Looking Ahead at Chemical Engineering: 25 Years, 25 Visions

A project of the AIChE Centennial Committee

Phillip R. Westmoreland
U. S. National Science Foundation, Engineering Directorate: Chemical, Bioengineering, Environmental, and Transport Systems Division, and
University of Massachusetts Amherst, Department of Chemical Engineering

VISIONS FROM INDUSTRY

VISIONS OF CHE FACULTY

VISIONS OF POST-DOCS AND STUDENTS

Foreword

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 like industrial chemistry, electrochemistry, oil processing, and food processing. Looking to that history, AIChE has composed lists of achievements, of pioneers, and of texts that show the evolution and notable highlights of chemical engineering.

This collection of thoughts looks in the other direction – to the future of the chemical engineering profession. Just as with looking backward, efforts to look forward are limited by the vision and experience of the participants. However, it is further hampered by our simple inability to imagine what advances will have the most impact.

We asked three small groups of chemical engineers to offer their visions. First, we approached department heads of the U.S.'s largest ChE 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 represent what the department heads consider to be the hottest research areas. These individuals are truly at the cutting edge of chemical-engineering advances, and they are sufficiently experienced to have developed independent viewpoints.

Second, chief technology officers and other industry leaders were asked to respond or to nominate a responder. These chemical engineers were sought from a range of industries to elicit diverse viewpoints.

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

We asked for brief responses to our questions. The questions were posed in the context of responses for the responder's industrial sector in order to solicit specific visions, still leaving room for generalizations. For academics engaged in fundamental science that might be tied to a present or future industrial sector, we asked for responses that would address the most relevant sector.

The four questions asked for extrapolation, new impacts on existing sectors, new sectors, and an optional, more open-ended comment on the future of the profession as a whole. They are re-stated with each response.

Visions from industry

F. Emil Jacobs, ExxonMobil

Chemical engineering of energy from oil, gas, and beyond

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

The petroleum industry will grow all segments of its current business (upstream, downstream, and petrochemicals) to meet society's energy and hydrocarbon-based product needs. Driven primarily by growth in the developing countries, the world's energy requirements over the next 25 years are expected to grow at ~1.3% per annum, from the current 240 MBDOE to approximately 350 MBDOE. The demand for both hydrocarbon-based chemicals and fuels is expected to keep pace with global GDP growth.

In the industry's upstream segment, which includes 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, including heavy oil, tar sands, and shale oil. The resource slate is likely to grow increasingly more hydrogen-deficient and viscous requiring advanced technology for extraction, transportation and processing.

The industry's petrochemical segment will see demand for its aromatics, olefins and polymer products grow primarily in the developing countries. It will confront challenges to manufacture its traditional products with less energy and lower greenhouse gas (GHG) emissions, while expanding its slate of specialty products to meet growing markets.

The industry's downstream refining and manufacturing segment will grow to provide cleaner fuels and higher performing lubricants for evolving engine technologies. The trend toward larger, more integrated refining and petrochemical complexes will continue, brought about by the efficiencies of scale and a greater emphasis on energy efficiency and GHG reduction. There will also be an increased focus on hydrocarbon-based fuels that meet the demands of advanced engine technologies. Improved lubricant technology will be driven by demands for greater energy efficiency and wear resistance as well as the evolution of new stationary and vehicular technologies including, for example, wind turbines and continuously variable / infinitely variable transmissions (CVT/IVT).

Advances in technology will play a pivotal role in growing the petroleum sector. Opportunities for chemical engineers in this sector will be found in many areas including: (1) development of advanced simulation models for hydrocarbon reserves, (2) new processes for conversion of a heavier slate of feedstocks to clean fuels, (3) development of economic, high-performance fuels, lubes, and chemicals from alternatives such as biomass, (4) conversion of natural gas, natural gas condensates, and gasification products (synthesis gas and intermediates) to transportation fuels and basic chemicals, (5) improved refinery and petrochemical plant energy efficiency through process intensification, integration, and creative energy management, and (6) process reconfiguration and reengineering to facilitate carbon capture.

The core skills needed to address these challenges will include advanced modeling, novel materials development, advanced separations, reaction engineering (including biochemical) and sensor development.

(2) Traditional core areas of ChE 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?

We anticipate a significantly greater focus on the development of advanced algorithms coupled with advanced sensor and characterization capabilities. These changes are expected to improve speed and value in all aspects of the refining business from R&D to crude selection to decision making. For example, use of computational fluid dynamics (CFD) and advanced optimization algorithms will provide much greater process flexibility in refineries and petrochemical plants and should greatly expand plant capacity. Advanced compositional models will allow for the introduction of a variety of alternative feedstocks (e.g., syncude or bio-derived feeds) and will also allow for more consistent fuels through blending.

Advanced computational methods will also enable process development at a significantly smaller scale. Thus, large pilot or semi-works units will be replaced by much smaller scale experimentation where the focus will be on establishing fundamental parameters that feed computational models. The ability for models to span the length scales (e.g., from density functional theory, to molecular dynamics, to CFD) will enable engineers to both scale up and scale down processes with much greater efficiency and certainty.

Catalysis involves reactions at surfaces and is focused on manipulation of molecules and surfaces at the nanometer scale. Newer analytical and modeling capabilities brought about by advances in related areas of nanotechnology will allow more precise design and development of advanced catalysts for more selectively and efficiently producing both fuels and chemicals.

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

Knowledge capture and management will be critical to all technology sectors over the next 25 years. These will be especially important to the petroleum and petrochemical sector because of the very large installed capital base and the premium on knowledge workers. The demographics of the current workforce make these needs especially acute; see the National Petroleum Council's recent report, *Hard Truths* (2007).

Visualization technology will progress very quickly in response to needs for faster and more accurate identification of key information as well as the need for improved accuracy and speed in decision-making. This will be true in R&D as well as in manufacturing and marketing.

Energy management, which is directly related to greenhouse gas management, will also become more prominent. Exergy analyses will become as common as economic analyses for process design and evaluation.

Advanced separations (gas-gas, liquid-liquid, gas-liquid) will almost certainly continue to emerge as a large opportunity area, brought about by the aforementioned need for improved energy efficiency along with a greater focus on the need for efficient separation of, e.g., CO_2 from exhaust gas.

Finally, the development and application of advanced sensors that both actively and passively monitor equipment, processes, and product quality should become even more critical to the petroleum exploration, production, refining and petrochemical segments.

Companies that specialize in each of these areas are likely to be the foundations for new sectors that provide products and services to firms not only in the refining and petrochemical business but also in many other manufacturing businesses. The petroleum industry will undoubtedly continue to provide ample career opportunities for chemical engineers. This robust demand for chemical engineers will be supplemented by the growth of new sectors focused on improving energy efficiency and utilization and on improving our environment.

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For chemical engineers 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.

Emil Jacobs is Vice President, Research & 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 Company

Technology-driven and need-driven changes

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

Alternative fuels and energy will receive increasing focus and raw material and energy sources will change dramatically over the next 25 years. Energy costs will drive changes in products offered and pricing. Alternative feedstocks that compete with food sources will not flourish.

Production of commodities will move to the regions where the raw materials and conversion costs are the least expensive, resulting in new global partnerships. R&D and academic collaborations will begin to shift to these regions as well. Global competition will cause the market for people, services and cost to equalize across geographies.

Sustainability will drive changes in many products and processes.

Diversified chemical companies will increase focus on performance-based products and participate in more downstream markets, while continuing to participate in commodity production through joint ventures and alliances. Customers will be more in control of new performance product design. New techniques for producing high-performance materials and products at small scales will drive marketplace changes.

Technology breakthroughs in new materials will result from better understanding of biomimicry.

The aging population will drive development of new and different products and services.

The availability (or lack) of process water will cause significant process redesign for operation in arid geographies.

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Continuing increase in computational power at low cost will greatly augment experimentation, yielding additional speed of process and product design at lower cost. This increase, along with improvements in modeling systems for computational chemistry will greatly reduce the amount and cost of experimentation for new product development.

High-throughput experimental techniques will replace traditional methods in catalysis, materials, and formulation design, further reducing the amount of laboratory experimentation and generating information at higher rates, requiring new methods for data management and analysis.

New optimization algorithms, coupled with availability of inexpensive computing cycles, will impact the efficiency of enterprise-wide and supply chain optimization for both new and existing operations. This same technology will have a significant impact on process control efficiency.

The ability to predict micro and meso-scale structures will improve our effectiveness at creating high-performance materials from low cost raw materials.

The increased computing power and ability to manage large amounts of information, coupled with many more alliances and joint ventures, will increase the challenge of maintaining trade secrets and proprietary information.

The disruption in energy supplies and costs as well as greater emphasis on sustainable chemistry and processes will result in reformulation of heuristics traditionally used in process synthesis and design.

Biological systems-engineering improvements will provide tools to design and produce products that will compete effectively with commodities today.

All of this will take place in a global environment with industrial and academic groups co-operating across geographic boundaries.

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Sectors focusing on alternative raw materials will develop, as will sectors around sustainable products.

The energy sector will change dramatically from one focused primarily on petroleum and natural gas to one that embraces a number of sources and products.

The aging global population will change the nature of the human health sector, opening a wide variety of opportunities for the development of new products in pharmaceuticals, nutraceuticals, and biomedical areas.

The increasing demand for reliable sources and distribution of potable water will also provide opportunities. The increasing global nature of companies and alliances will feed increasing demand for cyber communities that will enhance communication and collaboration and ease language barriers.

Hank Kohlbrand is Global R&D Director for Engineering & Process Sciences at The Dow Chemical Company and is a past member of the AIChE Board of Directors.

Ann L. Lee, Genentech

Biotechnology in chemical engineering for medicines and energy

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

We are likely to see an increase in demand for medicines that will enhance quality of life, increase longevity and allow some life-threatening diseases (e.g., some types of cancer) to be managed through chronic use of "safe" biotechnology-produced medicine. With increasing demand for new biotech medicines, as well as pressures to address rising health care costs and reduce drug prices, bio/chemical engineers will play a key role in developing highly cost-effective and efficient manufacturing processes for these products.

Biotechnology has become a mature industry with regard to recombinant-DNA-derived protein products, converging on a core set of technologies (CHO & E. coli, conventional separations) for most products. The monoclonal antibody platform will continue to be exploited, and to be produced in existing manufacturing facilities.

Follow-on biologics production (generics) will ramp up in the next ten years while innovative biotech companies will focus on new and improved products with lower dose and improved therapeutic windows.

These innovative medicines 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. Finally, novel delivery technologies and devices will grow in importance and be developed to improve patient convenience and therapeutic compliance. Oral protein delivery forms and new biotech product types such as RNAi and stem cells will become commercialized.

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The core ChE curriculum (kinetics, thermodynamics, transport phenomena) will persist as the base for undergraduate education, supplemented by emerging technologies and a strong focus on biology. However, there will be a shift in the educational focus to tools, skills, and development methodologies (statistics, design of experiments, high throughput screening techniques, data reduction, bioinformatics) rather than on traditional focus such as on unit operations.

The chemical engineers in the biopharmaceutical industrial sector will transform into biological engineers. The ability to work across disciplines will become ever more important. Chemical engineers will continue to uniquely apply their mathematical modeling capabilities to complex biological systems. These mathematical models will become sophisticated enough to predict, for example, the performance of a cell culture in a bioreactor and reduce the need for lab-scale experimentation for process development.

Also, due to the funding limitations that academics will continue to face from government funding agencies, there will become a real partnership and much more active collaboration between academia and industry such that students and faculty will begin to work on the "real, industrially relevant" problems.

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

Novel nanotechnology-based drug delivery systems will be realized and enable full exploits of new product types such as DNA vaccines, gene therapy, and Ran. Drug delivery devices that incorporate microelectronic-guided sensors will open many possibilities. Oral delivery of protein therapeutics is currently considered the Holy Grail for protein delivery.

Development of diagnostics and sensors that will measure drug response within a couple of days to determine whether a medicine is working, or sensor technology to provide feedback control for administering adequate amount of drug.

Currently, the most expensive part of drug development is running the clinical trials. The future could see replacing the need for large-scale human clinical trials with a smaller number of patients and supplementing with in vitro or in silico testing. Animal preclinical toxicology testing would also be replaced by "lab on a chip" technology.

Green factories with more efficiency in energy reuse and or recovery and lower carbon footprint will abound.

Industrial biotechnology (biofuels and biopolymers) will emerge as a key to the energy sector.

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In 25 years, chemical engineering will be an even more exciting profession. It will be a vibrant profession with branches into many different sectors. Chemical engineers working in the energy field will make a real impact in addressing global warming and help reduce US dependence on foreign oil. Chemical engineers will also work on other environmental issues. It has already been mentioned above the many different areas in biomedicine development that chemical engineers will impact. Chemical engineering will remain a profession that can help solve societal problems and continue to attract students.

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

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

The key aspect will be the drive to replace the classical raw materials gas, oil and coal by renewable sources for energy and chemicals. The current efforts in this area will have enough momentum this time to continue in the future even if the natural gas and crude oil prices drop. This evolution will have a major impact:

- New processes will be conceived and materialized;
- The rate of adoption of new technologies by the chemical industry will be increase drastically;
- Huge opportunities will emerge for bio and non-bio based systems.

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The new core areas will accelerate the evolution mentioned above. The increasing adoption of a multi-scale approach will facilitate conceiving new processes. The increasing understanding of the necessity of using sustainable process will help in solving the environmental issues. The availability of ever more powerful hardware and the associated software will synergistically affect this evolution.

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

Most new sectors will be fitting between existing sectors:

- The continuing growth of data-producing systems will require new technologies to support the extraction of useful information out of a sea of data. The problem is how to classify and visualize this information in an attractive and informative manner than the human mind can assimilate. This issue has already been identified in the high-throughput experimentation activities but will also become more pressing in the process monitoring data flood as well.
- CO_2-based production of chemicals: CO_2 capture and sequestration will only be sustainable if CO_2 is used as a carbon source. There are already first results converting CO_2 in methanol and splitting CO_2 with solar energy.
- Distributed production: This methodology, which is under development, will allow localized production of chemicals and energy with a reasonable capital investment. This goes in the opposite direction of the economy of scale and will require a retooling of the engineers' minds.

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It will be a very exciting profession! During the next 25 years, the chemical engineers will have proven that they are able to solve the key issues with which we are struggling now and will struggle in the future: the environment, the energy crisis, creation of sustainable solutions, increase the safety of products and processes, the domestication of bugs, and so on.

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

Multiscale chemical engineering needed for electronic materials

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

Rohm and Haas is a specialty materials company covering several different business segments.

- ENERGY and SUSTAINABILITY are enormous driving forces for change going forward. Materials will be intimately tied to the critical issues of what resources we deplete from our planet and how we manufacture our materials sustainably. Reliance on fossil fuels will be reduced. The focus on energy and transportation will accelerate regionalization.
- REGIONALIZATION or local differentiation in markets and products is a reality of today that is driven by local consumers and will persist going forward. A simple example of this is that different odors are acceptable for house paint in different countries. In addition to products themselves being customized locally, the most effective methods of manufacturing will be subject to different economic conditions and assumptions, and manufacturing approaches will fragment as well.
- SIZE REDUCTION for cost and speed will continue to drive innovation in the electronic materials sector. This will be attained by "reach" applications of existing manufacturing techniques such as deposition and lithography, and by broad implementation of novel fabrication techniques such as electro-jet writing and templated self-assembly. Fundamental limitations in miniaturization of electronic devices have already become clear; numerous elements of modern semiconductors have been reduced to only a few molecules in thickness. As shrinking hits limits, chip stacking will invoke the real estate in the z-dimension.
- A large part of technology development is and will continue to be focused on breakthrough combinations of chemical engineering, material science, chemistry, mechanical engineering, physics and other disciplines to meet these challenges.

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For the answer to this question, we will to focus on our Electronic Materials segment where nanometer scale is already relevant every day.

First, too much fundamental understanding lags far behind industrial practice. Material science and engineering presently do not provide the essential structure-property relationships needed for first-principles design of novel devices or their means of manufacture. Greater investment by industry and academia may someday reverse this situation.

Equally critical is a renewed emphasis on mechanistic modeling and rigorous linking of experimental results with theory, a cornerstone of chemical engineering of the 20th century that is in decline because the available theory at appropriate length scales has not kept pace with industrial development. Classical chemical engineering succeeded by treating transport, kinetics, solution thermodynamics and other aspects with enough rigor to separate leading-order responses while confining uncertain elements into coefficients found by experiment. Many of these constructs are no longer applicable in the electronics sector because the entire process of interest transpires within what was formerly called a boundary layer, mixing length, or chemical intermediate. Clearly, finer resolution of space and time scales is needed--but high-powered computational modeling, while illustrative, cannot substitute for closed-form expressions derived from core premises.

Massive intangible calculations prevent engineers from developing the visceral understanding of physical and chemical phenomena that ultimately sparks new insights. Chemical engineering in the future must include not only nanoscale and molecular understanding but also a core expertise in homogenizing small-scale characterization into larger-scale effects, to recover predictive tools at human scale.

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The earth needs more help from the chemical engineering professionals to provide clean water, renewable energy, food, education, and health for all of its creatures. Recycling and re-use will become an important sector relying on new disassembly, separation, and purification techniques. Bio-derived base chemicals will be prevalent. Pharmaceuticals will become more customized including new drug delivery techniques. 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.

Lastly, on a personal note, I have been waiting for a jet pack since I was six years old. I would also like it to be non-polluting!

Cathie Markham is Chief Technology Officer for Rohm and Haas Electronic Materials, joining the company after 20 years experience in the petrochemical industry including managing R&D, global technical service, engineering, new business development and leading organizational improvement activities.

Mayis Seapan, E. I. DuPont

Opportunities from new resources

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

Twenty-five years is not too far away. A dominating area in 25 years must have its indicators today.

- A switch from traditional sources of energy and raw material to biological resources will be the most dominant change. Opportunities to make new bio-based materials and processes are expected to advance significantly.

- Modification of surfaces and materials at molecular level, to create new materials with unique characteristics will be more opportunistic. Recovery of solar energy and energy storage are two promising areas.

- Globalization and the need to operate within the global regulations will create its own needs and opportunities.

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- Expertise in biological sciences will probably have the strongest impact, while nanotechnology areas will be more opportunistic.

- US industries will move away from manufacturing to creating newer products, processes, and opportunities.

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

- Scarcity of energy and raw materials resources and environmental concerns will create the need to close the loop of raw materials, waste recovery and recycle.

- Low greenhouse-gas technologies will grow to become economically important.

- Exploitation of less explored frontiers, such as solar, oceans, and polar resources, may create newer sectors in industry.

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Industry's need for better-educated and more specialized graduates with higher education will increase. A traditional BS ChE graduate, without further expertise, will gradually become a glorified operator. Academia in response to the needs of industry and interests of its funding agencies is expected to rise to the opportunity by augmentation of the educational system. Two areas of concern are 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.

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. Siirola, Eastman Chemical Company

Using and protecting the earth's resources

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

For a variety of economic and policy reasons, certain raw materials such as crude oil, natural gas, and some agricultural crops are experiencing significant price increases, while others such as coal and cellulosics are changing much less so. As this trend is not expected to reverse, new chemistries and new processes exploiting these alternative raw materials are likely to significantly impact the organic chemicals and polymers sectors. These changes will affect what fundamental intermediates evolve, where plants producing them are located, and how industries will compete in the expanding world economy.

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In the commodity organic and polymer industry sectors, relatively little. Biotechnology and nanotechnology may have impacts in selected specialty chemicals sectors.

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

The biggest new sector will be carbon management; that is, carbon dioxide capture from fossil energy production facilities and its ultimate sequestration. Most likely, efficient carbon management will depend significantly on chemical processing technology and expertise.

Another new sector will be water reclamation involving soluble salt removal, something not widely practiced today. This is expected to be tremendously energy-intensive and could largely offset energy conservation achievements in other parts of the economy. This too will depend significantly on chemical processing technology and expertise.

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Pretty much like it is today. We will have more and better tools and ever broader (and maybe deeper) backgrounds, but I think the profession will be quite recognizable by today's practitioners.

Jeff Siirola is a Technology Fellow in the Eastman Research Division of Eastman Chemical Company, Kingsport, Tennessee; 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, Acceleron Pharma

Chemical engineers in pharmaceutical and diagnostics manufacturing

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Twenty-five years is quite a long ways out. However, the pharmaceutical and medical industry must deal with the gradual aging of the population and the cost of medical treatment for individuals.

The most efficient way to provide medical attention is to treat early and treat prophylactically. Tools to determine the likelihood that an individual will develop a particular condition or that characterize an existing condition (e.g., breast cancer) already exist. I suspect such tests will be used more ubiquitously because I believe the benefit of knowledge brought by doing such tests will warrant the cost if the test is sufficiently specific and predictive. Making such test easy, reproducible, and simple will be a challenge, particularly if ultimately one monitors a wide spectrum of variables simultaneously. Thus, creating the processes to make the instruments and the test kits (and often the test reagents) could and may benefit from cross-functionally trained engineers. In addition, such predictive health scans may be based on DNA or serum proteins.

In both cases, the magnitude of data will be great even for one individual, let alone multiple runs over time so one can compare among populations. Cyber and data analysis tools (similar to those used by my son, a chemical engineer now working on monitoring a few such biomarkers in cancer cells) will need to be developed to handle the scope and breadth of data which could be mined to make drugs more specific for an individual. If successful, existing drugs could be better targeted for specific individuals which known genetic profiles that are most responsive to those drugs.

The converse may also be feasible. Specific disease states may also require individualized drugs. To a certain extent, this is being attempted now. Individual patient tumors are being used as the source of cancer antigens to make antibodies or T cells which are targeted to bind and destroy the antigen presenting tumor cell. Such individualized medicine for a limited number of patients with a specific set of disease characteristics (potential 10- to 100-fold less than an orphan drug which are limited to treating no more than 100,000 people) is a unique challenge for a process engineer worried about drug economics.

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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?

Having started my career in alternative energy thirty years ago, I also believe that chemical engineers will be essential to meeting the challenge of making the United States less reliant on external energy sources in the future. The fundamentals - heat and mass balances and a foundation in physical chemistry and thermodynamics - make a chemical engineer particularly useful in most of the alternative-energy sources as well as those activities involved in treating the waste from such activities, whether they be gaseous or solid.

In addition, some exposure to the fundamentals to biotechnology as part of the training would make a chemical engineer an essential part of the team developing any process or managing a plant which is based on a biological process. Given the importance of potential electrochemically based systems, some additional education in this area may be helpful.

Bob Steininger is Senior Vice President for Manufacturing at Acceleron Pharma in Cambridge, Massachusetts, having begun his career at Stone and Webster and moved upward through senior positions at Genetics Institute (now Wyeth) and Millennium Pharmaceuticals.

Visions of ChE faculty

Frances H. Arnold, California Institute of Technology

Renewable fuels by synthetic biology; industrial biotechnology

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

The development and production of renewable fuels will be the big growth area for chemical engineering over the next 25 years. The technological opportunities are enormous: the entire genetic engineering revolution has taken place since the last time we were interested in biofuels, in the 1970's, and we are moving quickly to expand genetic engineering to 'synthetic biology'. I also see a resurgence of interest in process engineering in the bio sector, with the need to squeeze every penny out of the cost of producing fuels.

(2) Traditional core areas of ChE 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?

These changes are critical. Biochemical engineers must be able to work at the molecular scale, to engineer proteins, organisms, and even ecosystems to solve human problems rather than their own.

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

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.

(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?

Wonderfully exciting and fulfilling. We will be solving the most important problems.

Frances Arnold is the Dick and Barbara Dickinson Professor of Chemical Engineering and Biochemistry at Caltech, 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 University / Oak Ridge National Lab

Molecular chemical engineering; ubiquitous computing; information sharing

(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 ChE 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?

I will, for the purposes of answering these two questions, regard my "sector" as molecular engineering. Molecular engineering, and its sub-specialities of biomolecular engineering and nano engineering, will grow dramatically in the next 25 years due to growing opportunities in the biomedical, biochemical, and energy arenas. All of these areas depend critically on molecular insight to develop new materials (for the conversion, storage and transmission of energy, for implants, or for nuclear waste containment, just to name 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).

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

Two sub-topics of sustainability - renewable energy and greenhouse gas abatement/reduction - will be increasingly important, and will receive an increasing share of funding from government and industry. These are problems in which chemical engineers can make very substantial contribution.

(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?

I expect chemical engineering to be a bigger presence in engineering as a whole, because of its relevance to so many of the big issues of our day - energy, human health, sustainability. In 25 years time, even the plant-level chemical engineer will be a molecular engineer. 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.

The era of ubiquitous computation and networking is rapidly approaching, which will revolutionize our personal and business lives in ways we cannot begin to imagine. Assuming the continuance of Moore's law for computing in some form or other, computers will be almost a hundred thousand times more powerful in 25 years time, allowing a staggering array of first principles approaches to many chemical engineering problems. Think back 25 years, to 1983, and the state of computing then. 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. Reflecting on how far we have come since then (the physical library has become almost superfluous), it is difficult to imagine where we will be in 25 years with computing technology. All we can say is that it will be transforming in ways that we cannot imagine, and that information on every conceivable subject and in every form will never be more than a few keystrokes (or its future analog) away.

One of the truly transformative results of the internet is the breaking down of barriers designed to keep information contained within an entity, such as a research group, a company, an institution or a country. As just one example, OpenWetWare.org is a place where biologists and biochemists share information about laboratory techniques, information that used to be held closely within each research group to maintain its competitive edge. The success of the open software movement, dedicated to community-based development of software that is freely available, is another example of the breaking down of information barriers. In time, could this lead to the elimination of proprietary information, as yet another information barrier? Only time will tell. Information transparency leads to self-correction, ongoing validation, and widespread application, but it levels the playing field to a very uncomfortable level. The publication of independent, validated steam tables in the mid twentieth century resulted in new levels of safety (for anything that relied on a boiler, for example); prior to this, each company had its own data and maintained it in a competitive way. Today we do not question for one moment the importance of having key thermophysical data in the public domain, yet this was once proprietary data.

Peter Cummings is the John Robert Hall Professor of Chemical Engineering at Vanderbilt University and Principal Scientist of the Center for Nanophase Materials Sciences at Oak Ridge National Laboratory.

Rafiqul Gani, Technical University of Denmark

Chemical product engineering based on sustainable process engineering

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

Market constraints will drive the industry to produce improved products (with desired end-use properties) manufactured through more sustainable processes. That is, technology for “process-driven” industries (such as, paper, petrochemicals, commodity chemicals, etc.) will become more compact, safer, environmentally friendly and sustainable. Technology for “process-enabled” industries (such as specialty chemicals, active materials, bio-materials, etc.) will be dominated by the control of the end-use properties of the product as well as synchronized (and rapid) development of the product-process that are safe and environmentally acceptable.

With respect to chemicals-based products, there will be growing marketplace demands for sophisticated, controlled, and structured products combining several functions and properties. Therefore, issues such as waste (percentage of raw material converted to valuable product), water-energy usage, environment, multi-scale, multi-dimension, etc, will play important roles in developing processing technologies.

Industries will have to be more responsible on social, economical, environmental issues in addition to the traditional engineering issues. Innovative solutions, expanded chemical supply chain (enterprise-wide optimization) will become important in making decisions.

Industry will need to increase productivity and selectivity through intelligent operations and multi-scale control of processes; design/implement novel equipments based on scientific principles and new modes of production such as process intensification; manufacture products with desired end-use properties (i.e., develop a multidisciplinary product-oriented engineering with special emphasis on solids technology and complex fluid processing); and implement multi-scale and multidisciplinary modeling and simulation to real-life situations (i.e., from the molecule-scale to the overall complex production-scale).

(2) Traditional core areas of ChE 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?

To convert molecules into useful products at the process scale, it will be necessary to understand and describe the relationships between events at nano- and/or micro-scales through organization of process engineering into appropriate (different) scales and levels. This will lead to development of new concepts and methods based on breakthroughs in molecular modeling, scientific instrumentation, and powerful computational tools (including image processing), in collaboration with chemists, biologists, physicists, instrumentation specialists and many more. Although industrial needs will drive developments, balances will need to be achieved between value preservation vs. value creation of products from chemical engineering, between expanding the scope vs. maintaining the core of chemical engineering, and between engineering and science in fundamental contribution of chemical engineering. Methods and tools to manage complexity, risk, uncertainty and resources will need to be developed, applied and taught.

Demand for better and improved products by society will lead to the synthesis/extraction of greater number of molecules by chemists and biochemists, and to handle them, advances will require greater interactions between processing technologies and chemistry, information science and communication science. Advances in micro and nano-fabrication processing technologies - together with new market objectives, sales, competitiveness, and chemicals-based products defined for their end use properties - will lead to the incorporation of new specialties and active material chemistry within chemical engineering. The system boundary of problems will need to enlarge from the current process boundary (including plant construction and decommissioning) to inclusion of extraction and manufacture of raw materials; extraction of fuels and energy generation; product use, reuse and recycling; and emissions and waste management.

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

Molecular engineering; life sciences and engineering; expanded scope of biochemical engineering (e.g., biorefineries, commodity chemicals produced through the bio-route); pharmaceutical engineering; product-process systems engineering (will include commodity chemicals, molecules with desired end-use properties, micro-structures with desired structural and end-use properties); process intensification with micro-engineering and micro-technology; process engineering for microelectronics; green chemistry and engineering.

(***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?***

Chemical engineers should be good problem solvers, are pragmatic, have skills to do rigorous mathematical analysis and are trained in systematic thinking when involved with multi-issue tasks. This means that issues such as multi-tasking, multi-disciplinarity, management of complexity, technology reuse/recycle, etc., will become part of chemical engineering. Chemical engineering will work for the benefit of the society by "putting chemistry to work" and by converting "molecules to money". Chemical engineering will need to respond to the environmental, societal, and economic requirements for the smooth transition towards sustainability.

Rafiqul Gani is Professor of Systems Design in the Department of Chemical Engineering at the Technical University of Denmark (DTU), co-Editor of Computers and Chemical Engineering, *and co-founder and director of CAPEC, the Computer Aided Process-Product Engineering Center. He acknowledges the thoughtful discussions with Prof Jean-Claude Charpentier, Prof Ignacio Grossmann, Prof E. N. Pistikopoulos, and Prof John Woodley that contributed to these responses.*

Christine S. Grant, North Carolina State University

Building and strengthening a diverse profession

(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 ChE 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?

To make full use of the national talent pool, I believe that a diverse workforce requires innovation in the recruitment, promotion, and retention of underrepresented groups at all levels in the academy. Up to now, AIChE's Minority Faculty Forum in the Minority Affairs Committee has provided particular leadership in the development of a diverse faculty in chemical engineering.

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 ChE 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.

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 and biomaterials, a former board member of AIChE, and a long-time mentor to underrepresented minority and women faculty.

Robert S. Langer, Massachusetts Institute of Technology

Chemical engineering and medicine

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

I expect the area I'm in - biotechnology, pharmaceuticals, medical devices, biomaterials - to 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.

(2) Traditional core areas of ChE 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?

Nanotechnology will affect drug delivery and delivery of new genetic drugs. Transport at the nanoscale level may also open up new possibilities in non-invasive delivery, cell-specific drug delivery, and sensing.

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

I see more sectors appearing at interfaces, for example, the influence of biology and materials, biology and informatics, and nanoscience and medicine.

Bob Langer is an Institute Professor at MIT in the Department of Chemical Engineering; has participated in the founding of more than two dozen companies; a member of the National Academy of Engineering, National Academy of Science, and Institute of Medicine; and winner of AIChE's Stine, Walker, and Founder's Awards.

Wolfgang Marquardt, RWTH Aachen

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

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

The chemical industries will continue to readjust their process technologies to the gradual shift in the raw material base from petroleum to gas, coal, and eventually to bio-renewables.

Process engineering will see a revival due to the expected construction and commissioning of many new large- to mega-scale plants for bulk and intermediate chemicals to satisfy the needs of the developing countries. At the same time, radically new processing technologies leveraging on multi-functional and microscale reaction and separation equipment will be developed to facilitate not only a more efficient but also a very flexible production. The availability of such plants may lead to decentralized manufacturing sites and hence to completely different supply chains and logistic networks.

The ongoing shift toward bio-catalysis will continue, often not to replace but to complement chemical catalysis in multi-step chemical synthesis. A continuing diversification of chemical products is expected to better satisfy customers' needs. Product properties will be tailored to the specific application of a customer.

(2) Traditional core areas of ChE 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?

Cyber tools will see increasing attention to support the whole development process in the chemical industries beyond current data integration. Semantic technologies will be used to develop work-process centered tool suites to manage and assist collaborative development processes spanning from discovery, to product and product design and to operation support and marketing. Integrated multi-scale modeling of products and processes will facilitate an even larger degree of virtualization of the development process.

High-performance computing will act as an enabler and will become available as a commodity on the chemicals engineer's desk. Advanced visualization and serious gaming will be increasingly used to support decision making in product, process and infrastructure design to better capture the social dimension of engineering design. Cyber tools will also facilitate a closer link between experimentation, modeling, design and development if data-rich high throughput experimentation is exploited not only by data-driven but rather model-based techniques.

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

A new field - sometimes called "bioeconomy" - is emerging which aims at the exploitation of biorenewable raw materials to produce not only food but also performance and functional materials, chemicals and fuels. The processing of biorenewables will aim at exploiting the synthesis power of nature. Rather than defunctionalizing biomass (traditionally by cracking and production of synthesis gas), the naturally occurring molecular structures have to be reused to the extent possible and refunctionalized into desired molecules. New kinds of molecular products, reaction pathways, and processing technologies will be required to exploit the properties of the raw material. The biorenewable raw material itself is not a given but can be tailored in chemical composition by various means including selection of plant types, plant breeding, genetic engineering and agricultural technologies.

Water technologies will get increasing attention - not only because of climate change and increasing world population but also because of a potentially higher demand resulting from a water-intensive industrial production of tailored biomass.

Computational systems engineering could emerge as a new scientific field that, on the one hand, builds on the foundation of general systems theory and systems engineering and, on the other hand, computational methods and tools to address integrated product and process analysis and design. While process systems engineering has been maturing for more than five decades, other systems-centered scientific fields - most notably systems biology - have been emerging. Though emphasizing different objects of study, all these systems-oriented fields share the same methodological foundation. A consolidation of the current, rather self-contained, research fields into computational systems engineering would act as a catalyst for all the sub-disciplines and finally result in a larger impact of the field in science and engineering.

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Systems problem solving will become even more important than it is today. The system boundaries considered during development processes have to be extended continuously - towards the molecular scale on the one 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.

Consequently, there will be an increasing conflict in chemical engineering education with respect to the subjects to be covered. A focus of chemical engineering education on the scientific fundamentals of the field and the systematic cultivation of interface capabilities will position chemical engineers in the systems engineering tradition as integrators of the perspectives of the basic sciences, the engineering sciences, and marketing in development teams. Consequently, chemical engineers will need excellent communication and management skills.

Wolfgang Marquardt is Professor and Head of the Institute of Process Systems Engineering, RTWH Aachen University, co-editor of the Journal of Process Control*, and the 2008 P. V. Danckwerts Memorial Lecturer of the Institute of Chemical Engineers.*

Jan B. Talbot, University of California San Diego

Chemical nanoengineering; energy conversion; computational nanotechnology

(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 ChE 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?

As innovations in chemistry and chemical engineering underpin the emerging discipline of Nano-scale Engineering, this seems a major direction for the future of Chemical Engineering in education and in industry. In fact, UCSD recently inaugurated a new Department of Nanoengineering, which is the administrative home for Chemical Engineering.

Particularly important to nanoengineering will be the development of novel fabrication technologies, which will lead to viable manufacturing processes. Many of the manufacturing scale-up issues associated with nanoscale functional materials have strong connections to Chemical Engineering fundamentals.

Generally, self-assembly-based systems integration is envisioned as one of the more revolutionary outcomes of nanotechnology. There are now numerous examples of promising nanocomponents such as organic electron transfer molecules, quantum dots, carbon nanotubes and nanowires, and also some limited success in first-level assembly of such nanocomponents into simple structures with higher-order properties.

Living systems provide some of the best examples of self-assembly or self-organization processes. The molecular biology of living systems includes many molecules that have high-fidelity recognition properties such as DNA, RNA, and many types of protein macromolecules.

Nevertheless, the issue of developing a viable cost-effective self-assembly nanofabrication process that allows billions of nanocomponents to be assembled into useful systems is a considerable challenge.

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

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 a 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.

Computational methods offer an arsenal of tools for tackling problems specific to nanotechnology. Computational nanotechnology is all-encompassing, in the sense of embracing classical computational techniques of computational chemistry, physics, mechanics and fluid dynamics, in addition to molecular-level approaches.

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Although we are developing a new curriculum for Nanoengineering, I regard this curriculum development as the future of chemical engineering education for an industry based on nanoengineering. Nanotechnology and nanoscience are producing a wide range of new ideas and concepts, and are likely to enable novel nanoelectronics, nanophotonics, nanomaterials, energy conversion processes and a new generation of biomaterials, biosensors and other biomedical devices. This new educational curriculum and technology will address ways to carry out effective hierarchical assembly of diverse molecular and nanoscale components into higher-order structures that retain the desired electronic/photonic, structural, mechanical, or catalytic properties at the microscale or macroscale level.

This future for Chemical Engineering will use our successful approaches to problem solving with the promise of new discoveries and technological innovations in nanoengineering.

Jan Talbot is Professor of Chemical Engineering and Materials Sciences at the University of California San Diego and is past president of the Electrochemical Society.

Thomas M. Truskett, University of Texas Austin

Computing impacts on technology; sustainability; insights into the solid state; bio-chemical engineering; globalization

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

Engineering science and discovery, and chemical engineering as a key part of those efforts, are being transformed by the availability of robust, high-performance commodity clusters for computing. Computational modeling has long served as a central component of the chemical engineering toolkit, but advances in new algorithms, supercomputing, and the cyber-infrastructure necessary to bring together distant resources will soon make it possible to study problems that few anticipated a decade ago. Some of the most important efforts for the next 25 years will involve using modeling studies to guide molecular-scale processing and manufacturing of innovative new sensor technologies, drug delivery devices, and high-throughput industrial tools for patterning at molecular length scales. Expect modeling by chemical engineers to also contribute to new insights in protein folding and aggregation, the design of advanced materials, and even nucleation and transport processes in oceanic and atmospheric sciences. Problems in these areas remain "open" not only because they involve multiple length and time scales, but they also because they occupy a part of parameter space for which few general principles are known. If we are to fill the void in our understanding of these issues and make important technological progress in the next 25 years, advances in computational modeling will have to play a critical role.

(2) Traditional core areas of ChE 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?

One notable trend is that sustainability is beginning to refocus current efforts in modeling on the discovery and engineering of new materials for energy storage. Expect activity to intensify further in response to increased demand for products like rechargeable lithium batteries for portable electronics, hybrid vehicles, and innovative means for storing power from renewable resources. In some respects, chemical engineers are well suited to help meet this challenge, with their understanding of molecular transport processes and nanomaterials. But an increased focus on the solid state in chemical engineering education and research, including electrochemistry and *ab initio* methods, will also be necessary for us to make lasting contributions. One of the main challenges faced by educators and research teams is finding where to fit these topics into already packed undergraduate and graduate curricula. Establishing close collaboration with experts from chemistry and materials science is part of the answer, and the barriers between these disciplines continue to diminish. But even those collaborations will require chemical engineers to bring a firm understanding of the solid state to the table, and the sooner we recognize this, the better.

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

Chemical engineers have successfully contributed to solving a wide variety of problems because thermodynamics, transport phenomena, kinetics / reactor design, and systems engineering are important parts of many disparate manufacturing processes and technologies. Still most chemical engineers identify with one of a few major industrial sectors (e.g., chemical, petrochemical, biotechnology and pharmaceuticals, food/consumer products, electronics, and environmental engineering).

- As mentioned above, sustainability will require a significant future investment in the discovery and manufacture of new electrical energy storage materials, and it would be natural for chemical engineering to play an important role there.
- Chemical engineers have made major contributions to biotechnology, protein engineering, and drug delivery in recent years. Expect the fraction of chemical engineers working in those areas to increase.
- Another major challenge that involves kinetics, transport, thermodynamics, and materials science is helping to improve the shelf life of commercial pharmaceuticals, although the magnitude of the future participation of chemical engineers in that effort is still unclear.
- Finally, while it is provocative to propose new sectors, it also is realistic to believe that some of the traditional areas of chemical engineering will persist, and likely even expand, to address many of the economic, environmental, and geopolitical challenges that we continue to face. There will certainly be opportunities for chemical engineers to contribute to improved refining processes for shale oil, liquefying coal, and the design and manufacture of composite materials for wind turbines and fuel-efficient ground transportation and aircraft, to mention but a few.

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- Chemical engineers have historically recognized the importance of developing high standards for professional conduct and investing in higher-level and continuing education. However, growing concerns about global warming and the environment have now also brought into sharp focus the need for chemical engineers to take a stronger leadership role in helping to protect the future of the planet. Fortunately, chemical engineers are uniquely well positioned to design environmentally friendly processes and products. It is critical to recognize that unintended environmental consequences inevitably accompany the introduction of new technology. I expect the chemical engineering profession not only to strive to anticipate and understand these consequences, but to formally treat their analysis and remediation as basic steps in the process.
- We should recognize that while the United States 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 of education will play in the next 25 years of chemical engineering - will be no small task.

Tom Truskett is Associate Professor of Chemical Engineering at the University of Texas Austin, an NSF CAREER awardee, and 2007 winner of AIChE's Colburn Award.

Jackie Yi-Ru Ying, Institute of Bioengineering and Nanotechnology, Singapore

Medical chemical engineering; nanotechnology for energy conversion

(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 ChE 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?

Chemical engineering will continue to address the great challenges faced by mankind in the coming century. There are urgent needs pertaining to the sustainability of civilization and quality of medical care that can be tackled by the chemical engineers.

Our current dependency on fossil fuels has led to increasing demands on a diminishing source of energy, as well as global warming effects that threaten major climate changes. We need to develop alternative forms of energy, such as solar energy and biomass, and make them viable and affordable. We should also create technologies that would enable the fixation of carbon dioxide, and better still, convert this greenhouse gas to a useful form of energy. Nanostructured materials have a role to play in these emerging platforms. To render solar cells cost-effective and highly efficient, we would need to design and process novel nanocomposite systems. To convert biomass and carbon dioxide into practical forms of energy and useful petrochemicals, we would require new advances in catalytic chemistry and processes, most likely based on nanocomposite catalysts.

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

Chemical engineers can also make a significant impact in engineering better medicine. This would involve the diagnosis of diseases at an early stage, and optimal treatment to individual patients. The former will require combined advances in nanosensors, nanofluidic devices, genomics and bioinformatics. The latter can take the form of selective drug delivery and regenerative medicine. For example, 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.

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Chemical engineers are uniquely positioned to contribute towards the above sectors with our ability to engineer at the molecular, nanoscopic, microscopic and macroscopic length scales, and integrate the multiscale processes involved.

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.*

Visions of post-docs and students

Marc Birtwistle, University of Delaware

Using and protecting the earth's resources

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

…and…

(2) Traditional core areas of ChE 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?

Incorporation of systems biology into chemical engineering as a core science can have significant impact on multiple industry sectors by enabling rational engineering and manipulation of biological systems ranging from bacteria to humans. Systems biology is an emerging discipline focused on understanding how the behavior of living systems arises from their individual pieces.

- In the petrochemical sector, series of energy-intensive reactors and separators can be replaced with a single vessel containing rationally engineered microorganisms capable of performing multiple catalytic steps. Additionally, customized biomass feedstocks with optimal processing properties can help to replace the dwindling oil feedstocks. The net effect of increased use of renewable raw materials, coupled with decreased energy consumption, will be a more sustainable petrochemical industry.
- The pharmaceutical and biomedical sectors can be impacted by understanding of human systems derived through systems biology. "Network-based drug design" using predictive models for how drug-induced changes at the molecular level affect physiological function would allow the pharmaceutical sector to become more cost-effective by abandoning potentially ineffective or dangerous drug candidates early rather than late in the drug-development pipeline.
- The biomedical sector can use such predictive models for "model-based personalized medicine" to customize multivariate treatments for diseases such as cancer or autism that arise from non-unique interactions between numerous environmental and genetic factors.

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

As systems biology matures over the next 25 years, in addition to these impacts on existing sectors, we may also see the arrival of a new sector devoted to modeling, design, production, and utilization of engineered living systems.

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, California Institute of Technology

Biotechnology; ChE for developing countries; education and ethics

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

The world faces serious challenges right now that must be addressed quickly, namely energy, food supply, and healthcare. The urgent nature of these challenges will drive change in the biotechnology sector over the next 25 years.

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."

(2) Traditional core areas of ChE 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?

We have already seen molecular engineering and nanotechnology appear in biotechnology research in the laboratory. It is becoming obvious that control at these levels elicits new interactions with biological systems that are not possible with bulk materials of larger length scales. A significant challenge faced by the biotech industry will be how to define these materials and establish their safety with respect to both human health and the environment for the FDA and EPA (and similar agencies worldwide). There is still a great deal to be learned about the therapeutic and diagnostic potential of "nanomedicines" and other molecular tools. To realize this potential, the industry will see significant push in research and academic partnerships in this area of biotechnology.

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

In the US, the biotech industry will strengthen its ties with the traditional energy sector. There has been and will continue to be significant progress made in the efficiency of extracting energy and fuels from plants and microbes. However, integration between the biotech and energy sectors is necessary to expand current production and realistically bring biological based energy and fuels to actual customers at substantial volumes.

(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?

What chemical engineers do is still a mystery to most people. Even in college, many undergraduates choose ChE because of its reputation as one of the most difficult and employable engineering disciplines without truly knowing what it is to be a chemical engineer.

This will not be the case in 25 years because in the next few decades we will have opportunities to use our core skills to change the current global food, energy, and health situations significantly for the better. These issues are critical to all people, and chemical engineers will be the ones who engineer cellulases for biomass conversion to energy, design drug delivery systems that prevent antibiotic resistance, or identify strategies to reduce greenhouse gas emission, for example.

The ability to fill these roles in the very near future is dependent on education and collaboration. The challenge of educators is to prepare future chemical engineers for fields so diverse that it is impossible to cover all of them within a single reasonable curriculum. Future ChE students will see more real-world guest lecturers, hands-on examples, and inter-departmental group projects to teach them that the core concepts of transport, kinetics, and thermodynamics can be applied to almost any problem, especially with the help of collaborators from other fields. They will use communication skills daily in class and will, therefore, be comfortable discussing their work appropriately with farmers, financiers, or physicists.

With the increased availability and necessity of multidisciplinary collaboration and internet technical resources, it is critical that high ethical standards be maintained. Their responsibilities to society will be instilled in ChE students from their first class and emphasized throughout their formal academic and informal training.

The world has provided incredible challenges and in the next 25 years, chemical engineers will step up and be an integral part of the solutions.

Julie Champion earned her PhD at the University of California Santa Barbara with Prof. Samir Mitragotri and is presently a post-doctoral researcher at Caltech working with Prof. David Tirrell; she will join the faculty of chemical engineering at Georgia Tech in 2009.

Christopher J. Ellison, University of Minnesota Twin Cities

Market-driven changes will dominate, but watch nano- /molecular- engineering

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

In my opinion, most industry sectors (categorize them any way you like) in the US are more likely to be impacted by market opportunities than technological opportunities over the next 25 years (as they have in the past). As an example, in recent years, the US economy has been stagnant while the economies of India and China have experienced periods of rapid growth which is projected to continue into the foreseeable future. This has motivated many major technology companies (The Dow Chemical Company and General Electric to name two) to locate significant research centers in India and China. These decisions are purely driven by the idea of being close to market opportunities. At the same time, the answer also lies in the question of the chicken and the egg. In other words, it doesn't matter how much technology you incorporate into a product … if there isn't a healthy market for it, you can't profit from that technology. This principle is universal and independent of industry sector.

(2) Traditional core areas of ChE 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?

Since the time of its inception, chemical engineering has been an ever-evolving discipline. While traditional / core chemical engineering could be considered to be founded in the chemical production industry, chemical engineers are increasingly finding that they are involved in more diverse roles. One of the more recent drivers for this diversification is due to the focus on technologies incorporating nano- /molecular- engineering. Running parallel is the fact that advances in technology over time lead to more complex problems with solutions that demand a progressively expanding range of expertise. 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. Due to our intrinsic versatility and emerging paradigms in technology, we will surely witness continued evolution of the chemical engineering profession with reform at all levels, from the curriculum taught at universities to the industries which offer employment, regardless of whether the influence comes from nano- /molecular- engineering or something else (e.g., energy, biosystems, sustainability, etc.).

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

Two sectors that I see as currently emerging as focal points are alternative energy and sustainability. These issues are not new but have been brought to the forefront by both the general public and the scientific community. This interest has been sparked by the steady rise in the price of gasoline since roughly 2002, the increased atmospheric CO_2 levels (and potentially related global warming) and budding research funding programs. Nano-/molecular- technologies will likely play a critical role in new developments in these two areas, whether they involve improved photovoltaic devices for solar cells or new catalysts for higher efficiency chemical transformations, among a multitude of other possibilities. Regardless, I believe chemical engineers are well suited to play a key role in the emerging issues of alternative energy and sustainability, because of their strong and diverse training in fundamental principles and their keen skill in assembling the necessary principles to attain solutions. Many issues associated with alternative energy and sustainability are centered at the crossroads of chemistry, transport and process analysis and design…simply put, this is the territory of chemical engineering. However, chemical engineers alone will not solve these problems, but multidisciplinary teams incorporating chemical engineers as key members will likely be the most effective at addressing these pressing issues.

(***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?***

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. Due to our intrinsic versatility and emerging paradigms in technology, we will surely witness continued evolution of the chemical engineering profession with reform at all levels, from the curriculum taught at universities to the industries which offer employment, regardless of whether the influence comes from nano- /molecular- engineering or something else (e.g., energy, biosystems, sustainability, etc.).

Chris Ellison earned his Ph.D. with John Torkelson at Northwestern University, has been conducting postdoctoral research at the University of Minnesota with Prof. Frank Bates studying polymer phase behavior for nanostructured materials, and in August 2008 started at the University of Texas Austin as an Assistant Professor of Chemical Engineering.

Curt R. Fischer, Massachusetts Institute of Technology

Biocatalysts, biomass, and tailored molecular products

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

In the traditional chemical process industries, market fundamentals will result in increased prices for fossil fuels. As a result, non-traditional feedstocks such as biomass will increasingly displace fossil fuels as feedstocks of choice.

Additionally, because of highly distributed nature of biomass, solar energy, carbon dioxide, and other non-traditional feedstocks, the chemical process industries will increasingly prefer processes and products viable at scales much smaller than is common in today's integrated petrochemical refinery complexes.

Focusing specifically on the industrial biotechnology sector (as opposed to the chemical process industries in general), however, gives somewhat the opposite impression. Industrial biotechnology will find increasing application in the manufacture of high-volume commodity chemicals, not just niche higher-value fine chemicals as is common today. The examples of Cargill's production of poly(lactic acid) and DuPont's production of 1,3-propanediol serve as early examples of this trend.

Emerging capabilities in the design of microbial, enzymatic, and "traditional" catalysts will shorten and facilitate process development times. As a result, the industry will become more a field of molecular design as well as process design. This trend is already well apparent in the medical biotechnology sector, and I believe it will cross over into the industrial sector increasingly in the next 25 years.

(2) Traditional core areas of ChE 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?

Advances in molecular simulation are already facilitating the de novo design of enzyme biocatalysts. In parallel, "omics"-based analytical technologies are beginning to permit the de novo design of desired functions in living microbial systems. For example, microbes can be synthesized which catalyze not only a single reaction, but entire desired reaction pathways. Additionally, quantum computing is driving advancements in the design of traditional homogenous and heterogeneous catalysts as well.

In time, these techniques for catalyst design will become commoditized. The chemical process industries will be increasingly reliant on them for the rapid development of high-yielding, specific processes for the conversion of feedstocks to new molecular products. These techniques will shorten process development times for the manufacture of new molecular products.

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.

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

Chemical process industries that are fed by biomass rather than fossil fuels will likely constitute one such new sector. This new sector has been widely heralded and I have highlighted possible elements of its development above.

Other new sectors in the chemical process industries based on alternate feedstocks are also likely to develop. For example, as nanotechnology and materials science develop improved photoharvesting materials, the sun may become an important feedstock for some chemical manufacturing operations. Carbon dioxide captured at the stacks of fossil fuel-burning power plants or even from the atmosphere is another example. Integration of the chemical process industries into newly constructed nuclear power plants is another sector that may possibly develop in the chemical process industries.

All of these examples serve to illustrate that the feedstocks for the chemical process industries will diversify relative to the petroleum and natural gas feedstocks preferred today. This move toward diversity will likely make the chemical process industries more complex – atmospheric carbon dioxide, agricultural biomass, and nuclear-derived heat energy obviously differ radically in their physicochemical properties. New sectors will likely develop to handle the technical idiosyncrasies of each.

Curt Fischer is a Ph.D. candidate in Chemical Engineering at MIT, conducting research in the Laboratory for Bioinformatics and Metabolic Engineering under the supervision of Prof. Greg Stephanopoulos.

Meredith C. Kratzer, University of Illinois at Urbana-Champaign

Microelectronics and microchemical systems; ChEs as interdisciplinary leaders

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

The industry sector comprised of microelectronics and microchemical systems will adapt to changing energy, sustainability, and security demands over the next 25 years. The market will be driven by the producers and consumers of the "Millenial" generation, also referred to as the "Millenials." The generation is comprised of those born between 1980 and 2000; social scientists describe them as optimistic, educated, interdependent, and achievement-oriented. The demands and habits of these individuals will have a profound effect on the evolution of the chemical engineering technologies mentioned above. For example, portable fuel cells and miniaturized devices for power generation must satisfy a market that values not only performance, but also cost-effectiveness and aesthetics.

Engineers are only just beginning to be challenged by the push towards sustainability and environmental responsibility. Luckily, the Millenials, who value ingenuity and creativity, will understand how to rework traditional technologies and production methods. For instance, one could envision integrated circuit fabrication techniques being used to create sustainable consumer products, and the environmental footprint of traditional chemical reactors being all but eliminated.

Lastly, the Millenials will ensure that miniaturized electronic and chemical platforms advance to meet their concerns regarding terrorism and homeland security. Devices for the detection of explosives, biological agents, and nuclear weapons must evolve as global threats change, a greater public understanding of the value of technology develops, and the consequences of failure become graver.

(2) Traditional core areas of ChE 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?

Microelectronics and microchemical systems are not traditional core areas of ChE. Instead, the disciplines are illustrative of the intersection that has already taken place between "engineering at small length scales" and transport processes, chemical kinetics, thermodynamics, and materials engineering.

Nevertheless, 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. More drastic changes will occur over the next 25 years as the "green engineering" practices of the integrated circuit business advance to match those of the commodity chemical, petroleum, and pharmaceutical industries.

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

I foresee new sectors of chemical engineering emerging as a result of rejuvenated ties with the social sciences disciplines of economics, communications, government, and international relations. Students are increasingly drawn to institutions of higher education that allow them to obtain first-class engineering degrees while pursuing ancillary interests in business, journalism, and government. New concentrations and advanced degrees in topics such as "Energy Economics and Engineering," "Science Journalism," and "Technology and Policy" have already begun to be developed. Chemical engineers will be drawn to these emerging interdisciplinary fields as they possess strong communication and analytical skills; additionally, they tend to excel at evaluating and taking into consideration the broader impact of their work.

Most importantly, however, I believe that the next 25 years will herald in the emergence of the truly "global" chemical engineer. Recent ChE graduates are among the first to have been encouraged to pursue international internships and research experiences. Foreign students from technologically booming countries such as India and Singapore are sharing their expertise with their US peers. Revolutionary models for global ChE departmental partnerships and collaborations are being developed that address the need for well-trained engineers and cross-cultural research initiatives in historically insular countries. With such programs in place, the discipline of chemical engineering is poised to experience a hitherto unknown degree of diversification that will benefit students and professionals alike.

Meredith Kratzer is conducting Ph.D. research at the University of Illinois Urbana-Champaign with Prof. Edmund G. Seebauer, expecting to graduate in 2010.

Patrick McGrath, University of California, Berkeley

Biotechnology in chemical engineering for medicines and energy

(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 ChE 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?

The first generations of chemical engineers built what has become the modern petroleum industry. Innovations in catalysis combined with the improved understanding of thermodynamics and separations facilitated the production of extraordinarily high energy density fuels that are transported safely and easily. This is a remarkable legacy, both for the technological challenges overcome and for the lifestyle petroleum has enabled.

Unfortunately, it has become increasingly clear that we have not fully accounted for the true costs of fossil fuels, and our reliance on petroleum is not sustainable over the long term. The key challenge for future generations of chemical engineers is to find alternative sources of energy to reduce (or eliminate) our dependence on fossil fuels. There are many options on this front -- batteries for plug-in hybrid electric or all-electric vehicles, biomass-derived fuels, and hydrogen fuel cells are all showing some promise -- and each technology requires the accumulated expertise of chemical engineers.

To push these technologies forward, the "classical toolkit" of chemical engineering (kinetics, thermodynamics, transport) and some newer tricks of the trade (advanced modeling, metabolic engineering, materials design and control on multiple lengthscales) will be required. The energy infrastructure for modern transportation was created by chemical engineers; as we face the challenge of revamping and replacing that infrastructure, chemical engineers must remain at the forefront.

Patrick McGrath recently completed his Ph.D. in chemical engineering at the University of California, Berkeley, with Prof. Jeffrey Reimer and is presently a Senior Consultant with Booz Allen Hamilton.

Ryan C. Snyder, University of California, Santa Barbara

Drug manufacturing; food and water infrastructure

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

The cost of discovering each new active pharmaceutical ingredient (API) has steadily risen over the past 10-20 years. While biotechnology and genomics have potential to change this tide, it is likely that discovering new APIs will continue to become more and more costly. Additionally, the pharmaceutical industry faces potential challenges in their ability to maintain pricing power over the coming years due to either the challenge of passing on these increased costs to the consumer or potential reforms to the US healthcare system. Nonetheless, due to generic competition, pharmaceutical companies must continue to find new drugs in order to stay economically viable.

Over the next 25 years, I expect that chemical engineers will have a dramatic impact on the pharmaceutical industry through improved process development methodologies. These methods will help to enable a driving down of costs and a mitigation of risk through more rapid development and scale-up.

(2) Traditional core areas of ChE 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?

Twenty to thirty years ago (or so I have heard), scale-up of a new traditional liquid-phase chemical process required large amounts of experimental data, extensive calculations and many incremental increases in production scale before reaching the full plant level. However, today the path to full-scale production can often be performed rapidly while coupled with a minimal set of experiments. Often process simulation can even be performed simultaneously with the new research projects to immediately bear out their economic potential. This rapid process intensification was due in large part to chemical engineering contributions through the development of predictive thermodynamic models (e.g., UNIFAC), process synthesis methods and detailed process simulations that can be implemented on time scales relevant for process development.

In much the same way, in order to reach full-scale production of a new 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 suggests that the development of new solid-state chemicals such as APIs twenty to thirty years from now may follow a similar course. One may only require a minimal set of experiments, coupled with as of 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.

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

Looking to the future, chemical engineers will have a continued influence in areas where we have traditionally contributed greatly such as energy and healthcare. Additionally, I expect that chemical engineers will have an increasing role in managing and maintaining both our food and water infrastructure. While these are both areas where chemical engineers have had some influence in the past, their growing importance (along with energy) will drive the need for more work in these areas. This could range from the development of methods to avoid residual pharmaceuticals from reaching the water supply to the development of new nutrition replacements (meal in a pill).

Chemical engineers will likely also play a role in new markets that will develop further in the decades to come. For instance, challenges in space will force us to reexamine our existing expertise with new constraints (e. g. travel costs, transportation of equipment) that have not been considered in the same way before (although one can likely assume an ideal gas at those pressures.) Food, water, and energy needs over longer distances, times and on unearthly bodies will not just be problems for astrophysicists.

Ryan Snyder is conducting Ph.D. research at the University of California, Santa Barbara, with Prof. Michael F. Doherty.

James A. Stapleton, Stanford University

New biochemical-engineering knowledge, highlighting the common ground

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

Huge shifts in global demographics in the next 25 years will create market opportunities that will drive the evolution of chemical engineering. The aging of the populations of developed countries, the emergence as global consumers of the populations of developing countries, and the spread of the kind of urbanization we are witnessing in China will create vast new markets and increase the strain on our environment. Every aspect of our civilization will need to be rethought as the global population grows and natural resources (and waste sinks) become scarcer.

Chemical engineers will be instrumental in redesigning wasteful processes and developing new technologies to increase the value we create from each unit of input, while turning waste streams into useful recycle loops. Biochemical engineers in particular will be challenged to develop renewable sources of energy, new materials, green catalysts, water treatment technologies, and sustainable fertilizers, and to quickly scale them to meet global needs.

Biochemical engineers will also be instrumental in making healthcare more effective, affordable, and accessible to 10 billion people, and in finding cures to diseases from malaria to cancer. As DNA sequencing technologies develop, the genomes of billions of unculturable and undiscovered microorganisms will offer starting points and inspiration, and our growing abilities in genetic and protein engineering will provide tools with which to solve many of these challenges.

(2) Traditional core areas of ChE 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?

Given enough computing power, density functional theory and molecular dynamics will one day do for chemical engineering what finite element analysis has done for mechanical engineering. The ability to model and predict the behavior of increasingly complex systems will revolutionize the way we design catalysts, materials, and processes. In the next 25 years, increased computational capabilities will transform my field of biochemical engineering. The first brewers and bakers used biocatalysts because they performed transformations for which there were no alternative catalysts while reproducing and repairing themselves using common elements at environmental temperatures and pressures. Today we use them for much the same reasons, and though we have expanded their utility by learning how to engineer cells and proteins with abilities for which nature never selected, we still do not fully understand them, nor can we match their abilities with our own designs. In the next 25 years, the ability to design highly stable enzymes to catalyze any desired reaction in silico will usher in a new era of efficient, green chemistry, with huge savings in energy and feedstock costs. As our knowledge of biocatalysis grows, we may eventually abandon biology for biomimicry, designing atomically precise nano-machines inspired and perhaps assembled by enzymes but free of their industrial limitations.

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

Because the multi-faceted challenges we will face in the next 25 years will require engineers to develop equally multi-faceted solutions, well-roundedness will become a very important virtual sector of its own. The parallels that engineers with diverse expertise can draw between fields make them much more than the sum of their experiences. Specialized scientists who are only able to approach a problem from a single area of expertise are often left trying to force their square peg into round holes. Engineers must have a holistic view of real-world problems and be able to consider the scientific, economic, cultural, pragmatic, and interpersonal forces influencing a situation. Otherwise we risk developing technologies that are exciting but do not quite fit the hole - like corn ethanol, which increases greenhouse gas emissions by encouraging deforestation.

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.

Jim Stapleton is completing his Ph.D. research at Stanford University with Prof. James Swartz.