulating and guiding the US Nuclear Regulatory Research program in areas of reactor safety, waste management, and fuel-cycle safety, and for significantly advancing seismic probabilistic risk assessments as applied to nuclear power worldwide.”

**Emily A. Carter**, Gerhard R. Andlinger Professor in Energy and the Environment at Princeton University, is the winner of the **William H. Nichols Medal** for 2024. The medal is a prestigious annual honor bestowed by the American Chemical Society’s New York Section for outstanding contributions in chemistry. Professor Carter was chosen for “groundbreaking quantum insights in sustainable catalysis.”

**Robert L. Crippen**, president (retired), Thiokol Propulsion, was selected by the National Aeronautic Association as the recipient of the **2023 Wright Brothers Memorial Trophy**. Captain Crippen is recognized for his devotion to public service and the advancement of American aerospace; his achievements as an aviator, astronaut, and leader; and his selfless dedication to the future of humankind. The trophy, established by NAA in 1948 to honor the memory of Orville and Wilbur Wright, is awarded annually

to a living American for significant public service of enduring value to aviation in the United States.

**Earl H. Dowell**, William Holland Hall Professor and chair, Mechanical Engineering and Materials Science, Duke University, was awarded the **J.S. Rao Medal in Vibration Engineering** at the 18th International Conference on Vibration Engineering and Technology of Machinery in December 2023. The award committee called his book *A Modern Course in Aeroelasticity* “amazing” and applauded his contributions to engineering that span a storied career.

**Eric R Fossum**, John H. Krehbiel Sr. Professor for Emerging Technologies, Dartmouth University, received **Trinity College’s inaugural President’s Medal for Science and Innovation**. The medal recognizes a prominent, internationally renowned individual in science, technology, engineering, or mathematics who has influenced STEM with marked success and who represents the liberal arts ideal of empowering humanity through the sciences. Professor Fossum is the inventor of the CMOS image sensor “camera on a chip” used in almost all smartphones and webcams, as well as in medical imaging and more.

**Michimasa Fujino**, retired president and CEO, Honda Aircraft Corporation, has been awarded the **2024 Daniel Guggenheim Medal** by the American Institute of Aeronautics and Astronautics. Dr. Fujino was chosen for technical innovation and leadership in conceiving, designing, and bringing HondaJet to a leading position in the business jet market. He will receive the prestigious award during the 2024 AIAA Awards Gala on May 15 in Washington, DC.

The inaugural **TIME100 Climate List** recognizes the 100 most innova-

tive leaders driving business climate action. **Jennifer R. Holmgren**, chief executive officer of LanzaTech, is on that list. Under Dr. Holmgren’s leadership, LanzaTech became the first carbon capture and utilization technology company to go public and demonstrated that its commercial-scale biorecycling approach can play a pivotal role in keeping our planet livable for the long term. To date, LanzaTech has prevented more than 330,000 tonnes of carbon from entering the atmosphere across six commercial plants.

**Simon S. Lam**, Regents Chair in Computer Science at the University of Texas at Austin, was inducted into the **Internet Hall of Fame** in September 2023. The honorary award, dedicated to internet pioneers, was given to Dr. Lam in recognition for his contributions to internet application safety, including his development of secure network programming and the invention of secure sockets.

**Robert Langer**, David H. Koch Institute Professor, Massachusetts Institute of Technology, has been awarded the **2023 Dr. Paul Janssen Award**. Dr. Langer is being honored for his pioneering research into biomedical compounds for drug delivery and tissue engineering, which has impacted a wide range of medical technologies. He accepted the award in a virtual symposium on February 8, 2024.

**Asad M. Madni**, independent consultant and president, chief operating officer, and CTO (retired), BEI Technologies Inc., has been awarded the **2023 IEEE-USA George F. McClure Citation of Honor**. The award is presented annually to honor IEEE members who have made exemplary contributions toward securing recognition of professional activities in the United States. Dr. Madni is

honored for “significant contributions to the engineering profession through mentorship, leadership, and philanthropy.”

**Samir Mitragotri**, Hiller Professor of Bioengineering and Hansjorg Wyss Professor of Biologically Inspired Engineering, Harvard University, was presented the **AICHE 2023 Doing a World of Good Medal** at the 2023 AIChE Gala on December 7 in New York City. He received the medal for developing innovative technologies for easy-to-use, needle-free drug delivery via skin patches and oral pills for the treatment of such illnesses as diabetes, skin diseases, and multiple sclerosis. In addition, Professor Mitragotri has also developed new methods of targeted drug delivery for the treatment of cancer and vascular diseases.

**Arkadi S. Nemirovski**, John P. Hunter Chair and professor at Georgia Institute of Technology, shares the **2023 WLA Prize in Computer Science or Mathematics** with Yurii Nesterov of the Université Catholique de Louvain. The pair were chosen for “their seminal work in convex optimization theory, including the theory of self-concordant functions and interior-point methods, a complexity theory of optimization, accelerated gradient methods, and methodological advances in robust optimization.” The 2023 WLA Prize Award Ceremony took place in Shanghai on November 6.

**Nicholas Peppas**, Cockrell Family Regents Chair in Engineering #6 and professor of chemical & biomedical engineering, University of Texas at Austin, received the **2024 CMBE Shu Chien Achievement Award** at the Cellular and Molecular Bioengineering annual conference in San Juan, Puerto Rico, in January.

Named after renowned bioengineer Shu Chien, it is the most prestigious honor granted to members who demonstrate significant contributions to the field of cellular and molecular bioengineering. Peppas was recognized for his research that focuses on biomaterials and drug delivery, specifically within the human body.

**Kimberly A. Prather** (NAS), Distinguished Chair in Atmospheric Chemistry, University of California at San Diego, has been awarded the **2024 NAS Award in Chemical Sciences**, which honors innovative research in the chemical sciences that contributes to a better understanding of the natural sciences and to the benefit of humanity. The award recognizes her research for “revolutionizing our understanding of atmospheric aerosols and their impact on air quality, climate, and human health.” She is also recognized for being “an active leader and communicator, providing key guidance on the role of aerosol transmission of SARS-CoV-2 during the COVID-19 pandemic.” She will receive the award during the National Academy of Sciences 161st annual meeting in April.

**Christine A. Shoemaker**, the Joseph P. Ripley Professor of Engineering Emerita at Cornell University, has received the **2023 Harold Hotelling Medal for Lifetime Achievement** from the Institute for Operations Research and the Management Sciences (INFORMS). She received the award for her research developing optimization algorithms, modeling, and statistical analysis to address a wide range of environmental problems. In June 2023 she received the International Society for Industrial and Applied Mathematics (SIAM) Activity Group on Geosciences **Career Prize** for her mathematically based computational

algorithms and their applications to problems in geoscience including groundwater remediation and carbon sequestration.

**Gwynne E. Shotwell**, president and chief operating officer, SpaceX, is the distinguished recipient of the **2023 Green Sands Inspiration Prize**. The prize is awarded to trailblazers who have the courage to go first, take on risks and personal responsibility to open a path for others to follow. Dr. Shotwell was the unanimous selection of the nominating committee. She symbolizes progress, equality, and the limitless potential of individuals in the pursuit of groundbreaking achievements. In addition, Dr. Shotwell will share the **2024 Edison Achievement Award** with Dr. Laurie Leshin, director of NASA’s Jet Propulsion Lab. The award, which celebrates their contribution to human-centered design, the value and differentiation they create, the positive influence they have on existing, new and emerging markets and the impact they have on the world, will be presented on April 18 at a gala in Fort Myers, Florida.

**William L. Whittaker**, Fredkin University Professor at Carnegie Mellon University, received a **Career Achievement Award** as part of Pittsburgh Inno’s second annual Fire Awards. Professor Whittaker, Pittsburgh’s pioneer in robotics, has been a driving force who has reshaped industries across nations, one robotic innovation at a time.

**Blake S. Wilson**, director of the Duke Hearing Center and adjunct professor, Duke University Medical Center, has been selected as a co-recipient of the **2024 IEEE Medal for Innovations in Healthcare Technology**. Professor Wilson was cited for his “contributions to the development of the modern cochlear implant.”

The 35th annual Great Minds in STEM (GMiS) Conference has recognized **Yannis C. Yortsos**, dean of the USC Viterbi School of Engineering, with the prestigious **2023 HENAAC Chairman's Award**. The Hispanic Engineer National Achievement Awards are a celebration of talent, dedication, and innovation in the fields of science, technology, engineering, and mathematics. The honor is presented to those "who have used the highest standards of their profession to make exceptional contributions to their profession or to their community, thereby significantly advancing the positive image of STEM professionals in our society."

**Lily Y. Young**, Distinguished Professor of Environmental Microbiology and dean, International Programs, Rutgers University, was awarded the **Daniel Gorenstein Memorial Award** by the university for outstanding scholarly achievement and exceptional service.

The **National Inventors Hall of Fame** has announced its 2024 inductees. Included are **Andrea Goldsmith**, dean, School of Engineering and Applied Science, Princeton University, for adaptive beamforming for multi-antenna wi-fi; and **Asad M. Madni**, independent consultant and retired president, COO, and CTO, BEI Technologies Inc., for MEMS gyroscope for aerospace and automotive safety.

The **2023 National Academy of Inventors Fellows** have been announced. Among those chosen for this honor are NAE members **Christine A Ehlig-Economides**,

professor and Hugh Roy and Lillie Crazz Cullen Distinguished University Chair, University of Houston; **Eric E. Fullerton**, professor of electrical and computer engineering, University of California, San Diego; **Ashok J. Gadgil**, Professor Area Deputy for Science and Technology, University of California, Berkeley; **Brian McClendon**, research professor, University of Kansas; and **Susan S. Margulies**, assistant director, Directorate of Engineering, National Science Foundation—the first biomedical engineer to hold this position. The 2023 class of Fellows will be honored at the NAI 13th Annual Meeting on June 18, 2024, in Raleigh, North Carolina.

The Franklin Institute Awards Class of 2024 has been announced. **David A. Weitz** (NAS), professor of physics and of applied physics, Harvard University, will receive the **2024 Bower Award and Prize for Achievement in Science** for "transforming our fundamental understanding of squishy materials ranging from gels, polymers, colloids, and emulsions to living organisms." **Lisa T. Su**, president and CEO, Advanced Micro Devices Inc., wins the **Bower Award for Business Leadership** for "her transformational leadership of AMD, a leader in high-performance and adaptive computing and one of the fastest growing semiconductor companies in the world." **Paula T. Hammond** (NAS/NAM), Institute Professor and vice provost for faculty, Massachusetts Institute of Technology, will accept the **Benjamin Franklin Medal** for "innovative methods to create novel materials

one molecular layer at a time, and for applying these materials to areas ranging from drug delivery to energy storage." **Robert M. Metcalfe**, retired professor, The University of Texas at Austin, was awarded the **Benjamin Franklin Medal in Electrical Engineering** for "his pioneering role in the design, development, and commercialization of Ethernet, an interface for networking and file sharing between computers." **Mary C. Boyce**, dean of engineering, Columbia University, will receive the **Benjamin Franklin Medal** for "transformative contributions to our understanding of the physical behavior of polymers, materials made of long chains of molecules, leading to innovative product development of rubber and other soft materials." Awards will be bestowed during The Franklin Institute Awards week in April.

The New Year Honours List for 2024 recognizes the achievements and service of extraordinary people across the United Kingdom. **Sir James R. McDonald**, principal and vice-chancellor, University of Strathclyde, has been appointed a **Knight Grand Cross of the Order of the British Empire** for services to engineering, to education, and to energy. **Molly Morag Stevens**, John Black Professor of Bionanoscience at the Department of Physiology, Anatomy, and Genetics and the Institute for Biomedical Engineering, and deputy director of the Kavli Institute for Nanoscience Discovery, has been appointed **Dame Commander of the Most Excellent Order of the British Empire (DBE)** for services to medicine.

## The NAE Celebrates 60 Years of Leadership in an Accelerating World



### Celebrating 60 Years of Engineering

*Donald C. Winter*



Donald C. Winter, NAE Chair

As the NAE chair, it is my honor to welcome all of you to our 2024 annual meeting here in Irvine, California.

The remarks from NAE Chair Donald C. Winter, NAE President John L. Anderson, and NAE Executive Officer Alton D. Romig, Jr., were given at the NAE National Meeting on February 8, 2024. The meeting was held at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, California.

This is the 60th anniversary of the NAE, and we would like to take the opportunity to celebrate the many contributions that engineers and engineering have made to the world that we live in. While some of those contributions are front and center in today's public conversation, I will suggest that the depth and breadth of the role that engineering plays in the continuing evolution of our world is greatly underestimated.

From a macro perspective, engineering is simply how 8 billion people can live on this Earth. Engineering was the basis of much of the Green (otherwise known as the Third) Agricultural Revolution, which contributed to widespread poverty reduction and averted hunger for millions of people. Engineering also enabled the access to potable water that has been a principal factor in eliminating many forms of illness and pestilence. And engineering is the basis for the economic growth that underpins the quality of life that we all enjoy.

I suspect that if you asked people what the most significant engineering accomplishment of recent times was, they would likely focus on new products such as cell phones or electric cars, without noting the many additional roles engineering plays in bringing such products to fruition. That long process starts, for example, with the engineering of means to extract and refine rare earth minerals that enable many critical components. It includes the engineering of new means of production, such as additive manufacturing, and the development of highly automated factories capable of safely and efficiently producing new products, such as microelectronics and lithium batteries. And it includes the development and sustainment of the infrastructure needed to support complex supply chains and product distribution as well as to provide the energy and communication channels that enable such products to operate.

Since we just had our joint meet-

ing of the National Academies' Councils, the governing bodies of the National Academies of Sciences, Engineering, and Medicine, I will take this opportunity to add that much of the recent progress in the sciences and medicine has also been the result of engineering contributions. For example, the field of astrophysics is greatly benefiting from the 6.5-meter James E. Webb Space Telescope, operating a million miles from

our planet! And the field of surgery is benefiting from robotic assistants such as the Da Vinci surgical system.

Some historians like to characterize different time periods by the technological changes that occurred during those periods. They would note the steam era occurring between the eighteenth and nineteenth centuries and the electronic and information ages starting in the mid-twentieth century and continu-

ing today. Looking at the breadth of recent engineering accomplishments and their impact on society, I would prefer the term "the engineering age" for what is transpiring today!

I would like to conclude my remarks by welcoming all the students here today into the engineering community. I have found this to be a most satisfying and rewarding career, and I trust that you too will be pleased to call yourselves engineers!

## Celebrating 60 Years of Engineering Pioneers and the Future of Engineering

*John L. Anderson*



John L. Anderson, NAE president

Welcome to the 2024 National Meeting of the National Academy of Engineering!

We are pleased to have our NAE members and guests who have taken the time to join us today—both in person and virtually, via webcast.

And an enthusiastic welcome to the many students joining us today. Welcome to the students from Samueli Academy in Santa Ana, and welcome to the students from

Cabrillo High School in Long Beach. You are the future of engineering, and it is our pleasure to share with you the value, power, creativeness, and excitement of engineering.

NAE Chair Don Winter just spoke about the remarkable advancements that have shaped our world—all of which can be attributed to engineering.

This year, as the National Academy of Engineering celebrates its 60th anniversary, I'd like to honor the NAE members whose ideas, innovations, and sheer perseverance made these advancements possible. These pioneering engineers are true leaders of change.

- **Steve Fenves** — Holocaust survivor and early pioneer in CAD for large structures.
- **Frances Arnold** — recipient of the 2018 Nobel Prize in Chemistry, the 2011 NAE Charles Stark Draper Prize in Engineering, and member of all three of the Academies within the National Academies of Sciences, Engineering, and Medicine, for the directed evolution of enzymes.

- **John Brooks Slaughter** — pioneer in engineering education, leadership, and equal opportunity.
- **Marty Cooper** — who made pioneering contributions to the world's first cellular telephone, networks, systems, and standards.
- **Andrew Viterbi** — who invented the "Viterbi algorithm," a programming algorithm that can estimate the likely sequence of events in a given situation. Originally, the focus was on digital cellular technology; however, the Viterbi algorithm is commonly used in everything from speech recognition to keyword spotting. He is also co-founder of Qualcomm.
- And finally, **Lillian Gilbreth**, a pioneer in the field of management theory who is best known for her work as an industrial engineer.

Lillian and her husband Frank, and their time and motion research, are memorialized as the subjects of the book and subsequent movies *Cheaper by the Dozen* and its follow-up, *Bells on Their Toes*—written by two of their children.



Students from Cabrillo High School in Long Beach cheer at the 2024 NAE National Meeting held at the Arnold and Mabel Beckman Center of the National Academies of Sciences and Engineering in Irvine, California. Photo courtesy of Rasheed Riveroll Castillo, Instagram @Rasheed.photographs.

It is important to note that in 1935, Lillian became a professor of management at Purdue's School of Mechanical Engineering and the country's first female engineering professor. Today, Lillian is acknowledged as the founder of the field of industrial engineering. And, in a nod to women engineers, Lillian Gilbreth was the first woman engineer elected to the NAE, in 1965—one year after its founding!

It is in honor of Lillian Gilbreth that we hold the Gilbreth Lectures each year.

These are just a sampling of the many engineers whose innovations—and entrepreneurial spirit—have transformed our world. Along with Dr. Henry Samueli, cofounder of Broadcom and patron of the Samueli Academy.

We honor all these engineers for their perseverance, fortitude, and pioneering spirit. More importantly,

these engineering pioneers stand as a testament to the fact that engineering opportunities are as unique as the individual and can be tailored to fit your individual interests!

This afternoon we are fortunate to have with us four distinguished engineers who were selected by the NAE from among participants at previous Grainger Foundation Frontiers of Engineering symposia as the **2024 Lillian Gilbreth Lecturers**.

The **Gilbreth Lectures** recognize outstanding early-career engineers who are especially gifted in the presentation of their engineering ideas. Launched in 2001, the Gilbreth Lectures are funded by the Armstrong Endowment for Young Engineers, which was established by NAE member John Armstrong.

We have an exciting lineup of interesting topics covered by exceptional professionals. You can find their

bios in the printed program and on the NAE website, along with a brief description of their presentations, but I'll provide a brief overview for each.

Let's begin!

It's an honor to introduce our first Gilbreth Lecturer, Dr. Andrew F.J. Abercromby. Andrew is deputy lead for advanced human life support and performance at NASA, where he supports the identification and development of technology needs to enable NASA's future human exploration missions.

Andrew received a master's in mechanical engineering from the University of Edinburgh and a PhD in motor control from the University of Houston. Andrew has more than twenty years of experience at NASA and is the founder and former lead of the Human Physiology, Performance, Protection, and Operations Laboratory at Johnson Space Center.

Andrew will take us step-by-step through “Mars-Walking: Enabling Capabilities for Crew Health and Performance during Exploration Extravehicular Activity.”

Next, I’d like to introduce our next Gilbreth Lecturer, Dr. Isabel Barton. Isabel is an assistant professor in the Mining and Geological Engineering Department at the University of Arizona. Her research focuses on geometallurgy, using geological and mineralogical insights to make metal extraction more efficient.

She earned a bachelor’s degree in geology from the University of Oklahoma, master’s degrees in mining engineering and geosciences, and a doctoral degree in geosciences from the University of Arizona.

Isabel enjoys studying the history of geology, mining, and metallurgy, and runs the YouTube video series *How Minerals Made Civilization*.

Recognizing that the extent of human achievement has been a function of the quantity and variety of earth materials available for use, Isabel will discuss “Mineral Resources: The Materials Basis of Civilizations.”

Our next Gilbreth Lecturer is Dr. Chethan Pandarinath. Chethan is an associate professor in the Wallace H. Coulter Department of Biomedical Engineering at Emory University and Georgia Institute of Technology. He directs the Systems Neural Engineering Lab, whose research sits at the intersection of artificial intelligence, neural engineering, and systems neuroscience, with dual goals of better understanding the nervous system and designing assistive devices for people with paralysis.

Chethan received undergraduate degrees in computer engineering, physics, and science policy from North Carolina State University and a PhD in electrical engineering from Cornell University.

Chethan will address new developments in artificial intelligence and recent advances in understanding brain function in his presentation, “Machine Learning Algorithms for Neural Decoding.”

Our final Gilbreth Lecturer for today is Ms. Kathryn Zealand. Inspired by wanting to help her grandmother, Kathryn started a

wearable robotics project aimed at helping a billion people move. This resulted in her founding SKIP, a small company focused on engineering-powered wearables that fit seamlessly into daily life.

Kathryn’s entrepreneurial spirit includes applying methods from quantum mechanics to model climate change, founding several agribusinesses in East Africa to reduce rural poverty, and starting several high-tech projects within Google X that improve climate resilience. Kathryn holds an MBA from Stanford University and an MPA from Harvard University. Kathryn will discuss “The Arduous and Exciting Path of Commercializing Consumer Exoskeletons.”

I’d like to thank all the Gilbreth Lecture speakers and the students for your insightful and engaging questions. The Gilbreth Lecture series is available for viewing on the NAE YouTube channel.<sup>1</sup>

<sup>1</sup> <https://www.youtube.com/channel/UCDgsHhqf6a2IC9LT5hbUxpA>



From left to right: NAE Executive Officer Alton D. Romig, Jr., and NAE President John L. Anderson; 2024 Gilbreth Lecturers Andrew F.J. Abercromby, Isabel Barton, Chethan Pandarinath, and Kathryn Zealand; and NAE Chair Donald C. Winter.

## Honoring NAE Leaders

### Alton D. Romig, Jr.



Alton D. Romig, Jr., NAE executive officer

Engineers make a world of difference!

With us today are two engineers whose leadership at the NAE has helped us achieve our mission. I'd like to recognize them.

#### NAE Chair Donald C. Winter

Don is an independent consultant supporting national and international security interests in the United States and allied nations. He served as the 74th secretary of the navy from January 2006 to March 2009, where he led America's Navy and Marine Corps teams and was responsible for almost 900,000 people and an annual budget in excess of \$125 billion. Don's prior business career in the aerospace and defense industry spanned over thirty years as a systems engineer, program manager, and corporate executive.

From 2009 to 2020, he was a professor of practice at the University of Michigan, where he taught graduate-level courses on systems engineering, satellite design, and maritime policy.

Since 2011 he has served in multiple roles, assisting the Common-

wealth of Australia in its efforts to reconstruct the Royal Australian Navy's fleet and establish a sustainable shipbuilding capability. From 2019 to 2021 he also served as the US DoD's senior defense industry advisor for Ukraine. Don earned a bachelor's degree from the University of Rochester and both master's and doctoral degrees from the University of Michigan—all in physics.

He has served a four-year term as the NAE chair, overseeing efforts of the NAE Council and Executive Committee and working actively with the president in representing the NAE and its policies to the engineering community and the public.

#### NAE Home Secretary Carol K. Hall



Carol K. Hall, NAE home secretary

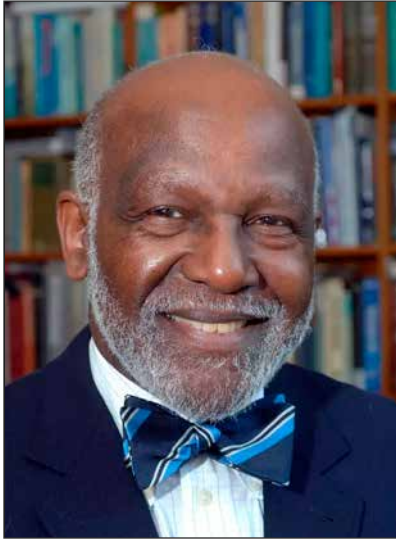
Carol earned her bachelor's degree in physics from Cornell University and her PhD in physics from the State University of New York at Stony Brook. After postdoctoral training in the Chemistry Department at Cornell and a brief period as an economic modeler at Bell Laboratories, Carol joined the

Chemical Engineering Department at Princeton University in 1977 as one of the first women to be appointed to a chemical engineering faculty in the United States. In 1985 she joined the Chemical Engineering Department at North Carolina State University, where she currently works as the Worley H. Clark, Jr. Distinguished University Professor of Chemical and Biomolecular Engineering.

Carol is the author of more than 300 publications and the recipient of numerous awards, including the Margaret Hutchinson Rousseau Pioneer Award for Lifetime Achievement by a Woman Chemical Engineer, which she received in 2020 from the American Institute of Chemical Engineers. Hall was elected to the National Academy of Engineering in 2005, and she has served a four-year term as the NAE home secretary (from July 2020 to June 2024).

Thank you, Don and Carol, for your engineering expertise and NAE leadership.

## Message from NAE Vice President Wesley L. Harris



Wesley L. Harris

It is my pleasure to report on the NAE's fundraising activities for 2023. Our donors' generosity, vision, and faith in the NAE to make best use of their contributions fills me with gratitude. Over the past year, we continued to focus on the NAE's comprehensive fundraising campaign, Leadership in a World of Accelerating Change,<sup>1</sup> and what a year it was. We had one of our most successful fundraising years with over \$11 million in generous gifts pledged, bringing our total in the campaign to \$67.4 million. Additionally, in 2023 we saw record numbers of donors join our lifetime giving societies, including two Lincoln Society, four Franklin Society, nine Curie Society, sixteen Einstein Society, and thirty-nine Golden Bridge Society members. My sincere thanks to everyone who supported the campaign last year.

Philanthropic support provides over 60% of funding for NAE's programs and initiatives. The NAE does not receive federal funding, so your

philanthropy is critical to our success. Below are selected highlights of the impact of philanthropy on the NAE since I wrote to you last summer.

When **Bill Wulf** stepped down as NAE President in 2007, the *Wm. A. Wulf Initiative for Engineering Excellence Fund* was created in his honor to provide support for the programs and activities Bill championed. These priorities include the diversity of the engineering workforce, ethics and engineering, EngineerGirl, and The Grainger Foundation Frontiers of Engineering. To honor Bill's life and legacy after his passing in March 2023, NAE Section 5 members **Susan Graham**, **Ed Lazowska**, and **Bob Sproull** spearheaded a fundraising effort with the goal of doubling the size of the *Wm. A. Wulf Initiative of Engineering Excellence* endowment and, with it, the funds at the disposal of the president each year. It is a result of their hard work that I can announce that over \$5 million has been raised in just five short months in Bill's memory. This would not have been possible without the dedication of our fundraising committee and the support of our NAE Development staff. Powered by weekly meetings and many emails over five months, we received 178 gifts to the Wulf Initiative, including 19 first-time gifts, 25 major gifts (\$100,000 or more), and 86 gifts from donors who had not given to the NAE in over a year.

With support from all these donors, **John Anderson** and future presidents are empowered to support programmatic work through The Grainger Foundation Frontiers of Engineering, EngineerGirl, CESER, and other programs that continue

Bill's legacy of striving to create an equitable and inclusive engineering community.

As I wrote in August 2023, the Arnold and Mabel Beckman Center in Irvine, California, is the NAE's headquarters on the West Coast and the only building the NAE co-owns with the NAS. The center is a vital resource and empowers our Academy to maintain a strong presence in the region, enabling us to better engage with members and volunteers in the West through member gatherings, committee meetings, and public forums. Each year the NAE hosts its National Meeting and the Gilbreth Lectureships at the Beckman Center. High school and university students, as well as academic and business leaders, also use the space—enhanced by the NAE's reputation—to convene on engineering, science, and education matters.

The Beckman Center has historically been supported through a modest endowment. The endowment is undercapitalized, so the NAE must provide supplemental funding through its unrestricted annual donations, which is simply unsustainable. To make needed improvements and secure the finances of the Beckman Center, the NAE has embarked on a fundraising effort to grow the endowment to \$10 million to ensure the NAE can cover its share of the expenses in perpetuity.

In August 2023, I announced that I had joined **Ross** and **Stephanie Corotis**, **John** and **Pat Anderson**, and **Robin** and **Rose McGuire** as a donor to the Beckman Center's Endowment with a major gift. I am honored to name a space at the Beckman Center with my gift and encourage other

<sup>1</sup> <https://www.nae.edu/acceleratingchange/>

members to consider joining me. We currently have commitments totaling \$1.9 million to support the Beckman Center endowment, but we still have a ways to go to raise the \$10 million that is required. We all hope our gifts will challenge members to match our commitments and keep our West Coast campus strong.

There are opportunities to name a space for you, a loved one, a mentor, etc. If you might be interested in joining us in making a gift to support the Beckman Center, please don't hesitate to contact me or Radka Nebesky at RNebsky@nae.edu or 202-334-3417.

Additionally, the NAE is celebrating its 60th anniversary in 2024. To help commemorate this milestone we have launched a few goals to help with our campaign based on the theme "60 for the 60th." These goals include:

- 60 new Curie, Franklin, and Lincoln Society Members.
- 60 new named or endowed funds.
- 60% member participation rate in the campaign.
- 60 planned gifts.

Planned gifts, or gifts that are a part of your financial and estate plans, are an easy way to ensure your legacy and the long-term sustainability of our programs and initiatives for future generations of engineering leaders. To learn more about how you can make a planned gift that aligns with your financial and charitable goals, contact Elana Lippa, director of Planned Giving, at ELippa@nae.edu or 202.334.1817.

Although I have highlighted only a few donors here, I want to once again say thank you to each and every mem-

ber and donor who supported our efforts to provide engineering leadership in a world of accelerating change. Your commitment to our mission to advance the welfare and prosperity of the nation by providing independent advice on matters involving engineering and technology and by promoting a vibrant engineering profession and public appreciation of engineering is inspiring. Please take a moment to look through our donor listing provided in the following pages.

Submitted by



Wesley L. Harris  
NAE Vice President  
(July 1, 2022–June 30, 2026)

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## 2023 Honor Roll of Donors

We greatly appreciate the generosity of our donors. Your contributions enhance the impact of the National Academy of Engineering's work and support its vital role as advisor to the nation. The NAE acknowledges contributions made as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. The gifts reflected on this list are as of December 31, 2023.

### Lifetime Giving Societies

We gratefully acknowledge the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of the National Academies as advisors to the nation on matters of science, engineering, and medicine.

### The Abraham Lincoln Society

In recognition of members and friends who have made lifetime contributions of \$1 million or more to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

Bruce and Betty Alberts  
Richard and Rita\* Atkinson  
**Norman R. Augustine**  
Craig and Barbara Barrett  
Jordan and Rhoda Baruch\*

**Stephen D. Bechtel Jr.\***  
**Arnold** and Mabel **Beckman\***  
Leonard Blavatnik  
**Harry E. Bovay Jr.\***  
Donald Bren  
**George\*** and Virginia **Bugliarello**

Ralph J.\* and Carol M. Cicerone  
Harvey V. Fineberg and Mary E. Wilson  
**Bernard M. Gordon**  
Cecil H. Green\*  
**John O.** and Candace E. **Hallquist**

\*Deceased

Michael and Sheila Held*	Whitney* and Betty MacMillan	Jonathan B. and Donna J. Perlin	William J. Rutter
Jane E. Henney and Robert Graham	John F. McDonnell	<b>Robert*</b> and Mayari <b>Pritzker</b>	Bernard and Rhoda Sarnat*
<b>William R.</b> and Rosemary B. <b>Hewlett*</b>	<b>Robin K.</b> and Rose M. <b>McGuire</b>	Richard L. and Hinda G. Rosenthal*	Leonard D. Schaeffer
<b>Ming</b> and Eva <b>Hsieh</b>	George P. Mitchell*	Martine A. Rothblatt	Sara Lee and Axel Schupf
<b>Irwin</b> and Joan <b>Jacobs</b>	The Ambrose Monell Foundation	Jack W. and Valerie Rowe	James H. and Marilyn Simons
Robert L.* and Anne K. James	<b>Gordon</b> and Betty <b>Moore*</b>	Fritz J. and Dolores H. Russ Prize Fund of the Russ College of Engineering and Technology at Ohio University	<b>John</b> and Janet <b>Swanson</b>
Kenneth A. Jonsson*	Philip and Sima Needleman		Marci and <b>James J. Truchard</b>
Fred Kavli*	Peter O'Donnell, Jr.*		Anthony J. Yun and Kimberly A. Bazar
Daniel E. Koshland Jr.*	Gilbert S. Omenn and Martha A. Darling		Anonymous (1)
Tillie K. Lubin*			

**The Benjamin Franklin Society**

In recognition of members and friends who have made lifetime contributions of \$500,000 to \$999,999 to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

<b>John</b> and Pat <b>Anderson</b>	Ross and Stephanie <b>Corotis</b>	<b>Wesley L. Harris</b>	Oliver E. and Gerda K. Nelson*
Rose-Marie and Jack R. Anderson*	Henry David*	<b>John L. Hennessy</b>	Shela and <b>Kumar Patel</b>
<b>John</b> and Elizabeth <b>Armstrong</b>	Richard Evans*	Alexander Hollaender*	<b>Henry</b> and Susan <b>Samueli</b>
Kenneth E. Behring*	Eugene Garfield Foundation	<b>Thomas V. Jones*</b>	Herbert A. and Dorothea P. Simon*
<b>Gordon Bell</b>	Theodore Geballe*	Cindy and <b>Jeong Kim</b>	<b>Raymond</b> and Maria <b>Stata</b>
Elkan R.* and Gail F. Blout	Penny and <b>Bill George,</b> George Family Foundation	<b>Ralph</b> and Claire <b>Landau*</b>	Roy and Diana Vagelos
Russell L. Carson	Christa and Detlef Gloge	Asta and <b>William W. Lang*</b>	<b>Andrew</b> and Erna* <b>Viterbi</b>
Charina Endowment Fund	William T.* and Catherine Morrison Golden	<b>Marcia K. McNutt</b>	<b>Alan M. Voorhees*</b>
James McConnell Clark*		<b>Ruben F.*</b> and Donna <b>Mettler</b>	Anonymous (2)
Barry and Bobbi Collier		<b>Dane*</b> and Mary Louise <b>Miller</b>	

**The Marie Curie Society**

In recognition of members and friends who have made lifetime contributions of \$250,000 to \$499,999 to the National Academy of Sciences, National Academy of Engineering, or National Academy of Medicine. Boldfaced names are NAE members.

The Agouron Institute	Gail H. Cassell	Rosie and Stirling A. Colgate*	<b>Lance</b> and Susan <b>Davis</b>
<b>W.O. Baker*</b>	<b>Chau-Chyun</b> and Li-Li <b>Chen</b>	<b>W. Dale</b> and Jeanne C. <b>Compton*</b>	<b>Nicholas M. Donofrio</b>
Warren L. Batts	Sigrid and <b>Vint Cerf</b>	<b>Ruth David</b> and Stan Dains	David and Miriam Donoho
<b>Elwyn*</b> and Jennifer <b>Berlekamp</b>	Clarence S. Coe*		Ruth and Victor Dzau
Daniel and Lana Branton			

\*Deceased

<b>James O. Ellis, Jr.</b> and <b>Elisabeth Paté-Cornell</b> Dotty* and <b>Gordon</b> <b>England</b> <b>William L.*</b> and Mary Kay <b>Friend</b> George and Christine Gloeckler <b>Paul</b> and <b>Judy Gray</b> <b>Diane Greene</b> and <b>Mendel Rosenblum</b> Diane E. Griffin Jerome H.* and Barbara N. Grossman Robert A. Hicks* Lyda Hill <b>Chad</b> and <b>Ann Holliday</b>	William R. Jackson* <b>Anita K. Jones</b> Mary and <b>Howard Kehrl*</b> Jill Howell Kramer <b>Kent Kresa</b> <b>Mark</b> and <b>Becky Levin</b> <b>Frances</b> and <b>George Ligler</b> <b>Azad M.</b> and <b>Carla C.</b> <b>Madni</b> Stella and <b>Steve* Matson</b> William W. McGuire Janet and <b>Richard M.*</b> <b>Morrow</b> <b>Clayton Daniel</b> and Patricia L. <b>Mote</b> Ralph S. O'Connor* <b>Kenneth H. Olsen*</b>	<b>Larry*</b> and <b>Carol Papay</b> <b>Stephen Quake</b> Ann and <b>Michael Ramage</b> <b>Simon Ramo*</b> <b>Richard F.</b> and <b>Terri W.</b> <b>Rashid</b> Anne and <b>Walt* Robb</b> Matthew L. Rogers and Swati Mylavarapu <b>Julie</b> and <b>Alton D. Romig</b> <b>Jr.</b> <b>Jonathan J. Rubinstein</b> Stephen* and Anne Ryan Wendy and <b>Eric Schmidt</b> H.E. Simmons* <b>Pradeep Sindhu</b> and Marie Bertrand	<b>Robert F.</b> and <b>Lee S.</b> <b>Sproull</b> Edward C. Stone Judy Swanson Ted Turner Leslie L. Vadasz Martha Vaughan* <b>Charles M.*</b> and <b>Rebecca</b> <b>M. Vest</b> <b>Robert</b> and <b>Robyn</b> <b>Wagoner</b> <b>David Walt</b> and <b>Michele</b> May Susan R. Wessler <b>Wm. A. Wulf*</b> Anonymous (2)
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## Madni Gift (Further) Advances Transdisciplinary Systems Engineering

Azad M. Madni, recipient of the 2023 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education (Gordon Prize), has generously designated his \$250,000 prize winnings back to the National Academy of Engineering, creating the Azad M. and Carla Madni Fund for Transdisciplinary Systems Engineering. Overseen by the NAE Council, this fund will support NAE programs, lectures, forums, research, and broader work with a focus on systems engineering.

Upon his election to the NAE, Azad was celebrated for having “defined the field of transdisciplinary systems engineering (TSE).” At the time, he was also lauded for the creation of transdisciplinary systems engineering education (TRASEE™), a tremendous achievement in higher education.

By designating the Gordon Prize money back to the NAE, Azad and Carla have made another significant impact on the emerging landscape of TSE. Azad explained that TSE “exploits the convergence of engineering with other disciplines to address complex, socio-technical problems that cannot fully be addressed by



Carla and Azad M. Madni

engineering alone.” Azad has already greatly contributed to this pioneering field and will empower countless engineers to benefit from and build upon his transformational work.

The Madnis’ gift qualifies them for the Curie Society of the National Academies of Sciences, Engineering, and Medicine. The Curie Society

acknowledges and honors members and friends whose lifetime giving is \$250,000 or more. The NAE is grateful to partner with an educator so instrumental in the field that the Azad M. and Carla Madni Fund for Transdisciplinary Systems Engineering will work to support.

## Remembering John Brooks Slaughter, Visionary Engineer and Champion of Diversity in Engineering

John Brooks Slaughter, a visionary engineer who established himself as a foremost champion of diversity in engineering and engineering education, passed away on December 6, 2023, at the age of 89. He

was elected to the NAE in 1982 for “contributions to the design of digital, sampled-data control systems, and leadership in shaping national engineering science policy and in fostering increased participation of

minorities in engineering.” He was the third Black person to become a member of the NAE.

Slaughter was born on March 16, 1934, in Topeka, Kansas, and grew up during racial segregation. In an



John Brooks Slaughter (Photo courtesy of USC Rossier School of Education)

interview<sup>1</sup> with NAE President **John Anderson**, one of Slaughter's last recorded interviews, he recalled, "We had to adjust our lives to the fact that there were things we were not going to be able to do." At the same time that racial segregation constrained the possibilities for Slaughter and his family, he said that it also "provided us an opportunity to develop some resolve that was necessary to be able to survive and be productive in that environment."

He had a front-row seat to the events surrounding the landmark *Brown vs. Board of Education* Supreme Court decision, which struck down the "separate but equal" doctrine. His cousin, Lucinda Todd, was among the original petitioners in the class action suit seeking to bring about integration in Topeka's elementary schools.

Slaughter began his formal education at Washburn University,

and then he transferred to Kansas State, becoming the school's first Black engineering student. "I had no Black classmates. I was the only African American in my graduating class," he remembered. He earned a BS in electrical engineering from Kansas State, an MS in engineering from UCLA, and a PhD in engineering science from UC San Diego.

Slaughter was a trailblazer throughout a distinguished, six-decade career that traversed government, nonprofits, and academia. He became the first Black chancellor of the University of Maryland and the first Black president of Occidental College. A cornerstone of his leadership in higher education was his belief in the importance of undergraduate education. Reflecting on why he accepted the position of president of Occidental College, an undergraduate institution, he said, "I believed that undergraduate education was critical. Too many large universities spent more focus on research

and graduate education than they did on preparing undergraduates." He also became the first Black director of the National Science Foundation, where he continued to advocate for the inclusion of women and minorities in science and engineering, and he served as president and CEO of the National Action Council for Minorities in Engineering, where he worked toward increasing the number of engineers of color.

Slaughter was never just focused on getting his own foot in the door. "John also used his professional success to further the cause of minorities in engineering," said **Percy Pierre**, Glenn L. Martin Endowed Professor in the Department of Electrical and Computer Engineering at the University of Maryland, College Park, former president of Prairie View A&M University, and former acting secretary of the United States Army. Slaughter made it his life's work to open the door for other Black engineers and engineers of color. "As

<sup>1</sup> The full recorded interview is available here: <https://www.youtube.com/watch?v=gUgn6N57tfw>.

a Black man born in segregated America, it was inevitable that, once having attained his education in engineering, against the odds, during America’s civil rights decades, almost every position he took was assumed as ‘the first.’ But throughout his career, he worked tirelessly to make sure he would not be ‘the last,’ ‘the only,’ or ‘one of a few,’” said Shirley Malcom, senior advisor and director of SEA Change at the American Association for the Advancement of Science.

Slaughter was unwavering in his commitment to the social good, and he saw engineering as responsible for ensuring the welfare of humanity. As such, he was steadfast in calling on the engineering profession to live up to its full potential. Nowhere was this more apparent than in his Special Lecture on Racial Justice and Equity,<sup>2</sup> which he gave at the 2020 NAE Annual Meeting amid the COVID-19 pandemic and weeks after the summer protests that took place across the globe in response to the murder of George Floyd. “I

<sup>2</sup> <https://www.nae.edu/238776/Special-Lecture-RacialJustice-and-Equity>

believe that the events of the past few months, where white supremacy and anti-Blackness have been on display in ways not seen heretofore in the twenty-first 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,” Slaughter said.

Slaughter stressed that diversity is crucial to the health of the economy, productivity, and the welfare of the United States’ citizens. He contended that “diversity drives innovation,” a fact that he pointed out the field of engineering has been slow to fully grasp. But Slaughter also reminded the audience that “mere diversity is not enough. While diversity is necessary it is not sufficient to ensure that an institution practices equity and inclusion [...] We must commit ourselves to make engineering a professional discipline that is an example of equity and inclusion.” For Slaughter, the ability of the United States to flourish hinged on removing systemic racial barriers. “If we were to eliminate the systemic

racial impediments that crush the aspirations and potentialities 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.”

Slaughter is remembered by friends and colleagues as a kind, humble advocate of all that was right and good. He was gracious and attentive to everyone who crossed his path. “I have always appreciated his warmth and his inquisitiveness,” recalled Warren “Pete” Miller, Distinguished Scholar Professor of Practice, Nuclear Engineering, at Texas A&M University. “We’ll miss his commitment and optimism,” said Shirley Malcom.

The Viterbi School of Engineering at USC, where Slaughter taught as a professor of education and engineering from 2010–2022, honored Slaughter by renaming the Center for Diversity the John Brooks Slaughter Center for Engineering Diversity. He is survived by his wife, Bernice Slaughter, his son, John II, and his daughter, Jacqueline.

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## Rebecca Blessing Joins Membership Office Staff

In her role as NAE membership associate, Rebecca manages the dues process, facilitates registrations for the annual and national meetings, and assists with the maintenance of member records and member elections. She previously worked on the programs staff at the International Center for Journalists. Her portfolio focused on USG grants in Latin

America and South Asia. Rebecca graduated from Baylor University with a degree in international studies and Spanish and is currently working on her master’s in Spanish linguistics at Middlebury College. In her free time, Rebecca enjoys traveling, teaching classes at the Washington English Center, and exploring coffee shops and bookstores around the DMV.



## Calendar of Meetings and Events

January 19	Public Release Webinar: Health Risks of Indoor Exposure to Fine Particulate Matter and Practical Mitigation Solutions Virtual	May 30	NAE Regional Meeting: Tensions at the Edge: Competing Objectives in Engineering Solutions to Society's Most Pressing Problems University of California, Davis
February 21	2024 Charles Stark Draper Prize Presentation By invitation only	June 5	Engineered AI Systems Virtual
March 7	Failures in Social Systems: Converging Biological, Behavioral, and Engineering Insights Virtual	June 17-20	2024 China-America Frontiers of Engineering Irvine, California
March 24-26	NAE Regional Meeting: Excellence in Manufacturing and Operations (XMO) at the Crossroads of America Purdue University	September 11-14	The Grainger Foundation Frontiers of Engineering Symposium Irvine, California
April 2	NAE Regional Meeting: Space and Time Texas A&M University	September 29-30	2024 National Academy of Engineering Annual Meeting Washington, DC
April 17	NAE Regional Meeting: Clean Hydrogen University of Delaware & Chemours		

## In Memoriam

**Geoffrey Boothroyd**, 91, co-founder, Boothroyd Dewhurst Inc., died January 3, 2024. Dr. Boothroyd was elected in 1989 for pioneering work in the field of design of assembly.

**Robert D. Burnham**, 79, retired vice president and chief technology officer, Phoenix Photonics Inc., died June 29, 2023. Mr. Burnham was elected in 1990 for pioneering contributions to semiconductor hetero-junction laser devices and materials.

**Albert A. Dorman**, 97, founding chairman (retired), AECOM, died November 14, 2023. Dr. Dorman was elected in 1998 for the integration of civil engineering and archi-

ecture for large-scale public works projects.

**Nancy D. Fitzroy**, 96, GE Corporate Research and Development (retired), died January 15, 2024. Dr. Fitzroy was elected in 1995 for contributions to technology in heat transfer and for serving as a mentor for women in engineering.

**Samuel C. Florman**, 99, retired chairman, Kreisler Borg Florman General Construction Company, died February 4, 2024. Mr. Florman was elected in 1995 for literary contributions furthering engineering professionalism, ethics, and liberal engineering education.

**Arthur Gelb**, 86, president, Four Sigma Corporation, died November 8, 2023. Dr. Gelb was elected in 2010 for leadership in applying Kalman filtering techniques to the solution of critical national aerospace problems.

**Joseph M. Hendrie**, 98, retired senior scientist, Brookhaven National Laboratory, died December 26, 2023. Dr. Hendrie was elected in 1976 for contributions to both physics and engineering of research reactors and to the safety of large power reactors.

**Allan S Hoffman**, 91, emeritus professor of bioengineering, University of Washington, died December 15,

2023. Dr. Hoffman was elected in 2005 for pioneering work on the medical uses of polymeric materials.

**Charles L. Hosler Jr.**, 99, professor emeritus of meteorology, The Pennsylvania State University, University Park, died October 29, 2023. Dr. Hosler was elected in 1978 for contributions in the application of meteorology to engineering problems, such as power plant siting and cooling.

**Robert C. Lanphier III**, 91, retired president and CEO, AGMED Inc., died December 30, 2023. Mr. Lanphier was elected in 1993 for contributions to application of electronic instrumentation to production agriculture and to assessment of quality of agricultural and food products.

**Stephen L. Matson**, 74, retired professor, Tufts University, died November 27, 2023. Dr. Matson was elected in 1995 for inventing new membrane technologies, including membrane reactors, and as an entrepreneur in the commercialization of these technologies.

**C. Denis Mee**, 95, Fellow (retired), IBM Corporation, died May 22, 2023. Dr. Mee was elected in 1996 for contributions to magnetic storage and the development of thin-film heads.

**David L. Mills**, 85, professor emeritus, University of Delaware, died January 17, 2024. Professor Mills was elected in 2008 for contributions to Internet timekeeping and the development of the Network Time Protocol.

**James K. Mitchell (NAS)**, 93, University Distinguished Professor Emeritus, Virginia Polytechnic Institute and State University, died December 17, 2023. Dr. Mitchell was elected in 1976

for leadership in studies of the engineering properties of soils and soil stabilization and their use in design.

**Ned Mohan**, 77, Oscar A. Schott Professor of Power Electronics and Systems, University of Minnesota, Minneapolis, died February 11, 2024. Professor Mohan was elected in 2014 for contributions to the integration of electronics into power systems and to innovations in power engineering education.

**Arno A. Penzias (NAS)**, 90, venture partner, New Enterprise Associates, died January 22, 2024. Dr. Penzias was elected in 1990 for engineering and management contributions in research on computers, communications, physics, and materials sciences.

**Markus V. Pessa**, 81, professor and director, Tampere University of Technology, died December 31, 2022. Dr. Pessa was elected a foreign member in 2006 for outstanding contributions to optoelectronic devices, and for exceptional leadership in establishing new semiconductor industries in Finland.

**Aristides A. Requicha**, 84, Gordon Marshall Chair in Engineering, University of Southern California, died December 30, 2023. Professor Requicha was elected in 2011 for contributions to solid modeling and programmable automation at the macro- and nano-scales.

**Robert E. Skelton**, 84, Daniel L. Alspach Professor of Dynamics, Systems and Controls Emeritus, University of California, San Diego, died February 15, 2023. Professor Skelton was elected in 2012 for contributions to robust control, system identification, and methodology for control-structure interaction.

**John Brooks Slaughter**, 89, professor of education and engineering, University of Southern California, died December 6, 2023. Dr. Slaughter was elected in 1982 for contributions to the design of digital, sampled-data control systems, and leadership in shaping national engineering science policy and in fostering increased participation of minorities in engineering.

**Charles H. Thornton**, 83, chairman, Charles H. Thornton & Company LLC, died December 12, 2023. Dr. Thornton was elected in 1997 for the design of major structures worldwide.

**Don Walsh**, 92, president, International Maritimes, died November 12, 2023. Dr. Walsh was elected in 2001 for contributions to the development and advancement of deep-sea engineering systems.

**Dianzuo Wang**, 89, vice president, Chinese Academy of Engineering, died October 25, 2023. Dr. Wang was elected an international member in 1990 for pioneering contributions in flotation theory for mineral processing.

**Vern W. Weekman Jr.**, 92, Faculty Industrial Lecturer, Princeton University, died January 14, 2024. Dr. Weekman was elected in 1985 for pioneering contributions in applying theory to practice and for combining technological achievement with engineering education.

**Kaspar J. Willam**, 83, Cullen Professor of Engineering, University of Houston, died January 7, 2024. Dr. Willam was elected in 2004 for contributions to constitutive modeling and computational failure analysis of concrete and quasi-brittle materials and structures.

**Niklaus Wirth**, 89, retired professor, ETH Zurich, died January 1, 2024. Dr. Wirth was elected an international member in 1993 for developing computer languages and systems having pedagogical and pragmatic impact.

**Theodore Y. Wu**, 99, professor of engineering science, emeritus,

California Institute of Technology, passed away on December 16, 2023. Dr. Wu was elected in 1982 for milestone contributions to hydrodynamics, and its application to the motions of vehicles and to the propulsion of animals through fluids.

**James C. Wyant**, 80, professor emeritus, University of Arizona, Tucson, died December 8, 2023. Dr. Wyant was elected in 2007 for the development of interferometric optical measurement techniques with nanometer precision for use in production environments.

# Invisible Bridges

## Engineering Our Wicked Problems



**Guru Madhavan** is the Norman R. Augustine Senior Scholar and senior director of programs at the National Academy of Engineering. His new book is *Wicked Problems: How to Engineer a Better World* (W.W. Norton, March 2024), from which this article is adapted.

Life comes with pernicious problems, some with recognizable plots. We excel in solving the well-behaved ones, but intractable problems create more questions. In a 1965 lecture, the British philosopher Karl Popper classified problems using the metaphors of *clocks* and *clouds*. He compared systems that obey logic to clocks and those that defy logic to clouds. Unlike a timepiece's predictability, the shifting subtleties of clouds reside in their myriad forms and shadows.

For William Shakespeare, clouds were simultaneously dragons, bears, lions, citadels, capes, and cliffs. And in John Constable's assiduous sky paintings, the cloudscapes were "the chief organ of sentiment." Their fluctuations and formlessness made it clear that "no two days are alike, not even two hours." Clock systems construct our comforts. They direct electrons to send messages, summon shared rides, trade stocks, swipe for dates, and livestream K-pop. With cloud systems, we have only shadowboxed the problems. And then there are the cloudiest of them, the "wicked" problems.

### Clocks and Clouds

Each wicked problem is unique. These challenges have vexing staying power, working like franchises, with premieres and prequels, remakes, reissues, reboots, sequels, spin-offs, and streaming on demand. One can't opt out, log off, autocorrect, unsubscribe, block, mute, cancel, or shut down wicked problems. Nor can we click and clear

them like browser history. As their forms change, so do their formulations. With wicked problems, we tend to carve off pieces that invite rational solutions, leaving the rest for others to manage. Often, however valuable, technical fixes and related policy statutes may become the first and the final solutions for problems that are otherwise significantly behavioral and cultural. But tackling part of a problem may deceive us into thinking that the whole problem is tamed. "Look, I've not tamed the whole problem," as scholar Charles West Churchman once observed, "just the growl; the beast is still as wicked as ever." And scholar John Warfield used the term "spread-think," the opposite of groupthink, to describe how, in a wicked problem, individuals cannot focus and agree on its critical elements.

A simple equation named "the monster" can help us think about wickedness:  $I=2^{n(n-1)}$ , where  $I$  is the number of states a system could have with  $n$  number of elements. Suppose all the components interact with one another straightforwardly. Then, a two-element system results in 4 states, and a three-element system has 64 states. In a ten-element system, the number of states will exceed the number of stars in our galaxy. While wicked problems are inherently knotty, we increase their complexity with our human bramble of beliefs and deficits, paradoxes and priors. And worse, wicked problems are invoked so often, they are tainted by simple familiarity; consider how often we evade—even disregard—the daily degradations from "climate change," even if those words are now routine.

Engaging with wicked systems requires more than good intentions, creativity, and expertise. We need a communal code of conduct—or in an engineering sense,

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

a *concept of operations* to train and treat our approaches (including, especially, education) to gain greater improvements. To do so, we need an engineering vision for civics and a civic vision for engineering. Engineers, after all, aren't commonly invoked as enablers of democracy, yet they do more than "tech support." Engineering is a carrier of history, simultaneously an instrument and the infrastructure of politics. It's among the oldest cultural processes of know-how, far more ancient than the sciences of know-what. And through engineering, civics can gain a more structured, systemic, and survivable sense of purpose. By applying engineering concepts in a civic context—and by proactively educating engineers how to do so by incorporating insights from history, philosophy, and cultural evolution—engineering can usefully grow the policy lexicon and enhance its cultural relevance. The usefulness of civics and engineering is often realized only in their breakdowns, much like trust, most longed for in their absence.

### **A Systems Engineering Sensibility**

Developing a civic consciousness to achieve democracy's goals will fundamentally require a systems engineering approach, which is not some specialty tool embedded in an AIE (acronym-intensive environment). Indeed, before specialization altered many engineering practices beyond recognition, a kind of "systems sensibility" pervaded early engineering. Consider the thinking behind the development of the Indus Valley from the Bronze Age. Sophisticated food production, grid-town planning, drains, dams, and dockyards were a testament not merely to civil engineering but to a form of *civic* engineering. They improved both standards of living and thinking. Systems planning to those engineers meant braiding commerce and culture, from recreation to conservation. Many Native traditions have applied such overarching awareness. Prominent successes of industrial systems engineering, including telecommunications and missile defense systems, were evident during World War II. The applications reached a broader scale between the 1950s and the 1970s in the defense, aerospace, urban-planning, and manufacturing sectors.

Systems engineering, like civic duty, occurs under the constraints of costs, schedules, and performance requirements. While systems engineers often focus on the needs, desires, end points, and context of a problem set, they know that local fixes will not produce a globally viable solution. An engineering process based on cost, sched-

ule, and performance requirements works well for aircraft assembly. Once that plane begins to fly, however, it enters a broader social system with different levels of complexity. Should we add capacity at a near-city airport or build new facilities farther away? Each option now involves considerations far afield from aircraft yet central to the aviation system. That's why systems engineering often works best when it's not expected to produce an "engineering" solution.

Taking a systems engineering approach—duly considering all facets of a problem—with a far broader scope might sound unnatural, especially for the issues of business, government, and civic life. The idea of dividing a year into days or a circle into degrees and using clocks was unnatural and required an initial mental leap. Even flying was—and *is*—unnatural for humans. Still, we acquired the skills to do it, with iteration eventually becoming intuition. In practice, systems engineers recognize *sensitivities* (as in all too commonly, when an economic incentive can deleteriously affect the environment), shape *synergies* (where multiple actions can achieve a benefit that a single activity cannot), and account for *side effects* (what influences what, beneficially and adversely).

The next time you drive across town, think about energy efficiency. You can technically express how efficient your car is in fuel use or how economical it is to get to your destination compared to other modes of transport. But the fact that you chose to drive could be behavioral, and having to go across town could result from poor urban planning, which may be political. Across these levels, engineers seek a baseline understanding of facts and assumptions, often shaping their products and services as an exercise in trade-offs. Certain factors and viewpoints are privileged over others, akin to a projector spotlighting the main actors, leaving the rest behind the scene. Further, engineers often characterize themselves as "problem solvers," so much so that it's part of their primary professional identity. But for wicked problems, one must go beyond mere problem-solving, and engineering education should contribute to this crucial cognizance.

Scholar Russell Ackoff observed that not all ways of viewing a problem are equally productive. Still, the most productive views are seldom evident. Problems should be approached from as many angles as possible before the measures are selected to address them. Effective problem formulation requires, first, awareness of the types of problems that lead to wickedness.

### **The Hard, the Soft, and the Messy**

Call the first type “hard problems.” They are bounded and boundable, and scientific principles, market pressures, and sponsor requirements neatly specify them. The outcomes are directed— even dictated—by customers, consumers, and clients. Have you used your smartphone to check into a flight? Or, did you self-checkout at the grocery store or use a QR code to order tacos at a chic gastropub? These outcomes are products of hard problems. And as with standardizing production processes for Coca-Cola, cars, and cans of crinkle-cut carrots, they can be solved by recombining and repurposing existing tools and techniques. Such problems can be mathematically manipulated, chemically configured, and materially improved. Ultimately, they can be “optimized” by applying available knowledge and experience with the idea that the best possible outcome exists and is achievable.

The second class, call it “soft problems,” is in the arena of human behavior, which is complicated by political and psychological factors. Because their end points are unclear, and thorny constraints complicate their design, soft problems cannot be solved like hard problems; they can only be resolved. There are no easy fixes to a problem like traffic congestion. Adding more road capacity won’t necessarily clear out bottlenecks on a throughway, nor can congestion pricing if the charges are unaffordable for most people who use a tunnel. Such interventions depend on the contexts for which they are designed: what works for Charing Cross Road may not work in Chengdu or Chennai. Even in the same city, what works for one bridge may not work for another.

Notably, soft problems often involve how we assign value to time and how much we are willing to pay for it. They require political buy-in that may eventually pay for a service and behavior change that might inspire elements such as added public transportation or more flexible teleworking arrangements. Since soft problems involve technology, psychology, and sociology, resolving them yields an outcome that’s not the best but only good enough—and what’s best for one area might not be always best for the others. As Ackoff characterized it, the results are based not on optimizing but on “satisficing,” an approach that satisfies and suffices.

The third class, “messy problems,” emerges from differences and divisions created by our value sets, belief systems, ideologies, and convictions. A disease out-

break may involve hard problems with solutions such as barcode-tracked supplies or antibiotic deliveries. The outbreak’s soft problems might require resolutions like mapping infectious disease spread or retooling the indoor environment to prevent the propagation of infection. Neither resolution is exact, but both are good enough. By contrast, a messy problem can involve a pathogen gaining antibiotic resistance or intersecting with delicate religious rituals, as was evident with the Ebola outbreaks in recent years. How can we reframe centuries of tradition into safe, acceptable burial practices while respecting cultural sensitivities? Such messy situations may only be abstractly dissolved by transforming them into a different, possibly manageable state. Messy problems can be reframed out of existence not by optimizing or satisficing but by “idealizing.” In Ackoff’s words, this entails getting the matter, as in creating dignified burial rituals and promoting safe public health practices, “closer to an ultimately desired state, one in which the problem cannot or does not arise.”

### **Solutions, Resolutions, and Dissolutions**

A wicked problem emerges when hard, soft, and messy problems collide. If they were works of art, hard problems would be photographs, offering clarity and directness. Soft problems are like blurry brushstrokes of impressionism, and messy problems are spilled and splattered abstractions. A wicked problem emerges when hard, soft, and messy problems collide. Think of them as a cubist collage where the truth is simultaneously sharp, shaky, and squiggly. All three are required for wickedness. Seen this way, there’s hardness nestled in soft problems, and hardness and softness reside within messy problems. By extension, a solution can be within a resolution, and a dissolution might contain resolutions and solutions.

Of course, one might absolve the world’s problems with a doomed shrug—but that’s not the point of good engineering education, let alone practice. Engineers should consider how hard problems become soft, how soft problems evolve into messy ones, and how hard, soft, and messy problems conspire to produce wickedness. This is a requisite competency—and consciousness—for us to develop a balanced blend of hard solutions, soft resolutions, and messy dissolutions to wicked problems. To do so, we’ll need to exercise and enrich a broader systems engineering sensibility—in education and practice.





# The BRIDGE

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