





Chemical Engineering in the Next 25 Years

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U. S. NATIONAL SCIENCE FOUNDATION
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Twenty-five of the profession's
thought-leaders speculate about
what the future holds.

In 2008, the American Institute of Chemical Engineers celebrates the 100th anniversary of its founding. The profession itself began earlier, taking shape from different sources, including industrial chemistry, electro-chemistry, oil processing, food processing, and mechanical engineering. To honor that history, AIChE's Centennial Celebration Committee has compiled (and *CEP* has published throughout the year) lists of achievements, of pioneers, and of texts that show the evolution and notable highlights of chemical engineering.

The collection of thoughts analyzed in this article journeys in the other direction — to the future of the chemical engineering profession. The participants' complete comments, from which this article is derived, are available on the AIChE Centennial Website: www.aiche.org/100.

How well can we predict?

Just as with looking backward, efforts to look forward are limited by the vision and experience of the participants. Looking forward is further hampered by our simple inability to imagine what advances will have the most impact.

It is difficult even to imagine the advances themselves. Each fall, Beloit College issues its Mindset List (www.beloit.edu/mindset), reflecting on what the newly entering students have never known and what they have always known. For this year's entering Class of 2012, the web (once known as the World-Wide Web) and the Hubble Space Telescope have always existed, Jay Leno has always hosted *The Tonight Show*, and apartheid and the Berlin Wall have always been only historical references. Superman hasn't changed clothes in a phone booth, either.

Similarly, consider a chemical engineer's perspective

25 years ago, in 1983. As **Peter Cummings** (Professor, Vanderbilt Univ.; Principal Scientist at the Center for Nanophase Materials Sciences, Oak Ridge National Laboratory) remarks, “Distributed computing was just coming into existence with Unix workstations, and personal computers were beginning to make their mark; the Apple Macintosh, the popularizer of window+mouse graphical user environments, was still a year away from introduction; the cell phone was the stuff of science fiction.”

Molecular biology had begun to have an impact on chemical engineering as the first genetic engineering companies began. Chemical engineers were familiar with materials like zeolites, whose features were of nanometer scale, and the term “nanotechnology” had been coined by Taniguchi in Japan in 1974, but it had only begun to be recognized as an organizing concept.

The same challenge was true at earlier quarter-century marks. By 1908, chemical engineers had become skilled in assembling the equipment needed for chemical processing, but the organizing principle of “unit operations” was yet to be established by Arthur D. Little in 1915. It quickly led to the prominence of continuous processing, aided by the burgeoning demand for gasoline. Neoprene, the first synthetic rubber, had been invented in 1930, but at AIChE’s 25-year mark in 1933, the invention of nylon by Wallace Carothers was still a year away. In 1958, many academics were working to articulate the organizing concept of “transport phenomena,” but the textbook of Bird, Stewart, and Lightfoot would not be published until 1960.

Plainly, 25 years is a reasonable horizon for our speculation. The ideas may not exist yet, but their seeds are already in place and visible.

Our visionaries and their charge

We asked three small groups of chemical engineers to offer their visions.

First, we approached department heads of top U.S. chemical engineering graduate programs to identify a particularly visionary and articulate post-doc or senior graduate student to respond. There were no instructions or restrictions on what topics should be represented, so in some measure, they often represent what the department heads consider to be the hottest research areas. These individuals (p. 34) are truly at the cutting edge of chemical-engineering advances, and they are sufficiently experienced to have developed independent viewpoints.

With graduates going into business, law and medical schools, chemical engineering has become an important “liberal engineering” degree.

Second, chief technology officers and other industry leaders were asked to participate personally or to nominate a participant. These chemical engineers (p. 36) were sought from a range of industries to elicit diverse viewpoints.

Finally, again seeking a diverse set of opinions, U.S. and international faculty were contacted. This group (p. 38) includes respected educators and researchers, many of whom have extensive consulting and entrepreneurial experience.

We posed four questions and solicited brief responses related to each individual’s industrial sector or area of research. This allowed respondents to discuss their specific visions, yet left room for generalizations as well. The questions asked for extrapolation, new impacts on existing sectors, new sectors, and additional comments on the future of the profession as a whole:

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

2. Traditional core areas of chemical engineering expertise like applied chemistry, transport processes, process analysis and design, and business/communication skills are being augmented and changed 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 sector?

3. What new sectors do you foresee, appearing as wholly new or between existing sectors?

4. These are important aspects that make up the future chemical engineering profession. So are the needs for advancing initial and continuing education; high standards of performance and conduct; effective technical, business, and public communication; and desires for a better and more sustainable future, individually and collectively. Considering all these factors, what do you think the chemical engineering profession will be like 25 years from now?

Evolution of energy and chemical sectors

Chemical engineers presently work in an amazingly diverse number of industries and jobs built on chemistry as the core science. The biggest sector for many years was “oil and chemicals.” In 1991, 63% of new graduates entered these companies, dropping to 41% during 1997–2000.

These fields remain major employers of chemical engi-

neers, while employment has increased dramatically in other sectors, including the food, personal care products, materials, electronics, pharmaceuticals, and environmental control industries. An important fraction of new graduates goes instead to business, law, and medical schools, making chemical engineering an important “liberal engineering” degree.

The energy sector still holds exciting possibilities. Air and highway transportation will continue to depend on liquid fuels because of high fuel-energy density, relying on improvements in efficiency to limit CO₂ emissions. Biomass-derived fuels can potentially balance CO₂ emissions with the CO₂ consumed by growth of new plant matter, although the current approaches of corn- and grain-derived ethanol do not.

In contrast, fixed-point and distributed energy use can draw from many sources. Chemical engineers are deeply involved in developing fuel-cell technologies, solar cell materials, energy storage, CO₂ sequestration for coal-generated electricity, and advanced approaches to nuclear energy for electricity and an eventual hydrogen economy.

Jeff Siirola (Technology Fellow, Eastman Chemical) sees carbon management becoming a major upcoming business sector, noting that “most likely, efficient carbon management will depend significantly on chemical processing technology and expertise.”

Emil Jacobs (Vice President of Research and Development, ExxonMobil Research and Engineering) points to coming growth in all segments of the petroleum industry: upstream, downstream, and petrochemicals. He asserts that for “exploration, development and production, the focus will be on using improved seismic and production technology to discover and produce increasingly more remote and difficult-to-extract hydrocarbon reserves.”

Processing will push toward cleaner and better-performing fuels and lubricants demanded by new engine technologies. Key enablers will be process intensification; energy integration; new catalysts from coupled experiments and modeling to produce liquid fuels from biomass, natural gas, and heavier feedstocks; new sensor and analytical technologies; advanced optimization algorithms; and faster scale-up by using scale-spanning models that are fed by fundamental parameters from small laboratory experiments.

Chemicals will remain a high-value product of petroleum but will increasingly be produced from additional feedstocks. Siirola notes that Eastman Chemical is already using coal as a principal feedstock for its organic-chemical product lines.

Jan Lerou (Manager of Experimental Operations, Velocys) remarks on the promise of CO₂-based production



Post-docs and Grad Students

MARC BIRTWISTLE holds a BS from the Georgia Institute of Technology, is completing his PhD research at the Univ. of Delaware with Professor Tunde



Ogunnaike, and will go on to post-doctoral studies at the Beatson Institute for Cancer Research in Glasgow, Scotland.

JULIE CHAMPION earned her PhD at the Univ. of California Santa Barbara with Professor Samir Mitragotri, and is presently a post-doctoral researcher at the



California Institute of Technology working with Professor David A. Tirrell; she will join the chemical engineering faculty at the Georgia Institute of Technology in 2009.

CHRIS ELLISON earned his PhD with Professor John Torkelson at Northwestern Univ., conducted post-doctoral research studying polymer-phase behavior of nanostructured



materials with Professor Frank S. Bates at the Univ. of Minnesota, and in August 2008 started at the Univ. of Texas, Austin, as an Assistant Professor of Chemical Engineering.

CURT FISCHER is a PhD candidate in chemical engineering at the Massachusetts Institute of Technology, conducting research in the Laboratory for Bioinformatics and



Metabolic Engineering under the supervision of Professor Gregory Stephanopoulos.

MEREDITH KRATZER is conducting PhD research on band engineering of semiconducting metal-oxide catalysts for environmental applications at the Univ.



of Illinois Urbana-Champaign with Professor Edmund G. Seebauer, and she expects to graduate in 2010.

PATRICK McGRATH recently completed his PhD in chemical engineering at the Univ. of California, Berkeley, studying fuel-cell catalysts with Professor Jeffrey A. Reimer,



and he is presently a senior consultant with Booz Allen Hamilton, Inc.

RYAN SNYDER is conducting PhD research on crystallization at the Univ. of California, Santa Barbara, with Professor Michael F. Doherty.



JIM STAPLETON is a PhD student at Stanford Univ., conducting biotechnology research with Professor James R. Swartz.



of chemicals. He emphasizes that “CO₂ capture and sequestration will only be sustainable if CO₂ is used as a carbon source. There are already first results converting CO₂ in methanol and splitting CO₂ with solar energy.”

The need for change will put pressure not only on petrochemicals, but also inorganic, agricultural, and specialty chemicals. **Hank Kohlbrand** (Global R&D Director for Engineering and Process Sciences, Dow Chemical) sees energy costs, sustainability, and market locations as driving forces causing dramatic shifts in raw materials and energy sources for chemical production.

Mayis Seapan (DuPont) declares, “A switch from traditional sources of energy and raw materials to biological resources will be the most dominant change.” Along those lines, **Marc Birtwistle** (PhD student, Univ. of Delaware) sees opportunities aided by genetic engineering: “Energy-intensive reactors and separators can be replaced with a single vessel containing rationally engineered microorganisms capable of performing multiple catalytic steps,” possibly using “customized biomass feedstocks with optimal processing properties.”

Likewise, small-scale, distributed chemical production is emerging to complement the large-scale, centralized processes that have been a hallmark of the success of chemical engineering. “Distributed production will allow localized production of chemicals and energy with a reasonable capital investment,” according to Lerou. “This goes in the opposite direction of the economy of scale and will require a retooling of the engineers’ minds.”

Curt Fischer (PhD student, MIT) agrees, pointing out that “as process development timelines shorten, so likely will the lifetime of any one particular molecular product — an improved replacement may never be far behind. These considerations, combined with the distributed nature of tomorrow’s feedstocks, may drive trends towards chemical processes with lower capital.”

Leaders from around the world echo and extend these points. **Jackie Y. Ying** (Executive Director, Institute of Bioengineering and Nanotechnology, Singapore) also sees great possibilities for advances in catalysis. She believes that conversion of biomass and carbon dioxide into practical forms of energy and useful chemicals will “require new advances in catalytic chemistry and processes, most likely based on nanocomposite catalysts.” China is applying significant resources to catalysis research for just such reasons.

Wolfgang Marquardt (Professor, RWTH Aachen) envisions “radically new processing technologies leveraging multi-functional and microscale reaction and separation equipment ... to facilitate not only more-efficient but also very flexible production.”

Rafiqul Gani (Professor of Systems Design, Technical Univ. of Denmark) adds that “technology for ‘process-enabled’ industries (such as specialty chemicals, active materials, biomaterials, etc.) will be dominated by the control of the end-use properties of the product, as well as synchronized (and rapid) development of a product and process that are safe and environmentally acceptable.”

Biology as a chemical engineering science

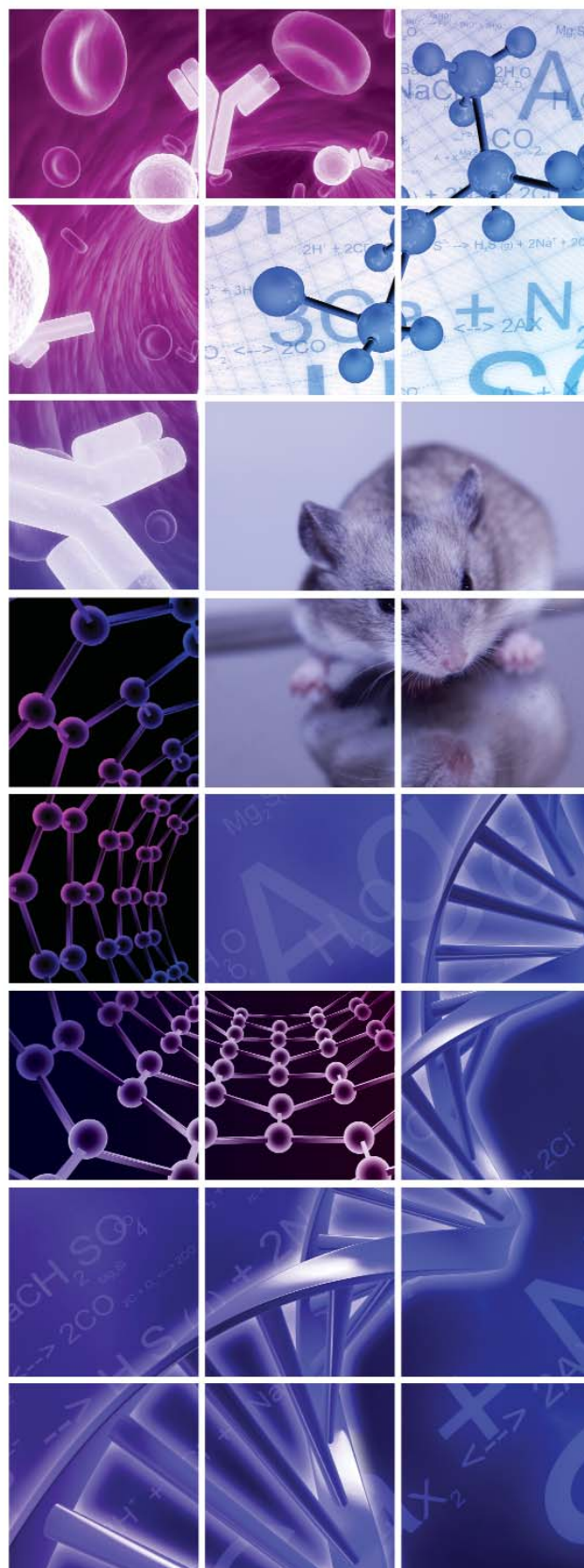
The most dramatic changes in chemical engineering seem likely to come from the increasing importance of biology and biochemistry. Chemical engineers have long applied biological processes for fermentation and waste treatment. Emphasis on bioreactor engineering was augmented in the 1970s and 1980s by advances in bioseparations. In parallel, chemical engineers became involved in biomedical engineering, a discipline that had been dominated by electrical and mechanical engineers.

However, the biggest transition began with the growing perception that biology has molecular foundations — that biology is based on chemistry. This shift has been, over the last two decades, the intellectual impetus for accepting biology as a core science of chemical engineering. It provides a basis for fundamental understanding and modeling of cellular processes, quorum sensing, drug docking, disease processes like Alzheimer’s-related amyloid plaque, and systems biology. Given this ability to make a difference, chemical engineers are further attracted by personal and social ideals: the importance of good health to an aging population, coupled with the accepted value of drugs and biologic pharmaceuticals for corrective and preventative health care.

Bob Langer (Institute Professor, MIT) sees chemical engineers playing vital roles as activities in biotechnology, pharmaceuticals, medical devices, and biomaterials expand considerably. “There will be new types of information in genetics leading to more personalized diagnostics and medicines. There will be new materials leading to new medical devices. Delivery of complex molecules, including potential new drugs such as siRNA and DNA, will also create opportunities. Transport at the nanoscale level may also open up new possibilities in noninvasive delivery, cell-specific drug delivery, and sensing,” he writes.

Ann Lee (Vice President for Process Research and Development, Genentech) and **Bob Steininger** (Senior Vice President for Manufacturing, Acceleron Pharma) are similarly excited.

Lee perceives production of biologics — protein products based on recombinant DNA — to have become a mature industry, converging for most products to a core set of technologies using CHO (Chinese hamster ovary) cells or *E. coli* with conventional separations, including the use of monoclonal antibodies. She also foresees innovative therapeutics



Industry

F. EMIL JACOBS



ExxonMobil

Chemical engineering of energy from oil, gas and beyond

Emil Jacobs is Vice President, Research and Development, for ExxonMobil Research and

Engineering, and is a former member of the Board of Directors of the Council for Chemical Research.

HENRY T. KOHLBRAND



Dow Chemical Co.

Technology-driven and need-driven changes

Hank Kohlbrand is Global R&D Director for Engineering and Process Sciences at The Dow Chemical Co. and is a past

member of the AIChE Board of Directors.

ANN L. LEE



Genentech

Biotechnology in chemical engineering for medicines and energy

Ann Lee is Vice President for Process Research and Development at Genentech and is a

member of the National Academy of Engineering.

JAN LEROU



Velocys

Chemical reaction engineering

Jan Lerou is Manager of Experimental Operations for Velocys, which develops process-intensification technology for energy and

chemicals; he has formerly worked with Novodynamics and DuPont conducting and managing research on catalysts.

CATHERINE L. MARKHAM



Rohm and Haas

Multi-scale chemical engineering needed for electronic materials

Cathie Markham is Chief Technology Officer for Rohm and Haas Electronic Materials, joining the com-

pany after 20 years of experience in the petrochemical industry with assignments in R&D management, global technical service, engineering, new business development, and organizational improvement.

MAYIS SEAPAN



E. I. DuPont

Opportunities from new resources

Mayis Seapan, a former Professor of Chemical Engineering at Oklahoma State Univ., is a Senior Research Associate in the

Reaction Engineering Group of DuPont Engineering Research and Technology in Wilmington, DE.

JEFFREY J. SIROLA



Eastman Chemical Co.

Using and protecting the earth's resources

Jeff Sirola is a Technology Fellow in the Eastman Research Div. of Eastman Chemical Co., Kingsport, TN, a member of the

National Academy of Engineering, past accreditation commissioner for ABET, and past president of CACHE and of AIChE (2005).

ROBERT J. STEININGER



Accelaron Pharma

Chemical engineers in pharmaceutical and diagnostics manufacturing

Bob Steininger is Senior Vice President for Manufacturing at Accelaron Pharma

(Cambridge, MA), having begun his career at Stone and Webster and moved upward through senior positions at Genetics Institute, Wyeth, and Millennium Pharmaceuticals.

that will include targeted medicine using diagnostic markers: "Antibodies conjugated to toxins (antibody drug conjugates) will provide the realization of the 'magic bullet' and emerge as standard therapy. Combination therapies will expand the use of current and new pipeline products."

From Steininger's perspective, chemically based health monitoring and individualized medication appear particularly promising areas for chemical engineering contributions. He sees benefits from having cross-functionally trained engineers who can combine expertise in biochemistry, problem-solving, data analysis, and systems engineering.

Biotechnology, bio-based energy, and biomaterials are also moving ahead. **Frances Arnold** (Dick and Barbara Dickinson Professor of Chemical Engineering and Biochemistry at Caltech) believes that "industrial biotechnology will be extremely important — especially fuels and chemicals from biomass. While not wholly new, this sector has been 'sleepy' for the last decades, eclipsed by medical applications. The next 25 years will see the dominance of industrial biotechnology." Commitments by companies to using biomass and bioprocessing reinforce this belief.

Nanotechnology will have mega impacts

Because chemical engineering works with molecules, nano-scale phenomena have always been a part of the profession. Organizing existing knowledge and thinking under the conceptual umbrella of nanotechnology has opened doors to new possibilities, especially in materials.

Some of these opportunities are products for biomedicine. Ying notes that "nanoparticles are being developed to target chemotherapeutics in killing cancer-specific cells, instead of creating horrible systemic side effects. Nano-biomimetic scaffolds may be constructed to guide the differentiation of one's own stem cells to regenerate damaged tissues and organs *in vivo*." These are tasks for systems approaches, even though the systems are dramatically smaller than the manufacturing processes chemical engineers have traditionally been taught to design and develop.

For microelectronics, manufacturing of nano-scale features is routine and routinely challenging. **Cathie Markham** (Chief Technology Officer, Rohm and Haas Electronic Materials) offers that “bio, pharma, and electronics will all drive to smaller-scale understanding, requiring more accurate nano-scale measurements, and holistic fundamental understanding of the state and properties of matter at nanoscale and below will be necessary to realize these new pursuits.”

Nanotechnology needs to develop green, sustainable practices, as discussed by **Meredith Kratzer** (PhD student, Univ. of Illinois, Urbana-Champaign): “New expertise in sustainability will prompt researchers to develop novel microchemical systems that reduce the need for hazardous reactants, minimize the production of polluting waste, lower energy demands due to heating and cooling, and enable the production of valuable chemicals in an assortment of environments by users of varying skill levels. Sustainability has often been a secondary concern for the energy-intensive integrated-circuit manufacturing industry; no one questions the necessity of information storage, processing, and communication. In recent years, however, some advances have been made in the optimization of energy, water, and chemicals in the cleanroom.”

Jan Talbot (Professor, Univ. of California, San Diego; past president, The Electrochemical Society) speculates that “nanotechnology could become the key to unlocking new energy-conversion techniques. Nanotechnology-based innovations are already impacting both solar energy and battery technologies, through improved efficiency of nanoscale conversion materials. Coupling of these capabilities with novel 3-D self-assembly techniques could open the door to enormous new energy potentials. Single-molecule motors, quantum dots, and nanopatterning are technologies being studied as possible means of powering nanoscale devices, improving solar conversion efficiency, and helping elucidate the fundamental mechanisms of photosynthesis, opening the door to truly green energy sources.”

Talbot also sees computational nanotechnology as potentially powerful, being “all-encompassing in the sense of embracing classical computational techniques of computational chemistry, physics, mechanics, and fluid dynamics, in addition to molecular-level approaches.” At the same time, nanoscale fabrication methods are crucial — and strongly connected with chemical engineering fundamentals. Success in the field to date leads her to

assert that “self-assembly-based systems integration is envisioned as one of the more revolutionary outcomes of nanotechnology.”

Computing to capture both molecular and global aspects

Chemical engineering is relevant to the truly big issues — health, energy, water, food, sustainability — yet to achieve its ends in those areas, it requires attention to molecules as well. Across wide-ranging scales of interest, the profession will be increasingly cyber-enabled to manage vast quantities of data; to predict molecular and system properties; to steer product design and the consequent configuring and reconfiguring of process development and process designs; and to conduct both manufacturing and commerce.

Cummings believes that “molecular engineering” is a particularly apt description of chemical engineering’s role, contending that the big issues “depend critically on molecular insight to develop new materials (for the conversion, storage, and transmission of energy, for implants, or for nuclear waste containment, to name just a few) and new molecules (as potential drugs, as replacements for existing

solvents in green chemical processes, as components in new energy-storage devices, and as new catalysts). Instrumentation increasingly provides molecular probes, and the detection and control capabilities 25 years hence will make it possible to answer the question: Where is

every molecule going in my plant? Regulatory and business considerations will make answering that question an imperative in 25 years’ time.”

Molecular and materials modeling is one aspect of molecular engineering. In molecular modeling (computational quantum chemistry), structure and energy are characterized by solving the electronic structure, converting the results into thermochemistry and kinetics through statistical mechanics. Molecular simulation is used to model larger structures or domains using either random structure variations (Monte Carlo models) or dynamic evolution based on Newton’s Second Law (molecular dynamics), guided by force fields, equations that represent the interaction energies between atoms. These calculations can be coupled to finite-element methods for calculating system performance.

These modeling methods are likely to have far-reaching benefits. **Jim Stapleton** (PhD student, Stanford Univ.) proposes the analogy, “Given enough computing power,

Nanotechnology could be the key to unlocking new energy-conversion techniques ... opening the door to truly green energy sources.

ChE Faculty

FRANCES H. ARNOLD



California Institute of Technology

Renewable fuels by synthetic biology; industrial biotechnology

Frances Arnold is the Dick and Barbara Dickinson Professor of Chemical Engineering and Biochemistry at the California

Institute of Technology, winner of AIChE's Professional Progress Award, and a member of the National Academy of Engineering, National Academy of Science, and Institute of Medicine.

PETER T. CUMMINGS



Vanderbilt Univ. and Oak Ridge National Laboratory

Molecular chemical engineering; ubiquitous computing; information sharing

Peter Cummings is the John Robert Hall Professor in Chemical Engineering at Vanderbilt Univ.

and Principal Scientist of the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory.

RAFIQUL GANI



Technical Univ. of Denmark

Chemical product engineering based on sustainable process engineering

Rafiqul Gani is Professor of Systems Design in the Dept. of Chemical Engineering at the Technical Univ. of Denmark

(DTU), co-editor of *Computers and Chemical Engineering*, and co-founder and director of CAPEC, the Computer Aided Process-Product Engineering Center.

CHRISTINE S. GRANT



North Carolina State Univ.

Building and strengthening a diverse profession

Christine Grant is Professor of Chemical and Biomolecular Engineering and Associate Dean of Faculty Development and Special Initiatives in the College

of Engineering at North Carolina State Univ., a researcher in surface and environmental science, a former board member of AIChE, and a long-time mentor to minority and other faculty.

ROBERT S. LANGER



Massachusetts Institute of Technology

Chemical engineering and medicine

Bob Langer is an Institute Professor at MIT in the Dept. of Chemical Engineering, has participated in the founding of more

than two dozen companies, is a member of the National Academy of Engineering, National Academy of Science, and Institute of Medicine, and has received AIChE's Stine, Walker, and Founders Awards.

WOLFGANG MARQUARDT



RWTH Aachen
Chemical process engineering; cyber-enabled and computational systems engineering; "bioeconomy"

Wolfgang Marquardt is Professor and Head of the Institute of Process Systems Engineering,

RTWH Aachen Univ., co-editor of the *Journal of Process Control*, and AIChE's 2008 P. V. Danckwerts Memorial Lecturer.

JAN B. TALBOT



Univ. of California, San Diego

Chemical nanoengineering; energy conversion; computational nanotechnology

Jan Talbot is Professor of Chemical Engineering and Materials Sciences at the Univ. of California, San Diego, and is past

president of the Electrochemical Society.

THOMAS M. TRUSKETT



Univ. of Texas, Austin

Computing impacts on technology; sustainability; insights into the solid state; biochemical engineering; globalization

Tom Truskett is Associate Professor of Chemical Engineering at the Univ. of Texas,

Austin, an NSF CAREER awardee, and the 2007 recipient of AIChE's Colburn Award.

JACKIE YI-RU YING



Institute of Bioengineering and Nanotechnology, Singapore

Medical chemical engineering; nanotechnology for energy conversion

Jackie Y. Ying is currently the Executive Director of the Institute of Bioengineering and

Nanotechnology, a national research institute in Singapore, and the Editor-in-Chief of *Nano Today*, and she has been a Professor of Chemical Engineering at MIT and winner of the 2000 Allan P. Colburn Award of AIChE.

density functional theory and molecular dynamics will one day do for chemical engineering what finite element analysis has done for mechanical engineering ... In the next 25 years, increased computational capabilities will transform my field of biochemical engineering."

Such results feed into process development and operation in various ways. For example, multi-scale modeling is a powerful approach when nested problems at pertinent time and distance scales can be modeled separately. An overall plant design may require modeling of an individual reactor, which may require modeling of combined transport and chemistry for a catalyst pellet, which may require

atomistic modeling of the surface events — and solving each stage can provide information necessary for solving the next.

Process simulation software has shortened the time to reach production in the chemical process industries, and the same may become true for development of pharmaceutical processes. Because of testing for regulatory purposes, pharmaceutical processes are often locked in early.

Ryan Snyder (PhD student, Univ. of California, Santa Barbara) envisions: "In order to reach full-scale production of a new active pharmaceutical ingredient (API) today, extensive experiments and calculations are required

through many stages of scale-up. While it may seem somewhat far-fetched, history and current research suggest that the development of new solid-state chemicals such as APIs 20 to 30 years from now may follow a similar course. One may only require a minimal set of experiments, coupled with yet-to-be-developed methods for the prediction of key process parameters (crystal polymorph, crystal shape, API solubility, etc.), coupled to a rapid process simulation suite.”

At the plant and enterprise scales, computational sciences will be employed to make zero-incident, zero-emission smart manufacturing possible. “Smart manufacturing” will be a design and operational paradigm involving the integration of measurement and actuation, safety and environmental protection, regulatory control, real-time optimization and monitoring, and planning and scheduling. It will provide the basis for a strong predictive and preventive mode of operation with a much swifter incident-response capability.

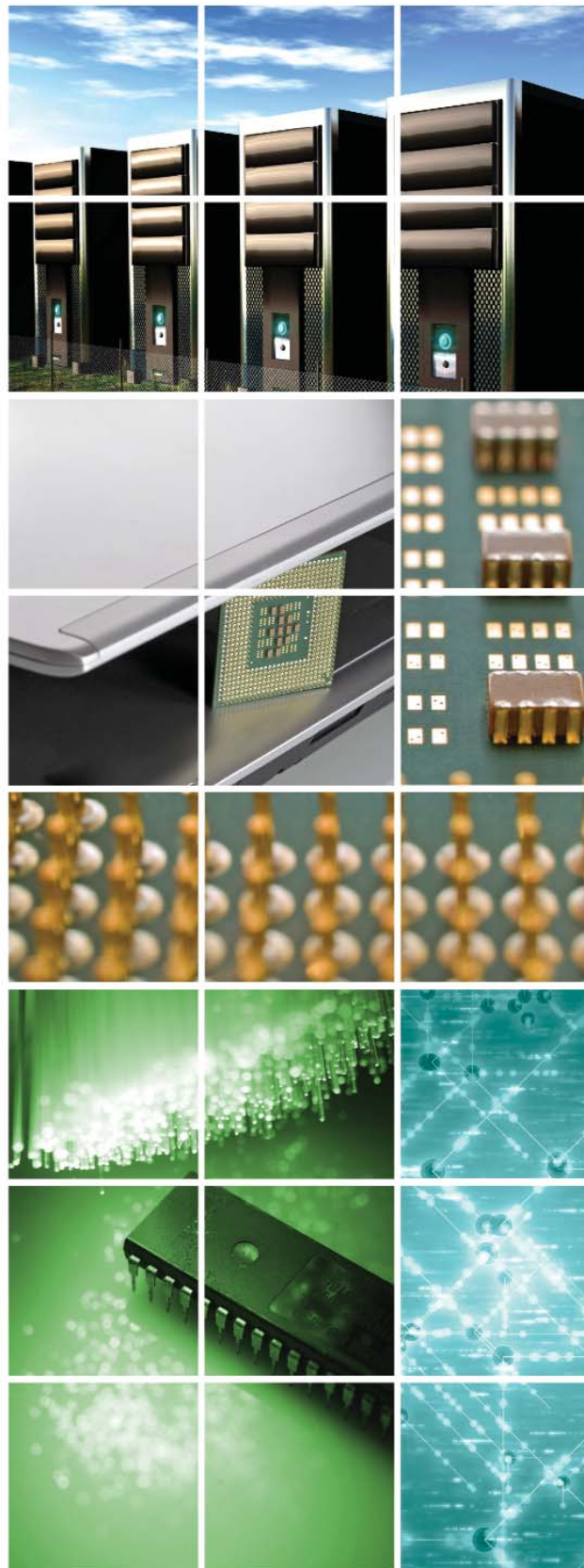
Incorporating a zero-emissions goal into the smart-manufacturing paradigm recognizes that energy usage, energy production, and environmental impact are tightly linked in high-volume manufacturing. Even now, a team of academic researchers and industrial practitioners is advancing toward that goal, led by Jim Davis, Professor and Chief Information Officer at the Univ. of California, Los Angeles, and sponsored by the industrial participants and the National Science Foundation. Using the nonprofit CACHE Corp. as the base for a “virtual organization,” a strategic plan is being developed.

Computing speed is a factor in many of these developments. Laptop CPU speeds are now faster than supercomputers used to be. Faster computation has turned from dependence on faster chips toward using parallel and multicore processors. **Tom Truskett** (Associate Professor, Univ. of Texas, Austin) observes that high-performance parallel computing can solve problems that lend themselves to a parallel structure faster and faster.

However, as one engineer put it, “If it doesn’t make *my* problem run faster, it isn’t faster to me.” These visions call for “high-performance computing” that is more than supercomputer usage. Truskett points out that “computational modeling has long served as a central component of the chemical engineering toolkit,” but that moving ahead requires “advances in new algorithms, supercomputing, and the cyber-infrastructure necessary to bring together distant resources.”

What do we need to know?

Undergraduate curriculum. To achieve these visions, chemical engineers need the right education, both in college and in their evolving careers. The participants generally agree on the value of the current curriculum. It typically includes a science base of mathematics, chemistry, physics, and biology; writing and other liberal arts courses; material balances;



thermodynamics; transport phenomena; kinetics and reaction engineering; process dynamics and control; laboratory experience; and a capstone design experience. Analytical and computational problem-solving are both emphasized. One challenge is adding new material and, inevitably, removing material.

Patrick McGrath (PhD graduate, Univ. of California, Berkeley) remarks that the classical toolkit was necessary to advance new energy technologies along with the additional topics “advanced modeling, metabolic engineering, materials design, and control on multiple length scales.” Some new topics can be folded naturally into the existing structure, such as supply-chain concepts and lifecycle analysis.

In the past few years, specific changes have begun to take shape. Professor Bob Armstrong of MIT has led a nationwide effort at curriculum review and reform titled “Frontiers of Chemical Engineering.” It has engaged 84 chemical engineers from 53 universities and five companies to forge a consensus view of how the curriculum might be re-imagined. Three basic technical threads were developed:

- molecular transformations (chemical and biological systems, physical as well as chemical structural changes)
- multi-scale analysis (macroscopic engineering tools combined with a molecular understanding of nature)
- systems analysis and synthesis (addressing all scales, supplying tools to deal with dynamics, complexity, uncertainty, and external factors).

Beyond the classroom. Demands on the chemical engineering professional will go beyond the technical aspects in other ways, too. Marquardt emphasizes that “systems problem-solving will become even more important than it is today. The system boundaries considered during development processes have to be extended continuously — toward the molecular scale on the one hand and the megascale on the other hand — to address the opportunities in product development and to reconcile the conflicting objectives of global and

sustainable production and distribution networks.”

Jacobs captures an even broader view, noting that “there will be a premium placed not just on communication skills, but also on the ability to negotiate effectively with key high-technology providers for the purpose of jointly developing advanced technology platforms. The chemical engineer will be the integrator of global resources to produce improved processes or products faster and more cost effectively, whether in R&D, engineering, or manufacturing.”

Seapan expresses two common industrial concerns that must be faced: “the lack of industrial experience of engineering faculty, and the potential for academia to lose its educational strength in the traditional areas, which will remain in demand, though to lesser extent.”

Fortunately, chemical engineers have a history of working well across boundaries and in multidisciplinary teams. Some of the cutting-edge developments require individuals involved to have broader, transdisciplinary expertise. Chemical engineers have proven successful in this regard in the past.

Chris Ellison (post-doc, Univ. of Minnesota, Twin Cities) writes: “Chemical engineers are well-suited to play a key role in the emerging issues of nano/molecular engineering because of their strong and diverse training in

fundamental principles and their keen skill in assembling the necessary principles to attain solutions.”

A profession with open eyes. Excitement about the breadth of chemical engineering is valuable for appealing to potential new members of the profession. Despite the daunting reputation of chemical engineering as a difficult degree, students are also typically drawn to this field by a combination of good employment prospects, high starting



▲ Eastman Chemical Co.'s Kingsport, TN, plant has been producing organic chemicals via coal gasification since 1983.

Photo courtesy of Eastman Chemical Co.

salaries, and their belief that they are strong in chemistry and math. Like every profession, we seek the best and brightest, and so our active mentoring is important. Chemical engineering has outstanding women and minority engineers, yet they are still underrepresented relative to the potential talent pool.

To make full use of the national talent pool, **Christine Grant** (Professor and Associate Dean of Engineering for Faculty Development and Special Initiatives, North Carolina State Univ.) believes that a diverse workforce requires innovation in the recruitment, promotion and retention of underrepresented groups at all levels in the academy. “The presence of underrepresented minority and women faculty as scholars, mentors and teachers will impact the profession beyond the walls of the university. These educators do much more than teach core chemical engineering subjects and perform research. They often open the eyes of students from many backgrounds to the opportunities within the profession.” At the same time, “the identification and hiring of diverse faculty must be coupled with an environment that celebrates them as scholarly colleagues and provides both peer and senior faculty mentoring to insure successful navigation of an often challenging career path.”

In a similar vein, many participants reflect on the broadening impacts of globalization on education and industry, illustrated by the challenge of defining an “American” company.

Truskett summarizes the parallel challenge and opportunity of globalization for education: “While the U.S. has served as home for much of the leading chemical engineering research of the past century, it is now truly a shared international endeavor. Fully understanding the implications that this will have — for the education of domestic students, the recruitment of international students, and the role that U.S. institutions of higher education will play in the next 25 years of chemical engineering — will be no small task.”

Julie Champion (post-doc, Caltech) comments on another side of globalization that is important to educating sophisticated chemical engineers of every age. She notes that First-World companies must adapt to Third-World markets. “Global inequities will create new market opportunities for chemical engineers to address critical issues in developing countries, such as drought, malaria, and water contamination. However, the same technologies used to solve these problems in the west cannot be reused. Technological advances must be harnessed to make solutions simpler, not more complicated. Biotechnology companies will evolve their products in creative ways to meet the requirements of customers ‘off the grid.’”

Will we still be “chemical engineering”?

Today’s discipline of chemical engineering extends far beyond what it included 25 or 100 years ago. One aspect of meeting new technical demands is new sub-disciplines. Many U.S. chemical engineering departments have been renamed Chemical and Biochemical, Chemical and Biomolecular, or Chemical and Biological Engineering. Some include the word Materials or Environmental in their names. At the Univ. of California, San Diego, the chemical engineering program is now part of a Department of Nanoengineering. It is unclear whether these actions will ultimately result in renaming or splitting of the chemical engineering profession itself.

However, evidence from other, larger engineering disciplines is that despite a profession’s diversity, companies, students, and the public most understand a broader lumping based on whichever fundamental aspect is at a profession’s core, such as electrical, mechanical, or civil engineering. “Chemical engineering” is still a powerful and effective description of the engineering field that most strongly has a molecular foundation.

This group of visionaries sees chemical engineering evolving in exciting new ways, and they think chemical engineering is here to stay. As Stapleton observed optimistically, “While new applications will drive the appearance of new sectors, and hot fields will come into fashion and fade away, in the long run I think that rather than further fragmenting chemical engineering, our new knowledge will highlight the common ground between many of its fundamental fields. Our discoveries will carve out new territory, but they will also erase some of the lines we have arbitrarily drawn, fill in the gaps between seemingly disparate fields, and highlight the continuity of knowledge.”

CEP

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