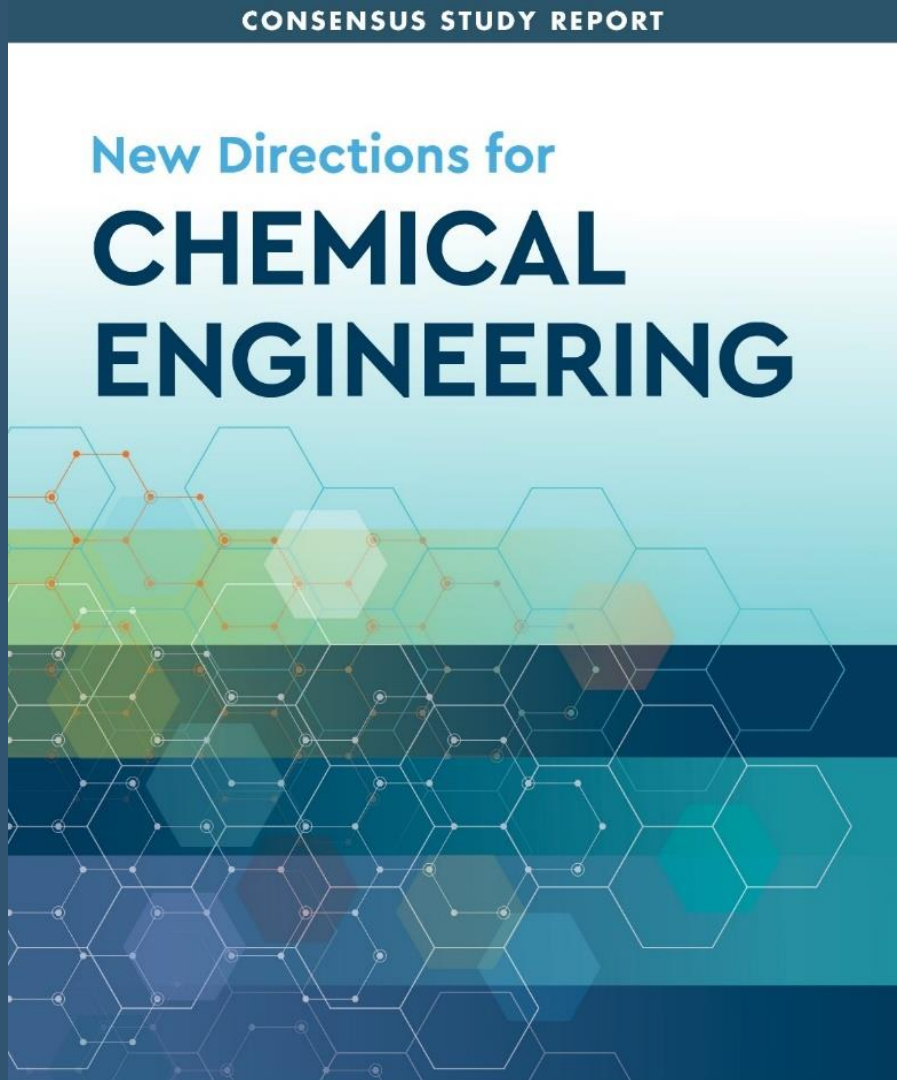
NATIONAL ACADEMIES Sciences Engineering Medicine

New Directions for Chemical Engineering

South Texas Section - AIChE
STS AIChE & TIEEP - Water Forum
May 4, 2023

Dr. José G. Santiesteban



New Directions for Chemical Engineering

Study Committee:

- **ERIC W. KALER**, Chair, Case Western Reserve University
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  EMD Electronics

Exciting Times for Chemical Engineers

- Chemical Engineers' ability to apply systems-level thinking from molecular to manufacturing scales uniquely positions them to address today’s most pressing problems, including climate change and the overuse of resources by a growing population.

- Chemical Engineering is highly interdisciplinary

- Chemical Engineering provides an excellent foundation for many career paths; exciting and rewarding careers in various sectors.

Topics

- Background
  - Motivation for Study
  - Statement of Task
  - Committee's Approach to Task

- Recommendation Areas
  - Energy
  - Food and Water
  - Health and Medicine
  - Manufacturing
  - Materials
  - Tools
  - Training and Fostering Next Generation of Chemical Engineers

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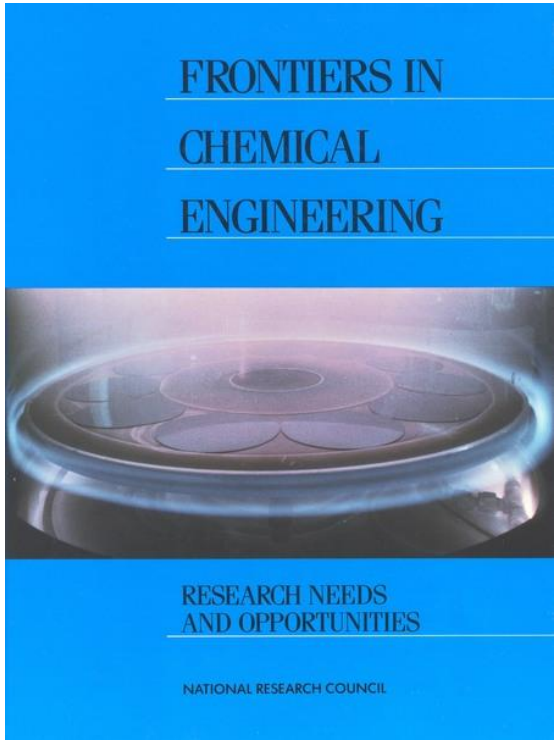
Motivation for Study



- Conclusion from an American Institute of Chemical Engineers (AIChE) Roundtable: the field of chemical engineering needs a new vision for the 21st century

- Need for a new “Amundson Report”
  - *Frontiers in Chemical Engineering Research Needs and Opportunities* (1988)

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Statement of Task

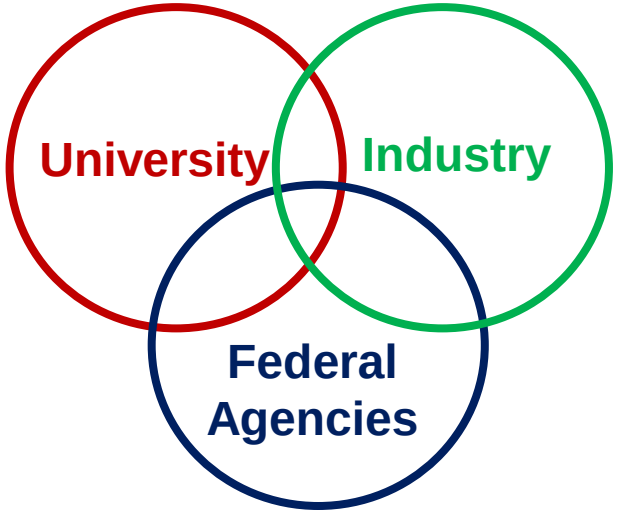
- Describe major advances and changes in chemical engineering over the past three decades, including the importance and contributions of the field to society; technical progress and major achievements; principal changes in the practice of R&D; and economic and societal factors that have impacted the field.
- Address the future of chemical engineering over the next 10 to 30 years and offer guidance to the chemical engineering community:
  - Identify challenges and opportunities that chemical engineering faces now and may face in the next 10-30 years, including broader impacts.
  - Identify a set of existing and new areas that offer promising intellectual and investment opportunities, as well as areas that have major scientific gaps.
  - Identify aspects of undergraduate and graduate chemical engineering education that will require changes.
  - Consider recent trends in chemical engineering in the United States relative to international research.

Committee's Approach to Task

- Committee first identified the major societal and environmental areas in which chemical engineers have, or are likely to have in the future, the largest impact:
  - Energy
  - Food and Water
  - Health and Medicine
  - Manufacturing
  - Materials
  - Tools
- Information-gathering and chapter writing were structured around these areas as well as chemical engineering education

General Recommendations for All Areas

- Interdisciplinary approach
- Cross-sector collaborations focused on pilot- and demonstration-scale of innovations



The three sectors benefit significantly from AIChE's crucial role in bringing them together

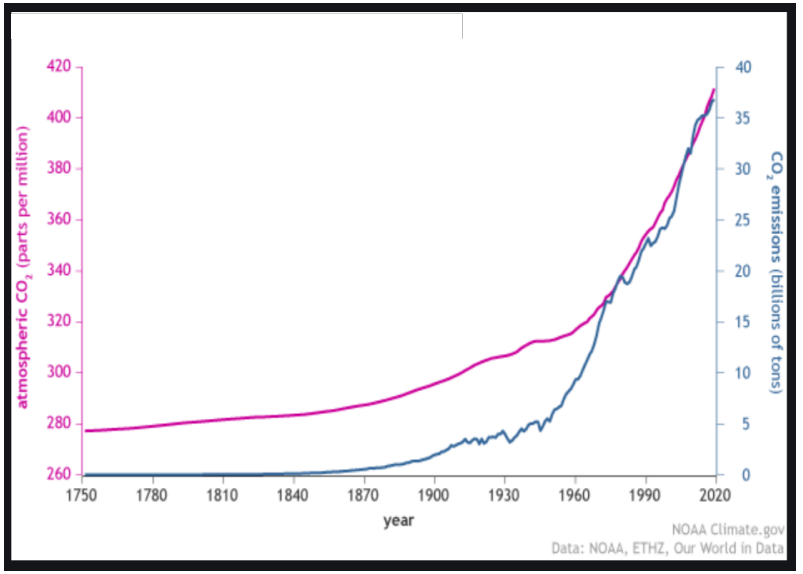
Report Recommendation Areas

- Energy - Decarbonization of Energy Systems
- Food and Water - Accessible and Sustainable Engineering Solutions for Environmental Systems
- Health and Medicine - Engineering Targeted and Accessible Medicine
- Manufacturing - Flexible Manufacturing and the Circular Economy
- Materials - Novel and Improved Materials for the 21st Century
- Tools to Enable the Future of Chemical Engineering
- Training and Fostering the Next Generation of Chemical Engineers
- International Leadership

Decarbonization of Energy Systems

- Climate change is one of the most pressing problems facing humans and the planet
- Addressing climate change will require the decarbonization of current energy systems
- Chemical engineers can contribute to decarbonization across the energy value chain

Carbon Dioxide Emissions and Atmospheric Concentration (1750 -2020)



Energy mix must change to meet climate targets

- Electrification - “clean” electrons
- ”Blue” and “Green” Hydrogen
- Liquid Synthetic Fuels and Biofuels
- Oil and Gas with CO_2 capture and sequestration

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Decarbonization of Energy Systems

Sources

- Advance solar technologies
- Innovations in shale oil and gas production
- Contribute to biofuels production and lignin alternatives

Carriers

- Re-imagine petroleum refineries
- Increase clean hydrogen production
- Increase efficiency of chemical transformations

Storage

- Increase battery lifespans and design for end-of-life disposal
- Design batteries that use earth-abundant elements

Use

- Contribute to advances in electric vehicles, fuel cell engines, and internal combustion engines
- Reduce emissions from cement, steel, and chemical production

Carbon Capture, Use, and Storage

- Design new solvents and sorbent materials
- New approaches to CO_2 conversion

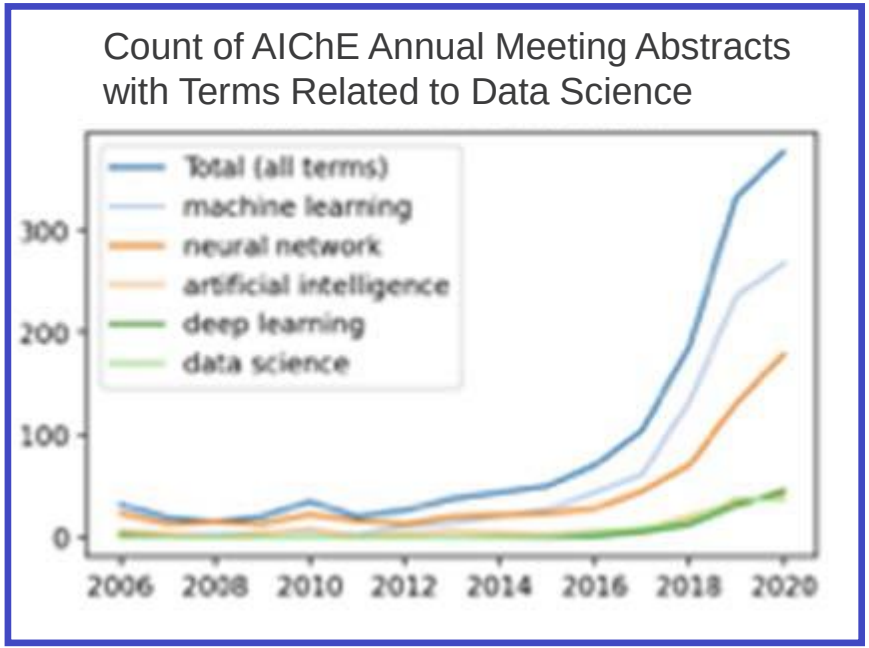
Decarbonization of Energy Systems

- Federal research investments:
  - Advance low- or zero-carbon energy technologies
  - Minimize water use in energy systems
  - Carbon capture, use, and storage
  - Advance photochemistry
- Interdisciplinary, cross-sector collaborations focused on pilot- and demonstration-scale projects for low-carbon energy technologies

Tools to Enable the Future of Chemical Engineering

Chemical engineers will need to navigate the interface between the natural world and the data that describe it, as well as use the tools that turn data into useful information, knowledge, and understanding.

- Federal and industry research investments:
  - Artificial intelligence, machine learning, and other data science tools
  - Improving modeling and simulation and life-cycle assessment capabilities
  - Developing novel instruments and sensors



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Thank You For Your Attention !!

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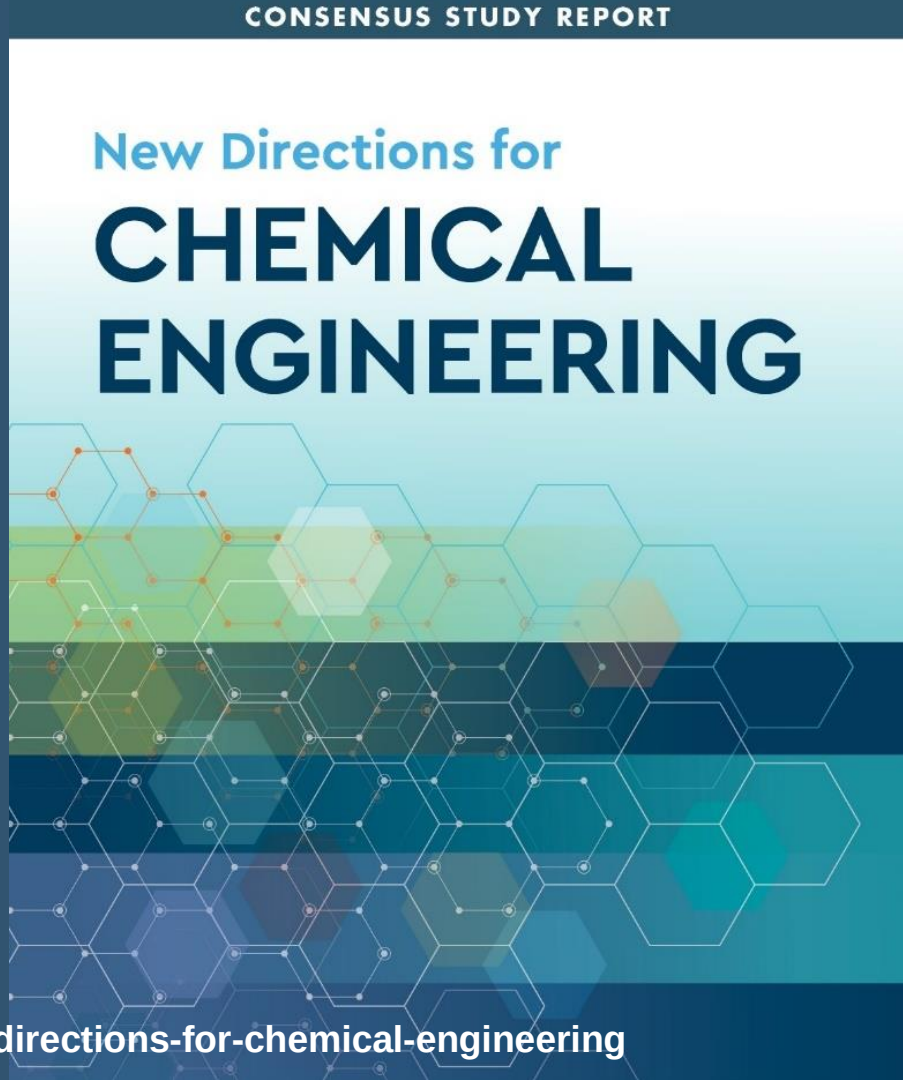

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In memory of Babatunde A. Ogunnaike

Additional Information

Sustainable Engineering Solutions for Environmental Systems

Chemical engineers bring both molecular and system-level thinking to pioneering efforts in this highly interconnected water-food-energy space

Sustainable Engineering Solutions for Environmental Systems

Water

- Advance separation and treatment technologies
- Improve understanding of interfacial layers

Food

- Improve per land area crop yields
- Pioneer ammonia production beyond Haber-Bosch
- Develop applications for agriculture and food processing waste streams

Air

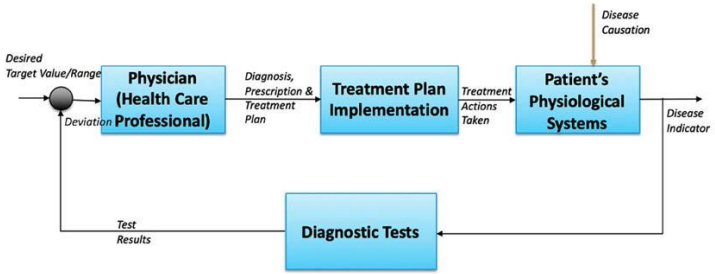
- Reduce emissions of pollutants
- Advance mitigation technologies
- Contribute to fundamental understanding of aerosols

Sustainable Engineering Solutions for Environmental Systems

- Federal research investments:
  - Fundamental understanding of the structure and dynamics of water
  - Develop advanced separation and water treatment technologies
  - Minimize the land, water, and nutrient demands of agriculture and food production
- Interdisciplinary, cross-sector collaborations focused on scale-up of innovations in:
  - Metabolic engineering
  - Bioprocess development
  - Precision agriculture
  - Food preservation, storage, and packaging
  - Lab-grown foods

Engineering Targeted and Accessible Medicine

There are few areas of science and engineering in which the rate of progress has been, and continues to be, more rapid than advances in biology and biochemistry aimed at treatments and cures for human illness



Feedback control paradigm for implementing personalized medicine (Ogunnaike, 2019)

- Personalized Medicine
- Improving Therapeutics
- Understanding the Microbiome
- Materials, Devices, Delivery

Engineering Targeted and Accessible Medicine

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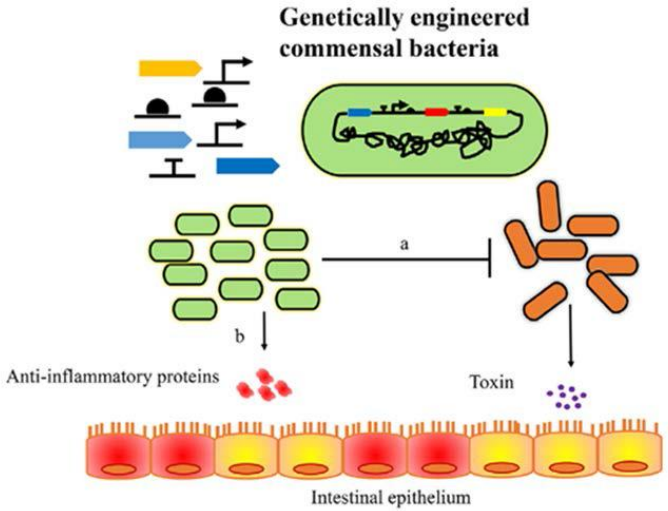
Engineering Targeted and Accessible Medicine



Engineered commensal bacteria as living therapy in the gut (Tan et al., 2020)

- Personalized Medicine
- Improving Therapeutics
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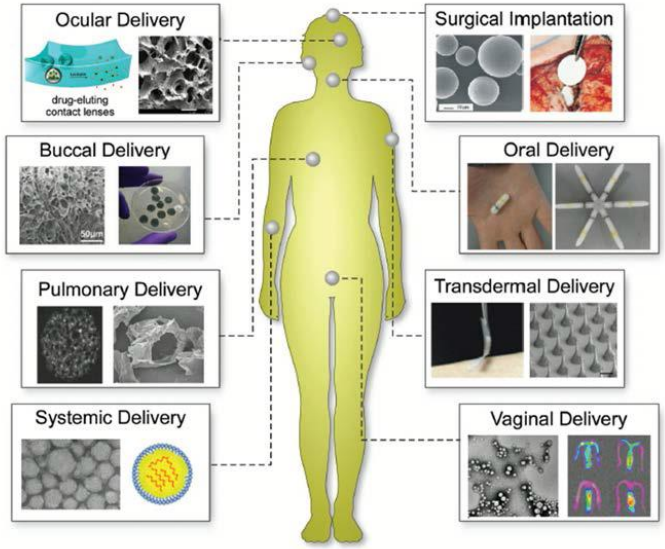
Engineering Targeted and Accessible Medicine



Examples of biomaterials and their delivery routes (Fenton et al., 2018)

- Personalized Medicine
- Improving Therapeutics
- Understanding the Microbiome
- Materials, Devices, Delivery

Engineering Targeted and Accessible Medicine

- Federal research investments in biomolecular engineering:
  - Advance personalized medicine and the engineering of biological molecules
  - Bridge the interface of materials, devices, and health
  - Improve the use of tools from systems and synthetic biology to understand biological networks and intersection with data science and computational approaches
  - Develop engineering approaches to reduce cost and improve health equity

- Interdisciplinary, cross-sector collaborations focused on pilot- and demonstration-scale projects for advanced pharmaceutical manufacturing processes

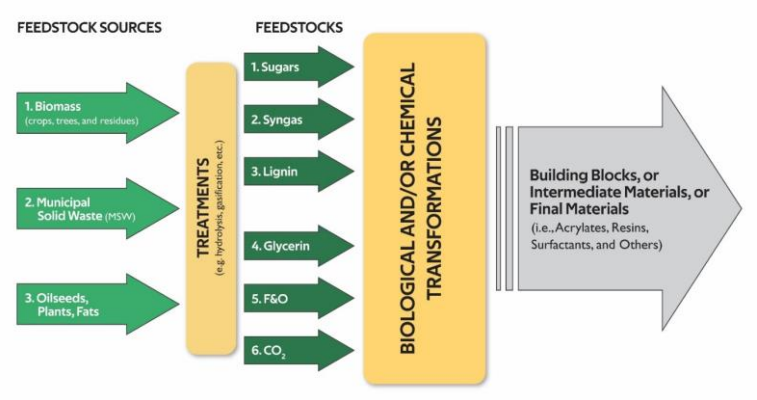
Flexible Manufacturing and the Circular Economy

Chemical engineering as a discipline was founded in the need to deal with heterogenous raw materials, especially petroleum, and this need will be amplified in the transition to more sustainable feedstocks

Feedstock Flexibility

Process Intensification

Circular Economy



Flexible Manufacturing and the Circular Economy

Feedstock Flexibility

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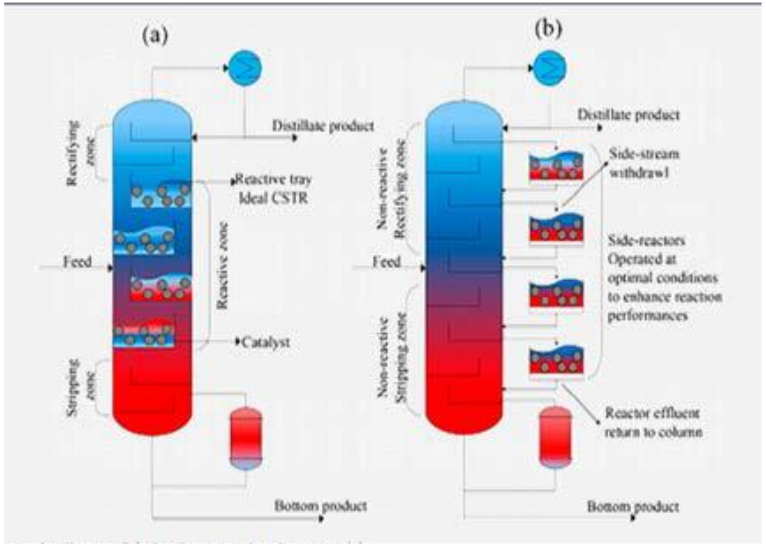

Reactive distillation in the electronics industry (Hussain et al., 2019)

Flexible Manufacturing and the Circular Economy

Feedstock Flexibility

Process Intensification

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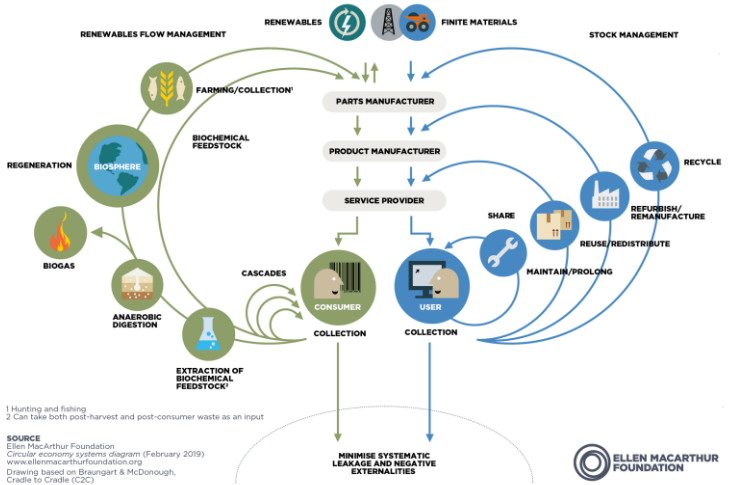


Flow of materials, nutrients, components, and products in a circular economy (EMF, 2019)

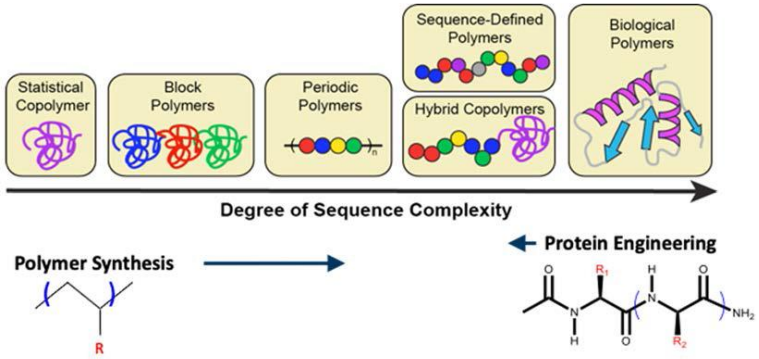
Flexible Manufacturing and the Circular Economy

- Federal research investments:
  - Distributed manufacturing
  - Process intensification
  - Improved product design and recycling processes to transition to a circular economy
- Interdisciplinary, cross-sector collaborations focused on pilot- and demonstration-scale projects in:
  - Scaled-down and scaled-out processes
  - Process intensification
  - Transition to sustainable feedstocks

Novel and Improved Materials for the 21st Century

- Chemical engineers have a critical role to play in the discovery/development of new materials and material processes from the molecular to macroscopic scales
- Integration of theory, modeling, simulation, experiment, and machine learning is accelerating the discovery, design, and innovation of new materials and processes

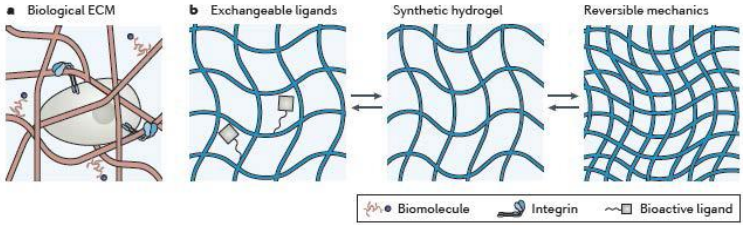
- Federal and industry research investments:
  - Polymer science and engineering
  - Complex fluids and soft matter
  - Nanoparticle synthesis and assembly
  - Electronic materials



Increasing complexity in the synthesis of polymers (Rosales et al., 2013)

Novel and Improved Materials for the 21st Century

- Federal and industry research investments:
  - Polymer science and engineering
  - Complex fluids and soft matter
  - Nanoparticle synthesis and assembly
  - Biomaterials
  - Electronic materials



Biological extracellular matrix and synthetic strategies (Rosales and Anseth, 2016)

Chemical engineering plays an essential role in advancing the development of biomaterials for both regenerative engineering and organ-on-a-chip technology, and chemical engineering principles are at the heart of understanding and improving targeted drug delivery both spatially and temporally

Tools to Enable the Future of Chemical Engineering

Chemical engineers will need to navigate the interface between the natural world and the data that describe it, as well as use the tools that turn data into useful information, knowledge, and understanding.

- Federal and industry research investments:
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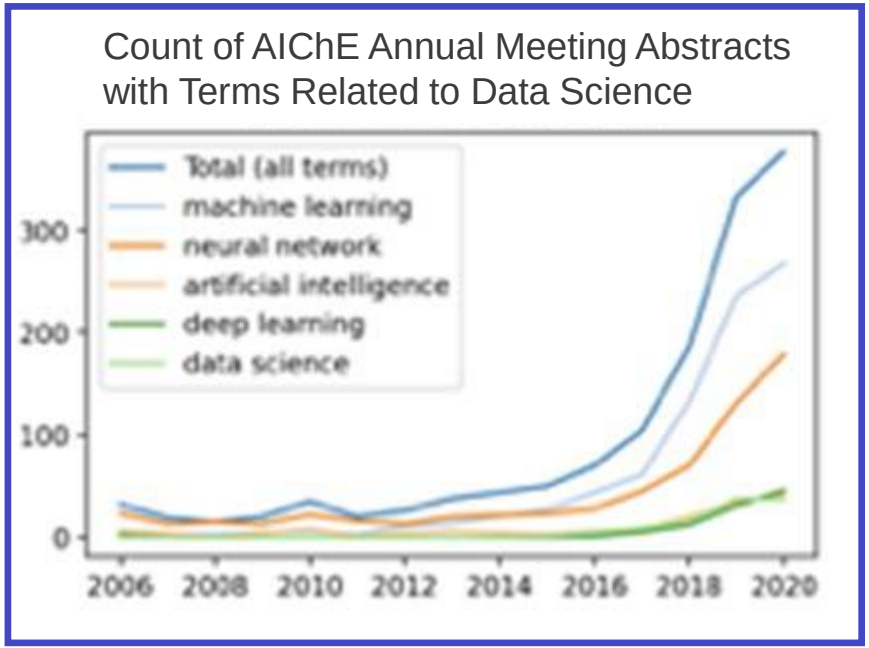
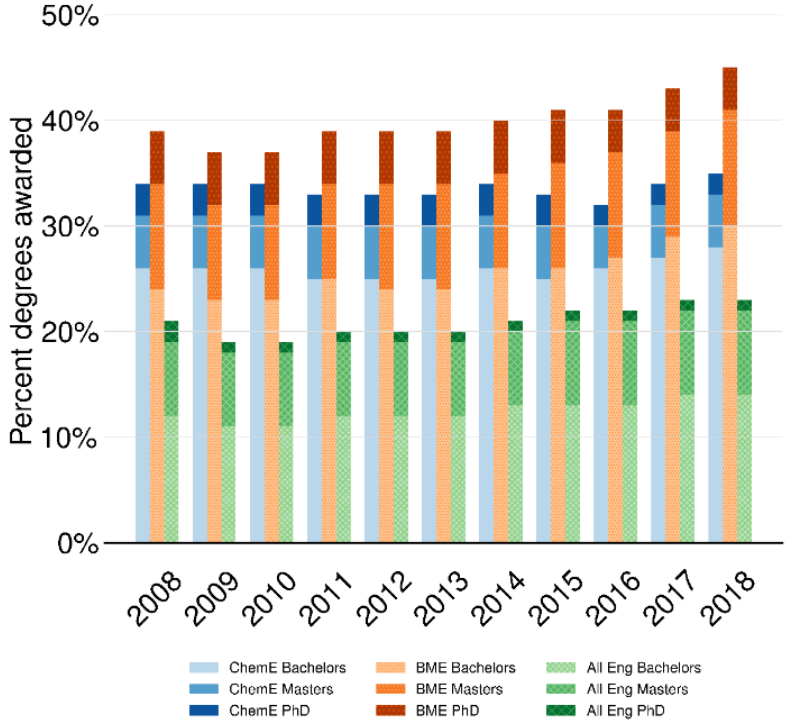


Training and Fostering the Next Generation of Chemical Engineers



- The percentage of chemical engineering degrees awarded to women remains relatively unchanged over the past decade

- The percentage of chemical engineering degrees awarded to Black, Indigenous, and People of Color (BIPOC) is also relatively unchanged over the past decade

Training and Fostering the Next Generation of Chemical Engineers

Undergraduates

Curriculum Revisions

- Connections across the core
- Experiential learning
- Math and statistics into the core

Attract more women and BIPOC students

- Opportunities for societal impact
- Effective mentoring and support structures
- Recruit and support transfer students

AIChE

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Training and Fostering the Next Generation of Chemical Engineers

Case Western Reserve University

Graduate Students

- Experiential Learning through Internships
  - Training revisions
  - Changes to funding structures
  - Coordination among universities, industry, funding agencies, and AIChE
- Attract more women and BIPOC students
  - Revise admissions criteria to remove barriers
  - Welcome students from related disciplines

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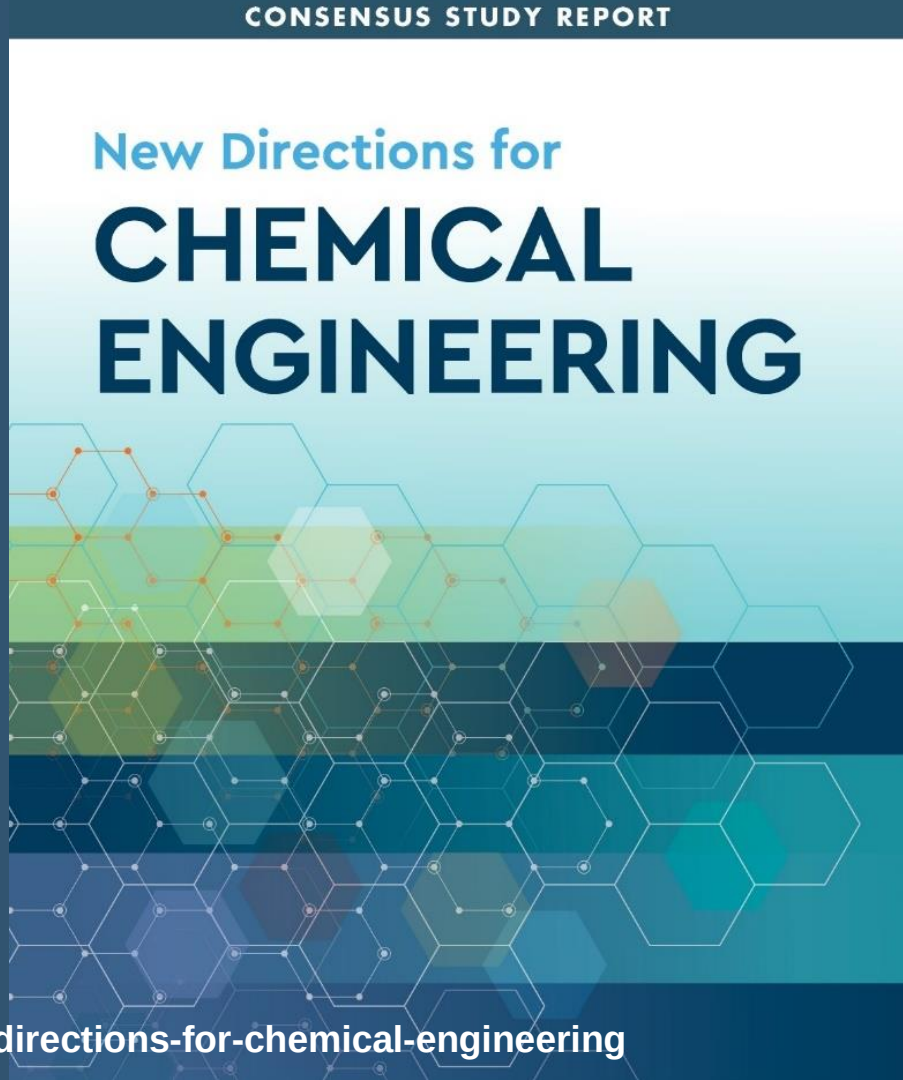

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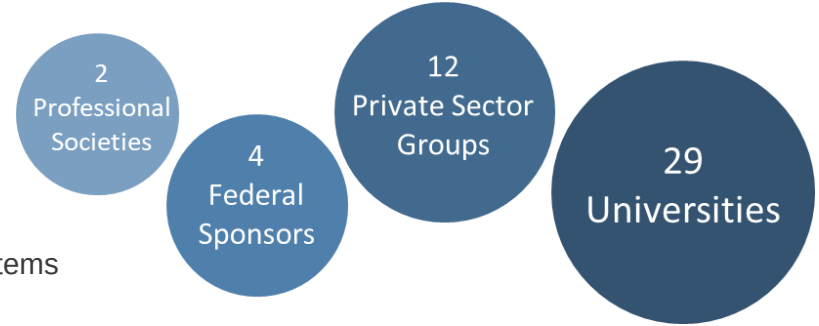

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DOE Office of Fossil Energy and Carbon Management
DOE Advanced Manufacturing Office
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Community Input

- The committee met 42 times to gather information, deliberate, and write
  - 27 meetings had a session open to the public and included over 60 guest speakers (see report Appendix D)
- Town hall-style session at the 2019 AIChE meeting and participated in a meeting of the AIChE Virtual Local Section
- Broadly distributed questionnaire for input on the future of the discipline (summarized in report Appendix C)