On the Horizon

Revisiting the Future of Chemical Engineering

Phillip R. Westmoreland
North Carolina State Univ.

Clare McCabe
Vanderbilt Univ.

Some of the profession's thought leaders share their visions of the future of chemical engineering.

As part of AIChE's Centennial celebration in 2008, leaders from industry and academia and a group of graduate students and postdocs speculated about chemical engineering 25 years in the future (www.aiche.org/resources/publications/cep/2008/november/chemical-engineering-next-25-years).

Ten years have brought changes in the world, changes in chemical engineering, and changes in the contributors' perspectives. In 2008, data analytics, CRISPR, cyberthreat analysis, exascale computing, fracking, Lyft, and Uber were obscure or nonexistent terms. The iPhone had just been introduced the year before. Now, everyone is contactable at any time, not just by text message and email but by voice and face-to-face video. Smartphones have become ubiquitous and extraordinarily powerful and versatile, both for personal use and in professional settings.

In 2008, it might have seemed ludicrous to predict that the future of the car would not include drivers or that parts delivery would be by speedy drones. In 2018, thanks to recent and extraordinary advances (sensors, computing power, artificial intelligence), it seems that driverless cars are now inevitable and could become a reality in the not-too-distant future. Just as the aviation industry grew up in a highly regulated environment, making commercial air travel extremely safe, so will driverless vehicles, resulting in far fewer accidents. Our work commutes and our supply chains will be affected, and warehouses and long-haul trucking companies will hire pilots for off-interstate maneuvering.

We also cannot predict perfectly where economics will take chemical engineering. When we posed our questions in late summer 2008, the Great Recession had not yet hit. In 2008, the five largest companies in the U.S. by market capitalization were ExxonMobil, General Electric, Microsoft, AT&T, and Procter & Gamble; the five largest in the world were PetroChina, ExxonMobil, General Electric, China Mobile and ICBC (China). In 2018, the five largest, both in the U.S. and in the world, are Apple, Google, Microsoft, Amazon, and Facebook. ExxonMobil has dropped to Number 7 in the U.S., and AT&T and Procter & Gamble are no longer in the U.S. Top 10. Largely on the basis of the iPhone, Apple went from 15th largest in the U.S. in 2008 to Number 1.

Setting the scene

In this article, many of the 2008 contributors reflect on their visions of the challenges and changes in chemical engineering. We also hear from some new contributors, including graduate students and postdocs with fresh points of view, sophistication in their subfields, and a willingness to speculate.

To help them frame their visions, we posed the same four questions as in 2008 and chose chemical engineers from different sectors and development areas, different locations, and different career stages, expecting them to build their visions from their particular perspectives. The questions were:

1. Looking into the next 25 years, how do you expect your industry/research area to evolve due to market and technological opportunities?

2. Traditional core areas of ChE expertise — such as applied chemistry, transport processes, process analysis and design, and business/communication skills — are being augmented by new expertise in science and engineering at molecular and nanometer scales, in biosystems, in sustainability, and in cyber tools. Over the next 25 years, how will these changes affect your industry/research area?

3. What new industries/research areas do you foresee, appearing as wholly new or between existing ones?

4. Taking into account the ongoing evolution of the profession — including the need for new modes of education; high standards of performance and conduct; effective technical, business, and public communication; and desires for a more sustainable future — what do you think the chemical engineering profession will look like 25 years from now?

One approach toward making predictions is to project from today's trends and breaking developments. However, such extrapolation is hard. Some predictions will inevitably be upended by unforeseen scientific discoveries, technical advances, product demands, and global economic and political swings. A complementary approach is to project backward from the future, envisioning future needs and demands then speculating about how we might meet them, challenging our imaginations. Many of the needs will be the same as today. Others will be startling, disruptive developments.

The visions shared here suggest how we can collectively shape our profession to be what we think it needs to be.

In their reflections, our respondents provided some terrific insights into where chemical engineering is now and where it's going. **Billy Bardin** of Dow Chemical expressed some of these needs:

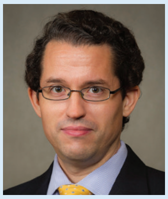
- The increasing economic power and the rise of the middle class in today's developing countries will drive demand for more materials, energy, products, and access to technology; new, more efficient methods of materials production; process intensification, energy intensity improvements, and zero emissions technologies.
- Consumers, society, and regulatory bodies will demand better carbon efficiency and reduced overall emissions to the environment.
- The ever-increasing demand for food will be satisfied by the application of enhanced farming and food-generation methods using nontraditional farming techniques, new bio-based active agents, and data sciences.
- Limited access to water will continue to drive technology advancements for purification, desalination, and recycle capabilities.
- Consequences of previous and current waste generation will require new industries built around the reuse and recycle of existing landfill materials. Demand for lighter-weight, more-durable materials that are fully and easily recyclable will increase.
- Renewal of civic infrastructure — bridges, roads, electric grids, water systems, and others — will involve more-cost-effective and innovational designs in which chemistry and materials will be key.

Viewing more broadly, **Jim Stapleton** from the Univ. of Oregon argued that chemical engineering must aim to "address the biggest problems facing humanity. To be welcoming to all. To connect theory, simulation, experiment, and analysis. To promote openness, reproducibility, civility, and reason."

Beyond satisfying our natural curiosity, such visions and this analysis matter because they can help us. We hope the contributors' thoughts will trigger ideas about how you might shape your own personal directions and those of the organization you work in. They suggest how you might respond technically and as a citizen of your community, your nation, and the world. Finally, they suggest how we can collectively shape our profession to be what we think it needs to be.

Article continues on next page

BILLY BARDIN, P.E.

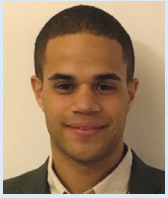


is the Global Operations Technology Director at Dow, where he is responsible for driving technology and innovation strategy. He serves on the AIChE Board of Directors.

MARC BIRTWISTLE

is Associate Professor of Chemical Engineering at Clemson Univ. In 2008, he was completing his PhD research at the Univ. of Delaware with Prof. Tunde Ogunnaike.

NICHOLAS BURTCH



holds a Harry S. Truman Fellowship in National Security Science and Engineering at Sandia National Laboratories. He earned his PhD in 2016 from Georgia Tech with Prof. Krista Walton.

Different worlds of energy in 2008, 2018, and 2043

The energy sector remains a vibrant part of the economic landscape. During the period 2008–2010, U.S. field production of crude oil had dropped to 5 million barrels per day; thanks to tertiary oil recovery methods — including fracking — and significant increases in efficiency, oil production reached 11 million bbl/day in 2018 for the first time ever, propelling the U.S. into second place among world producers (after Russia and ahead of Saudi Arabia).

At the same time, renewable energy (hydrothermal, wind, solar, geothermal, biomass) has increased from 9.25% of total U.S. electricity production to 17.12% in 2017. Clearly, chemical engineers have a role to play both in the traditional fossil-fuels-based energy sector and in the emerging renewables sector.

The resurgence of fossil fuels, and the attendant drop in the price of oil and natural gas, was a rueful surprise to several of the respondents who in 2008 had predicted increasing reliance on renewables like biofuels for energy. **Curt Fischer** of Stanford Univ. was one of them, acknowledging that "the annual failures of the renewable fuels industry to live up to Congress's 2007 production mandates do not bode well for near-term progress."

Jeff Siirola, of Eastman Chemical (retired) and Purdue Univ., summarizes the situation well: "A decade ago, we knew about shale gas, but we had no idea just how easy and inexpensive it would be to produce. … Predictions of the need to develop alternative chemistries and processing technologies for both fuels and chemical feedstocks (especially from coal and biomass) were not borne out." Siirola also makes salient points about shale gas, for which the primary saleable component is methane. However, because it is "wet gas," other light hydrocarbons are present. Their availability as a byproduct may drive their price toward zero, hence creating opportunities for new processes based on these essentially free feedstocks.

An optimistic, nuanced prediction comes from **Vijay Swarup,** Vice President for R&D at ExxonMobil Research and Engineering, who expects the demand for transportation fuels to continue rising due to economic growth and prosperity, particularly in developing countries, driven, unprecedently, "not by cars, but by demand for heavier fuels for trucks and airplanes." Swarup believes that chemical engineers will be able in the future to combine, for example, advances in computational modeling, data analytics, optimization tools, and next-generation and bio-based catalysts to produce fuels and chemicals at scale with lower emissions. "Simply put, we are moving to an '*and*' period in chemical engineering. The future of the energy industry will involve traditional chemical engineering areas like transport phenomena and process design *and* advanced computational capabilities *and* bio-catalysts *and* improved sensors and analytics," he believes.

Now and in the future, cost-effective renewable-energy sources affect processes and business. **Patrick McGrath**, of the U.S. Dept. of Energy's (DOE) Advanced Research Projects-Energy (ARPA-E) program, makes the point that, in many locations, the price of electricity being generated from solar energy is now lower than that of other forms of electricity generation, and it continues to drop. In a future scenario, a chemical plant powered by solar energy (combined with electrical power storage to smooth out availability) would have very different economics than one designed in an environment dependent on grid-based power sources. As he rightly points out, "it's hard to conceive the number of opportunities this [development] would present to reimagine chemical processes." At the same time, improved storage of electric energy is important. "Considering future needs for an electric grid with much greater penetration of cheap renewable (and variable) sources, we need to look beyond lithium," he notes.

Nuclear power, enrichment, and nuclear waste were not mentioned by the respondents, but these topics will still be with us in 25 years. The use of coal for fuel will likely decrease further, and abundant natural gas may be the dominant source of transportation and power-generation fuels.

Expanding health-related biotechnologies

Biotechnology as bioprocessing goes back to the beginning of chemical engineering, and now has broadened. Biology has become a molecular science; chemical engineers apply molecular sciences; thus, it is natural that chemical

JULIE CHAMPION

is Associate Professor in the School of Chemical and Biomolecular Engineering at Georgia Tech. In 2008, she had earned her PhD at the Univ. of California Santa Barbara with Prof. Samir Mitragotri and was a National Institutes of Health Postdoctoral Fellow at Caltech with Prof. David A. Tirrell.

PETER CUMMINGS

is the John R. Hall Professor of Chemical Engineering and Associate Dean of the Engineering School at Vanderbilt Univ. He is the winner of the AIChE Alpha Chi Sigma (1998) and Founders (2010) awards in recognition of his research accomplishments and leadership in molecular modeling and computational nanotechnology.

CHRIS ELLISON

is Associate Professor and Piercy Professor in the Dept. of Chemical Engineering and Materials Science at the Univ. of Minnesota (UMN). In 2008, he was a postdoctoral researcher at UMN with Prof. Frank Bates, and from 2008 to 2016 he was Assistant and then Associate Professor at the Univ. of Texas at Austin.

engineers are deeply involved in the expanding range of modern biotechnologies.

Consider the range of 25-year biotechnologies envisioned by **Bob Langer** of the Massachusetts Institute of Technology (MIT). In 2008, he predicted "new types of information in genetics leading to more personalized diagnostics and medicines … new materials leading to new medical devices … delivery of complex molecules, including potential new drugs such as siRNA and DNA," adding that nanotechnology and nanoscale transport offered "new possibilities in non-invasive delivery, cell-specific drug delivery, and sensing." So far, so good, he thinks in 2018, adding immunology and gene-editing drugs as more opportunities for chemical engineers.

How we got here. Industry has long used fermentation, bioreactants, extraction of natural dyes and drugs, and chemical syntheses to mimic or tweak biomolecules, applying the evolving biology and chemistry of the time. The useful reactor-engineering expression for enzyme kinetics by Michaelis and Menten dates to 1913, and was based on an empirical binding model from the time when the idea of enzyme-substrate binding was still new. Similarly, evolving higher-quality organisms and bioresources used empirical genetics effectively.

The turning point came in 1953, when the team of Watson, Crick, and Franklin found a physical and chemical structure of DNA that rationalized biological function and inheritance. Twenty-five years later, companies began forming to create biologic pharmaceuticals through molecular genetic engineering. They soon began hiring chemical engineers to make the biologics once the gene-splicing and expression were achieved.

In the 1990s, academic chemical engineering was getting deeply engaged in biological sciences, processes, and products. In 2004, AIChE established the Society for Biological Engineering (SBE) as a technological community, promoting the integration of engineering with biology.

Where we are now. Three dramatic developments in this area since 2008 are CRISPR-based tools for gene editing; affordable, practical gene analyses; and the popularization of data science and informatics.

CRISPR-Cas9 is the most talked-about method for gene editing, bursting onto the scene in just the past six years. A synthesized segment of RNA is used to recognize a DNA sequence while carrying an attached DNA-snipping enzyme to it. The DNA can then be altered, potentially correcting single-gene diseases like cystic fibrosis and hemophilia and, eventually, more complex genetic diseases. A key to gene editing and other advances is that examining genes is now quicker and more affordable. **Marc Birtwistle** of Clemson Univ. notes that for DNA sequencing, "the cost of sequencing a human genome decreased from ~$100 million to $1,000 in 15 years," pointing toward individualized targeting of medicines and treatments that is already happening in areas as diverse as liver function and chemotherapy. Interestingly, the period 2008–2018 has witnessed the most nonlinear reduction in cost. At the same time, he cautions, "statistical data mining and other big-data approaches alone are, in my opinion, unlikely to be sufficient in such regards. First-principles and mechanism-based thinking that defines us as chemical engineers will almost certainly be required to help separate signal from noise in the march towards improved ability to simulate and predict human system responses to therapy."

Rapid analyses of DNA and specific genes have transformed pharmaceutical development and manufacturing. As **Bob Steininger** of Surface Oncology, Inc., points out: "Genes and gene information are becoming more important to biochemical engineers. The biotech industry has expanded the monitoring of gene expression, used to determine the probability of a new drug's success. We are doing this regularly in the development of new drugs. In fact, the regulatory authorities expect submissions to include such data. As such, activity assays based not only on cell function but also on gene expression are becoming part of the release process. In addition, DNA analysis and DNA quantitation are now being used for release of product (gene therapy) and monitoring

CURT FISCHER

is Head of the Metabolic Chemistry Analysis Center in the Chemistry, Engineering, and Medicine for Human Health (ChEM-H) program at Stanford Univ. In 2008, he was a PhD candidate in the MIT Laboratory for Bioinformatics and Metabolic Engineering with Prof Gregory Stephanopoulos.

RAFIQUL GANI

is CEO of PSE for SPEED. He retired at the end of 2017 as professor of systems design in the Dept. of Chemical and Biochemical Engineering at the Technical Univ. of Denmark. He served as Editor-in-Chief of *Computers & Chemical Engineering* and President (2014–17) of the European Federation of Chemical Engineering.

CHRISTINE GRANT

is Professor of Chemical and Biomolecular Engineering and Associate Dean of Faculty Development and Special Initiatives at North Carolina State Univ., a researcher in surface and environmental science and biomaterials, a former board member of AIChE, and a mentor to underrepresented minority and women faculty.

the level of processes for impurities (virus, bacteria), helping to make production more cost-effective."

Where we're going. The hallmarks of the future rest on two factors. First, chemical engineers bring key tools and expertise into the fields of bioscience and biotechnology. Second, and perhaps more important, is chemical engineers' positive attitude toward partnering across disciplines, and learning about and benefiting from each other's expertise.

Synthetic biology is real now, and it has only scratched the surface of its possibilities. This field redesigns DNA — and thus cells — to create traits that did not exist before. It also creates biologically based chemistry with cells and even with amino acids and other bio-based molecules that do not exist in nature. **Ashty Karim**, a graduate student at Northwestern Univ., summarizes: "In the last 25 years, there has been a dramatic increase in the tools we have available to engineer and rewire biological systems. … These newfound capabilities along with the need for greener, more sustainable methods of producing chemicals and fuels, will ring in an era of biotechnology. … Specifically, we will see an increase in biotechnology products on the market for high-value chemicals, nutraceuticals, and medicines. We can also expect new biotechnological routes to carbon sequestration and recycling."

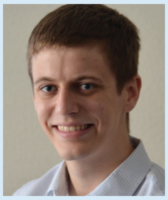
Another key to the future is applying chemical engineering's strengths to the modeling of systems biology and systems pharmacology. Systems biology, the computational modeling of biological systems as a dynamic reaction network, is a foundation for understanding how biology works and also for engineering it. **Marc Birtwistle** remarks, "Systems pharmacology models could account for important features of drug action, such as on- and off-target effects, potential toxicity, dosing, dynamics and sequence. … Such abilities are synergistic with simulation models that try to capture drug-response behavior, which can allow an exploration of which delivery mechanisms are likely to be more effective … [as well as] better prediction of how complex multifactorial diseases such as cancer will respond to drugs and drug combinations, or how otherwise healthy organ systems may have adverse reactions to the same."

Industry has sought to perform molecular design of drugs through computer modeling since the 1960s. Given the challenge of matching nature's inventiveness, a broader view now is that prediction should be integrated with high-throughput screening and the growing database of clinical observations. Personalized medicine presents new challenges, as clinical trials are now designed to examine large patient populations, not individual patients.

Ryan Snyder of Bucknell Univ. emphasizes that the full context of drug design and development has to be considered, including development cost, pricing, and government decisions. "In the pharmaceutical industry, it would be valuable for chemical engineers and other scientist and engineers to make contributions to challenging social issues such as the way in which pharmaceutical prices may be set, the extent to which regulations should dictate the marketing and advertising of pharmaceuticals, and the development of best practices in designing and implementing clinical trials. Thus, it is incumbent upon educators to provide not only technical content, but to interface technical content with broad perspectives in a student's university experience," he says.

Healthcare sensors, bioactive synthetic materials, and diagnostics are good examples of future transdisciplinary roles, calling for expertise in engineering, medicine, biology, data science, and polymer chemistry. Graduate student **David Mackanic** of Stanford Univ. remarks that "health-based wearable sensors are projected to receive widespread adoption over the next decade," thanks both to advances in electronics and to chemical engineers' creation of multifunctional polymeric materials. **Christine Grant** of North Carolina State Univ. points out that such smart electronics "provide instant access to information for both patients and the medical establishment" but also require combining expertise in sensing, analytics, interpretation, and communication of the medical data. Likewise, chemical engineers have already been involved in health informatics, seen by

MIKE HOWARD

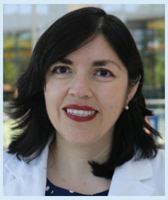


is a Postdoctoral Fellow at the Univ. of Texas at Austin working with Prof. Thomas Truskett. He recently earned his PhD from Princeton Univ. under the supervision of Prof. Athanassios Panagiotopoulos studying soft matter out of equilibrium.

JOSH HOWE

is conducting postdoctoral research at Georgia Tech under the direction of Prof. David Sholl. He earned his PhD in chemical engineering at the Univ. of California Berkeley.

CONCHITA JIMÉNEZ-GONZÁLEZ



is Director and Program Lead for Global Manufacturing and Supply at GlaxoSmithKline, lead author of a textbook on green chemistry and engineering, and served as Vice President of the Society of Hispanic Professional Engineers.

Cristina Thomas of 3M as “enhancing greatly every person’s medical care and improved responses to public health emergencies.”

Ashty Karim suggests broader possibilities still: “With rapidly increasing abilities to control biological systems, engineers play a unique role in being able to merge biology with materials and electronics for use in energy and medicine. You could imagine manufacturing of new materials containing both natural and synthetic biological systems, abiotic and biotic systems working together to develop emergent material properties. These materials could manifest as diagnostics for rare diseases, sensors for our bodies, or even energy storage devices. These fields, which seemed separated before, are beginning to intertwine in beautiful and unforeseen ways. Materials printed with circuitry and bacteria, or enzymes that can detect and react to many environmental situations, would be useful for both commercial and defense applications.”

Many contributors noted that it is crucial for chemical engineers to deal both with the bioscience and with its moral and ethical implications. For example, the potential for CRISPR-based methods to alter body (somatic) cells is one thing, but the feasibility of altering inheritable genes in reproductive cells raises profound ethical concerns.

Finally, biology, especially molecular biology, will become recognized as a necessary element of every chemical engineer’s skill set. At the 2013 AIChE Annual Meeting, John Chen led a plenary panel on how new chemical engineers need to be prepared. Panelists from oil, chemicals, and pharmaceuticals all emphasized that their new hires need to know basic modern biology. Why? As **Vijay Swarup** of ExxonMobil notes now, basically because “biology and bio-inspired processes from biofuels to bio-catalysis will likely increase in prominence.”

Computing, data, and what we’ll do with them

One of the potential changes that could affect the impact of computing on the future of chemical engineering is the looming end to Moore’s law (*i.e.,* the principle that the number of transistors in a dense integrated circuit doubles about every two years). Predictions made in 2008 were embedded in an environment where Moore’s law was still applicable, albeit by doubling the number of cores in processors rather than doubling processor speed, every 18–24 months. Many-core processors, including graphical processing units (GPUs), are now standard. While Moore’s law may be slowing, the staggering decadal increase in computing power will no doubt continue, and at some point in the not-too-distant future will be joined by the advent of commercial quantum computing. Several of the respondents indicated that aspects of chemical engineering will continue to be revolutionized by advances in computing power.

Ubiquitous computing power has made artificial intelligence (AI) an emerging practical tool; in particular, machine learning has begun to make inroads in the analysis of data, whether the data are experimental measurements, process data, or data obtained from simulations at scales ranging from electronic and atomic scales to macro scale. Data analytics, whether traditional (statistics) or informed by machine learning, is frequently cited as an expertise that will have dramatic impact on many aspects of chemical engineering, ranging from materials discovery to process design to process operations to supply chain management.

Peter Cummings of Vanderbilt Univ. pointed out that in 2008 the iPhone was just a year old; then, no one predicted the enormous progress that the iPhone and other similar smartphones would make as tools for personal pleasure, business, e-commerce, etc. Just trying to imagine what the smartphone could evolve into over the next 25 years, and how it could be used in the everyday work life of a practicing chemical engineer, suggests infinite possibilities. **Vijay Swarup** summed it up well in stating, “Increased computational capabilities as well as sensors and other analytical tools will continue to underpin technical developments in the energy sector. Modeling will become more efficient and [more] accurate, allowing for advances in multiscale process development. Improved data analytics and data storage (*e.g.,* the cloud) will allow for remote access of data and more efficient optimization of global networks.”

Ubiquitous computation will also lead to ever-expanding

ANDREW KARAS

completed his PhD at the Univ. of Michigan, supervised by Prof. Sharon Glotzer. He recently started a position in quantitative analytics and model development at PNC.

ASHTY KARIM

is an NSF Graduate Research Fellow conducting PhD research at Northwestern Univ. under the direction of Prof. Michael C. Jewett. He earned his BS in chemical engineering at the Univ. of Texas at Austin.

VICKY LANGE

is a Postdoctoral Research Associate at University College London, conducting research on ionic liquids for actinide and lanthanide separations and on countercurrent chromatography. She earned her MSc and PhD from the Univ. of Nottingham,

opportunities for chemical engineers to benefit from informatics: health informatics, process informatics, materials informatics, and so on. Informatics is related to the emergence of data science, but pertains to the raw data, while data science is the manipulation of raw data to infer insight. Health informatics is being driven in part by the proliferation of sensors on smartphones and fitness devices; people are recording more and more information about their daily health statistics, and new sensory devices will increase this in the future. One day, we may all be heading in the direction of the quantified-self movement and its most visible pioneer, Larry Smarr (www.quantifiedself.com/2013/02/larry_smarr_croneshope_in_data).

Process monitoring is becoming increasingly sophisticated and data-rich. Computational and experimental databases on materials properties are expanding dramatically, in part in response to the U.S. government's Materials Genome Project (www.mgi.gov), and in part because researchers recognize that unless their "measurements" (whether experimental or computationally derived) are incorporated into federated databases, they will have little impact on the design of new materials. The resulting material informatics "will give a true competitive advantage to scientists and engineers, since it can allow for discovery, understanding, design, selection, and use of truly novel materials at a much lower cost and within much tighter time frames," according to **Cristina Thomas**.

Computational science already plays a major role in chemical engineering, from quantum and molecular simulations to predict thermophysical, transport, and chemical properties needed for materials discovery, to fluid dynamics simulations and model fluid flow; from both static and dynamic process design simulations, to static and dynamic simulations of supply chains. Younger-generation chemical engineers foresee ubiquitous computation as brokering the merger of these currently scale-separated simulation capabilities. **Velencia Witherspoon**, a postdoc at the National Institute of Standards and Technology (NIST), sums it up: "The experimental description of dynamics, complemented by modeling at extended time scales, is the challenge presented to those who wish to employ molecular design to advance materials and process performance." **Michael Howard,** a postdoctoral researcher at the Univ. of Texas at Austin, expresses it as "engineering design problems will expand to encompass objectives at multiple scales, such as concurrently engineering the microscopic characteristics of a material with the process by which it will be manufactured or produced." Multiscale modeling has long been an as-yet elusive goal for the computational modeling community, but the next 25 years could well see it become a reality.

Computational design and evaluation of new materials is another aspect. **Josh Howe**, a PhD student at Georgia Tech, comments that "the availability of large material datasets in the form of databases … enables us to take more of a 'big data' or consensus approach to evaluating materials and validating modeling results. There is a need in the materials chemistry community to not only understand the sources for observed variations in material properties, but also to understand how to best describe materials characterization in light of this understanding. There is likely a wealth of replicate data that is unpublished and therefore widely unknown, and figuring out how to incentivize and credit release of this data to build on our understanding of materials will be a key to advancing the field in coming years."

Processing and products: Science, manufacturing, and sustainability

Process sciences and engineering are traditionally at the heart of chemical engineering and will surely remain so. However, "the heart needs to make room" for process+product co-design; technology-intensified processes; analytics; and sustainability.

Before we discuss these four aspects, let's consider what we mean today by process sciences and engineering. Process sciences include thermodynamics, transport phenomena, separations, kinetics and reactor engineering, process design, and process control, and are seen as the traditional building blocks of the profession. Our respondents think that this approach has proved complete enough and adaptable enough to persist as a model for the next 25 years and longer. At the same time, advancing fundamentals of process and product science and engineering is essential to the vitality and effectiveness of chemical engineering.

The sector employing the most chemical engineers is the chemical manufacturing sector itself. It remains one of America's top exporting industries, with $174 billion in exports in 2016, accounting for 14% of all U.S. exports. The U.S. had a trade surplus of $28 billion in industrial chemicals in 2016 and announced new investments in chemical manufacturing capacity that will generate over $100 billion in new shipments by 2023, inevitably subject to global economic conditions.

Clearly, manufacturing is a vibrant part of the present and future of chemical engineering. Analysis of the 2000 and 2017 AIChE salary surveys (Figure 1) shows that the dominant sectors of its membership are chemicals, petrochemicals, pharmaceuticals, and materials. There is great diversity beyond those, including environmental and safety (4.1% in 2017), foods and beverages (3.3%), equipment manufacturing (1.7%), and aerospace and automotive (1.6%). Some changes occurred between 2000 and 2017, including modest increases in pharmaceuticals and materials and significant growth in specialty chemicals.

The major business shift in the chemical process industries (CPI) has been a change in emphasis from commodity to specialty products. Non-petrochemical U.S. commodity-chemicals giants of 40 years ago, such as Dow, DuPont, and Monsanto, have morphed and/or have been taken over.

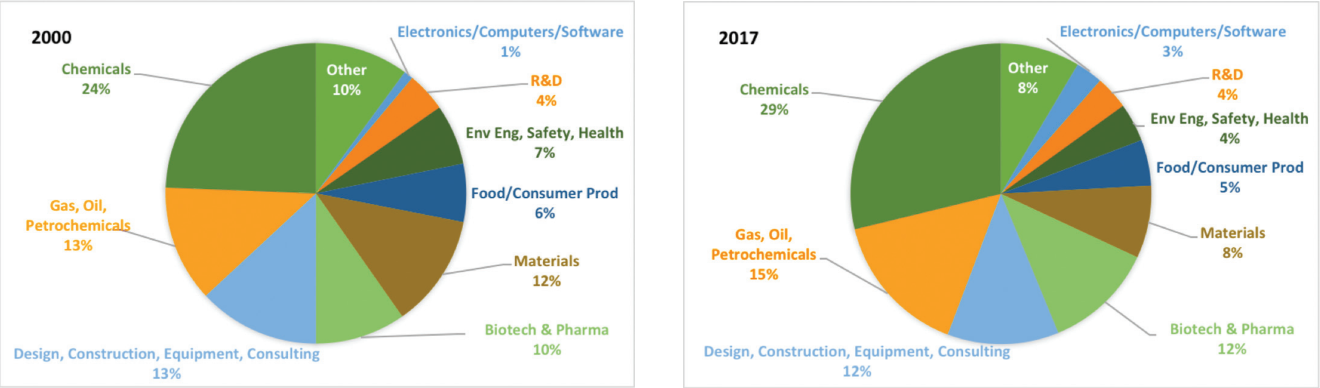
Future expansion in the process industries sector is expected in response to demand for new materials, pharmaceuticals, and agricultural products for industries such as transportation, housing, medicine, energy storage, carbon capture, and environmental protection/remediation. It is possible that commodity products themselves will be largely unchanged. **Jeff Siirola** speculates, "I suspect in the next 25 years there will be much increase in worldwide production (more than double?), but even so, more than 95% (by mass) of all chemical products made then will be compositions that are already being made today and they will be made by technologies again mostly already in use today (with the addition of carbon management). The profession will evolve but maintain its sensitivity to safety, environmental protection, social responsibility, ethics, and continuous improvement."

> Manufacturing is a vibrant part of the present and future of chemical engineering.

In addition to market growth coming from customer demand, new technologies and their combinations will provide compelling ways to control costs and create demand. **Cristina Thomas** sees "the convergence of chemistry, biology, engineering, and digital [constituting] the perfect storm for new platforms. Innovative materials platforms will be possible thanks to new processing technologies: additive manufacturing, bioprocessing, synthetic biology, digital twins, AI-driven processes and robotics, to name a few."

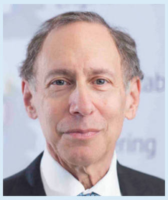
Many of these expectations can and likely will be altered by economic conditions and politics locally, nationally, and internationally. The best recent example is the impact of fracking-generated hydrocarbon resources on economies and the CPI around the world. **Chris Ellison** of the Univ. of Minnesota is in good company when he reflects on his 2008 vision: "I was wrong about increased prices for fossil fuels setting the stage for a biomass-fueled chemical industry. It hasn't happened yet, and the annual failure of the renewable-fuels industry to live up to Congress's 2007 production mandates do not bode well for near-term progress. It's too early to give up on the idea entirely, of course."

Jan Lerou of Jan Lerou Consulting LLC and formerly Catalytica and DuPont, responded similarly. "Natural gas



▲ **Figure 1.** Employment of chemical engineers by sector, based on the 2000 and 2017 AIChE Salary Surveys, excluding government and academic employment. Sources: "Salary Figures by Industry" as reported in the 2000 AIChE Salary Survey, web.archive.org/web/20010617072729/www.aiche.org/careerservices/trends/salarydata.htm; and "Median Salaries" as reported in the 2017 AIChE Salary Survey, *CEP,* June 2017, www.aiche.org/resources/publications/cep/2017/june/2017-aiche-salary-survey-overview.

BOB LANGER



is David H. Koch Institute Professor at the Massachusetts Institute of Technology, holder of more than 1,300 issued or pending patents, founder or co-founder of more than 26 companies, and a member of all three U.S. National Academies — of Science, Engineering, and Medicine.

JAN LEROU

consults as Jan Lerou Consulting, LLC, and has served as Professor of Practice in the Chemical Engineering Dept. of Washington Univ. in St. Louis since 2011. In 2008, he was CTO at Velocys Inc, after working at Catalytica and before that for 16 years at DuPont Research and Development.

JINGHAI LI

is President of the National Natural Science Foundation of China, Vice President of the International Council for Science, former Vice President of the Chinese Academy of Sciences, and lead author of the book *From Multiscale Modeling to Meso-Science.*

and crude oil prices did drop but the development of renewable fuels slowed as well. As a consequence, the rate of adoption by the chemicals industry increased only slowly," he says. At the same time, he felt that others of his 2008 predictions were on track: "Data mining, CO_2-based production of chemicals, and distributed production are expanding quickly and will come to full fruition in the next decade."

We'll now consider each of the four broad areas of change separately.

Process+product co-design. Chemical engineers are increasingly part of designing and developing new specialty products, formulations, and materials whose properties are often sensitive to or determined by optimally designed and operating processes. By integrating process and product design, both can benefit. **Rafiqul Gani**, retired from DTU and is now the CEO of PSE for SPEED (www.pseforspeed.com), expects that "methods and tools for design and development of multifunctional materials (catalysts, polymers, nanoparticles, etc.) will be established. Based on these, new tailor-made products (functional products and devices) will be routinely developed for different industrial sectors (chemicals, pharma, food). 3D-printer-based products in food and medicine will be available."

Pharmaceuticals are another case in point. **Bob Steininger** described the substance of the cross currents involved. From the process side, "many companies are considering the use of continuous production processes to better control product properties and cost. The need to maintain a continuous process in the context of growing organisms, and to monitor, understand, and control the variables that yield consistent product in a manufacturing environment, will be a challenge to engineers," he says. At the same time, he adds that "the processes used to make new biopharmaceuticals are changing. New drugs enable cells within the body to make products which the patient lacks (gene therapy, modified bacteria as drugs). Cells from the body are also isolated, modified, and reintroduced to the patient to eliminate cancer (cell therapy). The processes to make these new drugs require steps for production and purification that are similar, but not identical, to those used previously. Many of the assays used to monitor the process have to be developed. The product is often a live cell. In addition, the average target population is much smaller than the number of patients treated previously with the original biologic drugs." Integrating process developers in medicine-development teams is vital.

Technology-intensified processes. Unit operations — grouping of common features and fundamentals among processes — was and is a powerful concept. Additive manufacturing and process intensification move beyond existing unit operations, and process analytics and machine learning will change process workflows.

Several respondents highlighted additive manufacturing as an emerging technology that is poised to have a major impact on chemical production. Manufacturing goods like cars and appliances has been a mix of machining (subtractive manufacturing) and assembly, but they also use batch processes of casting and molding. Additive manufacturing takes that a step further. **Nick Burtch**, a Truman postdoc at Sandia National Laboratories, points out, "Additive manufacturing provides a degree of design flexibility not accessible via traditional manufacturing approaches, and with this will come unprecedented opportunities for process integration, including the rapid prototyping and manufacture of consolidated parts with greatly improved reaction and mass and heat transfer characteristics." In 2018, customized cars and houses are being 3D-printed, owing to spectacular advances in the field. Where once there was a small set of polymers that could be 3D-printed, now many different materials can be 3D-printed, including metals, biological tissue, and food. 3D-printed organs are nearing the point of clinical testing.

Process intensification has long existed as a concept with potential for:

- making hybrid processes like reactor-separators
- using intensified driving forces to reduce capital and energy costs
- making smaller process units that are modular and right-sized to deliver targeted amounts of product.

European and Chinese manufacturers are applying these

DAVID MACKANIC

is a PhD student at Stanford Univ., supervised by Prof. Zhenan Bao under an NSF Graduate Research Fellowship and the Stanford Graduate Fellowship. His research focuses on novel polymeric systems to improve the safety, longevity, and energy density of Li-ion batteries.

PAT McGRATH

is Deputy Director for Technology and a Program Director at the Advanced Research Projects Agency-Energy (ARPA-E). In 2008, he was a Senior Consultant with Booz Allen Hamilton, having recently completed his PhD research at the Univ. of California, Berkeley, with Prof. Jeffrey Reimer.

MEREDITH SELLERS, P.E.

is a Managing Engineer at Exponent, where she specializes in materials characterization and incident investigation. A licensed Professional Chemical Engineer, in 2008, she was conducting PhD research at the Univ. of Illinois Urbana-Champaign with Prof. Edmund G. Seebauer.

approaches successfully. The DOE/AIChE Rapid Advancement in Process Intensification Deployment (RAPID) Manufacturing Institute aims to develop new, intensified technologies, as well as ways to think about and create them.

Analytics and machine learning. Products, operations, and supply chains will shift rapidly to benefit from analytics — the discovery and expression of useful information in data, especially large datasets. The broader term "analytics" began taking over from "business intelligence" about the time of our 2008 study, popularized by the writings of Tom Davenport of Babson College and the 2003 book *Moneyball.*

The power of analytics will come from myriad small sensors, feeding data through radio frequency identification (RFID) and wireless technologies. **Andrew Kara**, PhD candidate at the Univ. of Michigan, foresees "increased adoption of lab-on-a-chip and more broadly micro-electro-mechanical systems (MEMS) devices. A key enabling factor for this area to take off will be the use of self-assembly processes for creating micro- and nano-scale features. I think one important consideration for commercializing such technology for sensors and control devices is that one doesn't necessarily need to create a device that has the best possible fidelity for single measurements. If one creates devices capable of making and transmitting many measurements, it would instead be possible to rely on the law of large numbers and data processing for accuracy."

A broader application is smart manufacturing, powering dramatic improvements in operational and business decision-making through data analytics. Illustrating the potential for many sectors, **Conchita Jiménez-González** of GlaxoSmithKline (GSK) comments: "I expect that the pharmaceuticals industry will incorporate even more automated processes that rely more on automated algorithms for control and supply-chain decisions. R&D will rely increasingly on *in silico* modeling for product and process development, shortening the development times. I expect co-boting (human-robot co-work in a shared workspace) and process intensification as normal experiences in manufacturing. Highly automated processes and controls will produce a level of data output and connectivity not seen before in the industry, potentially connecting directly to consumers, and perhaps moving more towards personalized medicines. Extensive use of data will bring challenges on analytics, visualization, and cybersecurity as part of that change." Similarly, **Ryan Snyder** expects that as solubility and polymorph prediction evolve in the coming years, "there are also significant current opportunities in development, not only to use predictive models but also to combine predictive methods with the growing opportunities to use 'big data' and machine learning to fully develop our understanding of these and other complex phenomena."

Process analytics and machine learning can be valuable aids to science, manufacturing, and safety. Anecdotally, 90% of the time required to perform analytics has been organizing and cleaning data. Hands-on work-up should be greatly improved by machine-learning assistance.

Sustainability. Analyzing the long-term "triple bottom line" of social, environmental, and financial impacts is the foundation for sustainability-based decisions about products and processes. GSK's **Conchita Jiménez-González**, author of *Green Chemistry and Engineering: A Practical Design Approach,* expects "the next 25 years will bring sustainability assessments that are intrinsically embedded in process and product development. Sustainability considerations will drive decisions in supply chain, products, and processes. Renewable energy use and alternative fuels will necessarily increase given energy demands and population increases. I expect the routine evaluation of alternative assessments for potential substitutions of chemicals of concern, particularly on consumer products. I expect the development of new materials to substitute for scarce ones (*e.g.,* metals). Data will be key to assessing impacts of materials across the value chain to avoid regrettable substitutions, where 'the remedy is worse than the illness.' As data will continue to be scarce, particularly with new materials, predictive algorithms will be needed to increase the accuracy of evaluations."

Flexibility is another aspect of sustainability. **Rafiqul Gani** foresees that "in order to become more sustainable,

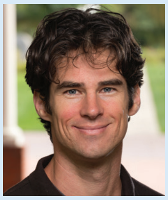
JEFF SIIROLA

retired in 2011 as a Technology Fellow at Eastman Chemical Co. and is now Professor of Engineering Practice at Purdue Univ. He is a member of the National Academy of Engineering and was the 2005 President of AIChE.

RYAN SNYDER

is Associate Professor of Chemical Engineering at Bucknell Univ. In 2008, he was conducting PhD research at the Univ. of California, Santa Barbara, with Prof. Michael F. Doherty.

JIM STAPLETON



is Courtesy Research Assistant Professor in the Dept. of Biology at the Univ. of Oregon. In 2008, he was completing his PhD research at Stanford Univ. with Prof. James Swartz.

technologies for ‘process-driven’ industries as well as ‘process-enabled’ industries will become versatile and intelligent. That is, from the same resources, they would be able to switch from one processing route to another so that a class of products depending on the need and demand can be manufactured.”

Managing finite resources will require substituting with regenerable or recoverable resources. Today’s landfills may become future mines. In her work, **Vicky Lange**, an NRC postdoc at NIST, deals with recovery of rare earths and other technological minerals that we need. “If we are to tackle these sustainability issues and fully embrace green technologies of the future, we will need to have an adequate supply of the rare earth metals and technological minerals that are needed to build or create that technology. These metals will be the catalyst for future development of green energy production and they will continue to be used in everything from electric motors to wind turbines,” she says. In the next 25 years I believe that better metal recycling routes and technology will be developed to help satisfy industrial hunger for these metals, while I also think that greater emphasis will be placed on the development of suitable substitutes (other metals or synthetic substitutes),” she adds.

Process safety impacts society’s acceptance of manufacturing. The fates of Union Carbide Corp. and Bhopal provide a tragic example. **Billy Bardin** emphasizes that technology can help: “The need for operators and engineers to work in potentially hazardous environments will be eliminated and no longer accepted as general practice. For example, confined space entries (CSE) into vessels and equipment will be obsolete due to the capabilities of robotic tools for inspection and maintenance work as well as *in situ* sensor technology. Dow is a leader in the application of robotics in the process industries and has goals in place to eliminate CSEs. Process equipment design will need to evolve in order to accommodate robotic work more easily.”

Decisions based on sustainability may become the norm, resting on accountability for decisions that can affect us now and in generations to come. For example, most countries and industries have accepted that we will have to cope with effects of climate change, although it has remained a hot-button issue in the U.S. **Peter Cummings** observed, “In recent years, companies have been going on record about the deleterious effects of future climate change, as they have to prepare to operate in a more challenging environment.” For manufacturing, adapting requires infrastructure protection, altering processes and feedstocks, and managing supply chains. For customers in agriculture, adapting to climate change means coping with temperature and precipitation changes by altering crops, livestock, and production locations. An important question for chemical engineering’s future is whether climate changes can be reversed, stabilized, or will accelerate.

Education objectives and approaches

A consensus view on education is that the fundamentals of chemical engineering — chemistry, mathematics, physics, material and energy balances, heat and mass transfer, separation processes, and thermodynamics — will still be as relevant 25 years from now as they are today, and as relevant as they were in 2008. Like many of the respondents, **Jinghai Li,** Director of the National Natural Science Foundation of China, feels that “traditional core areas of ChE expertise, such as applied chemistry, transport processes, process analysis and design, and business/communication skills, will continue to be important, but surely in a totally different paradigm.” The reason given by many is that this core education expertise has proven to be so adaptable and relevant.

All the respondents were confident that chemical engineering would exist as an identifiable discipline in 25 years’ time, albeit perhaps with additional specializations within the discipline (*e.g.,* nano-chemical engineering). Beyond the core fundamentals, skills that respondents saw as being important for the chemical engineer of the future include data analytics and machine learning, interdisciplinarity (the ability to interface with other scientific and engineering disciplines), systems biology, process intensification, sustainability, ethics, public communication, entrepreneurship, globalization, and additive manufacturing (also known as 3-D printing).

Another imperative, echoed by many respondents, is the

BOB STEININGER

is Senior Vice President for Chemistry Manufacturing and Control at Surface Oncology, Inc. He has worked for 34 years in pharmaceutical manufacturing. In 2008, he was Senior Vice President for Manufacturing at Acceleron Pharma.

VIJAY SWARUP

is Vice President for Research and Development at Exxon-Mobil Research and Engineering Co. Over his 27-year career with the company, he has held a variety of engineering, planning, and managerial roles.

JAN TALBOT

is Professor Emerita of Chemical Engineering and Materials Sciences at the Univ. of California San Diego. She is a past president of the Electrochemical Society.

need for diversity among chemical engineers. Diversifying the pool of engineers in general, not just chemical engineers, is a long-term process, with no easy solution in sight. According to statistics from the American Society for Engineering Education, the fraction of bachelor degrees earned by women has hovered at around 20% over the period 2006–2014, the fraction earned byAfrican-Americans has seen a decline from 5% to 3.5% over the same period, and the fraction earned by Hispanics has increased from 6% to 10%. At the doctoral level, the numbers are similar, with a notably lower percentage of Hispanics earning PhDs. Making increased diversity a goal for the profession requires the concerted effort of many stakeholders (industry, academia, high schools, etc.) in strengthening the STEM pipeline from the earliest ages.

As **Christine Grant** noted, "it will be critical to engage all segments of our society, broadening participation and drawing on the diverse perspectives of our entire population. The profession cannot afford to fail to utilize the entire demographic available to solve complex issues. In this regard, the authentic inclusion of women and underrepresented minorities in the profession will only enhance the robust, rich nature of the technologies that chemical engineers will create."

Jan Talbot of the Univ. of California, San Diego (UCSD) provides an interesting perspective. In 2008, the promise of nanoscience and nanotechnology led UCSD to create a Dept. of Nanoengineering, which is the administrative home of chemical engineering at UCSD. Both the nanoengineering and chemical engineering degrees offered by the Dept. of Nanoengineering are ABET-accredited. In developing the curriculum for nanoengineering, Talbot and her colleagues regarded this as "the future of chemical engineering education for an industry based on nanoengineering. … However, the attractiveness and rapid growth of this new discipline for students has not matched the need in the job market as yet." Another ambitious vision of chemical engineering, inspired by where the future of the field is heading, is the Dept. of Energy, Environmental and Chemical Engineering at Washington Univ. in St. Louis, founded in 2006. Only time will tell whether we will see more of these combinations of educational disciplines grouped with chemical engineering. However, given the increasing degree to which chemical engineering expands its reach into other fields (biological and medical sciences, electrochemistry, nanoscience and nanotechnology, informatics, to name just a few), additional such hybrid academic homes for chemical engineering may emerge.

Various aspects of biology feature in the respondents' comments on education. For example, **Marc Birtwistle** sees systems biology as an important component in the education of future chemical engineers. The implication for chemical engineering of the coming tsunami of sequence data, coupled to clinical data (*e.g.,* in databases such as BioVU, victr.vanderbilt.edu/pub/biovu) is not yet clear, but chemical engineers are sure to play a major role in so-called precision medicine, since the success of precision medicine relies on being able to design and synthesize drugs optimized to an individual patient's genetic make-up and disease state. To prepare chemical engineers for this new world, Birtwistle calls for "the acceptance of biology as a core chemical engineering science on the same level as chemistry and physics" and a possible future "shift from focus on scale-up to scale-down."

The big picture: The future of chemical engineering itself

The mosaic of contributors' ideas forms a picture of a discipline with divergent, multiple identities. That's upsetting to some people and ideal to others. In many ways, it's nothing new. Chemical engineers have long worked in diverse industries while using a remarkably consistent skill set, even while the distribution of subfields has changed a lot. These skills define the profession's core, but they shouldn't restrict it. Academically, chemical engineering has long been open to recruiting faculty members with nontraditional (*i.e.,* outside of chemical engineering) academic training, which has led to constant renewal of the field. It is vital that such recruits have the expectation and buy-in of being part of both fields: chemist-ChE, physicist-ChE, electrical engineer-ChE, biochemist-ChE, and so on.

Addressing society's needs requires many skills to be

CRISTINA THOMAS

is Senior Technical Leader in the Corporate R&D Services Center at 3M. Among her prior accomplishments, she led reinvention of the 3M window-film product platform and the design and implementation of new product introduction processes.

VELENCIA WITHERSPOON

is an NRC-NIST Postdoctoral Fellow in the Functional Polymers group of the Material Science and Engineering Div. at the National Institute of Standards and Technology (NIST). She earned her PhD in 2017 from the Univ. of California, Berkeley under the supervision of Prof. Jeffrey A. Reimer.

applied in concert. We can't be experts about everything, but we do need to understand each other's insights and expertise enough to be effective. **Meredith Sellers** of Exponent, Inc., observes, "New expertise in science and engineering at the molecular and nanometer scales has certainly led to a redefinition of what it means to be a chemical engineer. … Chemical engineers are increasingly working in embedded teams of materials scientists, electrical engineers, and physicists, and may feel equally comfortable characterizing carbon-based energy storage devices as assessing offshore platform operators' risk-based inspection programs. This diversification will only serve to reinforce chemical engineering as one of the most versatile engineering disciplines."

As **Conchita Jiménez-González** puts it, "For future chemical engineers, systems thinking will continue to be an ever-important asset given the convergence of all the disciplines. Cross-functional and multidisciplinary work will become more important for them."

This convergence isn't a merging of all disciplines; some may merge, and others may split out. Rather, it is professionals converging into a goal-focused collaboration, bringing their respective capabilities, perceptions, and considerations. They must learn enough about the system of interest and about all the resources at hand. **Pat McGrath** adds, "Chemical engineers, indeed all engineers, will need to work together to meet our needs across all sectors. Much of this will need to be built into our training, and we are already seeing that happen through innovative approaches in education, research collaborations, and in entrepreneurship." There will be changes of content, but as **Ashty Karim** asserts, we will "incorporate our new understandings of how chemical engineering is integral to manipulating biological, chemical, and material systems separately and together. Chemical engineering will keep its solid foundation in transport, thermodynamics, and kinetics, but there will be even more applications of this powerful discipline. The factors that will change are (1) which specializations will exist and thrive, and (2) how will we adopt new practices more quickly and not let tradition keep us from evolving."

A discipline cannot be a siloed section of knowledge. Rather, it should be transdisciplinary, a boundaryless core of expertise, expanding and collaborating to be most effective. By this measure, chemical engineering should be a model for all disciplines.

Finally, the future of chemical engineering rests on sharing an attitude about working toward the future we envision. **Julie Champion** of Georgia Tech was writing about education, but her comments speak to all of us: "The most successful chemical engineers will be those who are willing and brave enough to take risks, not with safety or the environment, but by taking on leadership roles even if their job title does not suggest it, and by challenging the status quo with new ideas, new questions, and new connections with other fields. It is not enough to produce students with good grades who can solve idealized problems if they do not reach their full potential in the face of real-world challenges. Rather, academic institutions need to insist, 'How do we instill this behavior in our students: To take risks, to encourage failure and learning from failure, and to step up to lead?'" **CEP**

To read more of the contributors' thoughts and to continue the discussion, see the blog series
"Revisting the Future of Chemical Engineering [Interviews]"
online at www.aiche.org/revisiting-future-interviews.

PHILLIP R. WESTMORELAND is Professor of Chemical and Biomolecular Engineering at North Carolina State Univ. (NCSU; Email: prwestmo@ncsu.edu). He was 2013 President of AIChE, was the founding chair of the Computational Molecular Science and Engineering Forum, is a Fellow of AIChE and the Combustion Institute, and is a trustee and past president of CACHE (Computer Aids for Chemical Engineering Education). He received the 2017 AIChE Institute Award for Excellence in Industrial Gases Technology for his experimental and computational achievements in the chemistry of fire suppressants and air-pollutant prevention. He also received the American Society for Engineering Education's 2002 William H. Corcoran Award, as well as AIChE's 2007 George Lappin Award, and shared the 2009 Gary Leach Award. His chemical engineering degrees are from North Carolina State Univ. (BS), Louisiana State Univ. (MS), and the Massachusetts Institute of Technology (PhD).

CLARE McCABE is the Cornelius Vanderbilt Chair and Professor of Chemical and Biomolecular engineering at Vanderbilt Univ. She is also Associate Dean of the Graduate School and Director of Vanderbilt's Office of Postdoctoral Affairs. McCabe received her bachelor's degree and PhD from Sheffield Univ. in the U.K. and moved to the U.S. in 1999 as a postdoc. After postdoctoral and research faculty appointments at the Univ. of Tennessee, she joined the Colorado School of Mines faculty as an assistant professor in 2002 and moved to Vanderbilt in 2004. She is a fellow of the Royal Society of Chemistry and a senior member of AIChE. She is a trustee of CACHE and in 2014 received the Computational Molecular Science and Engineering (CoMSEF) Impact Award.