Frontiers in Chemical Engineering Education

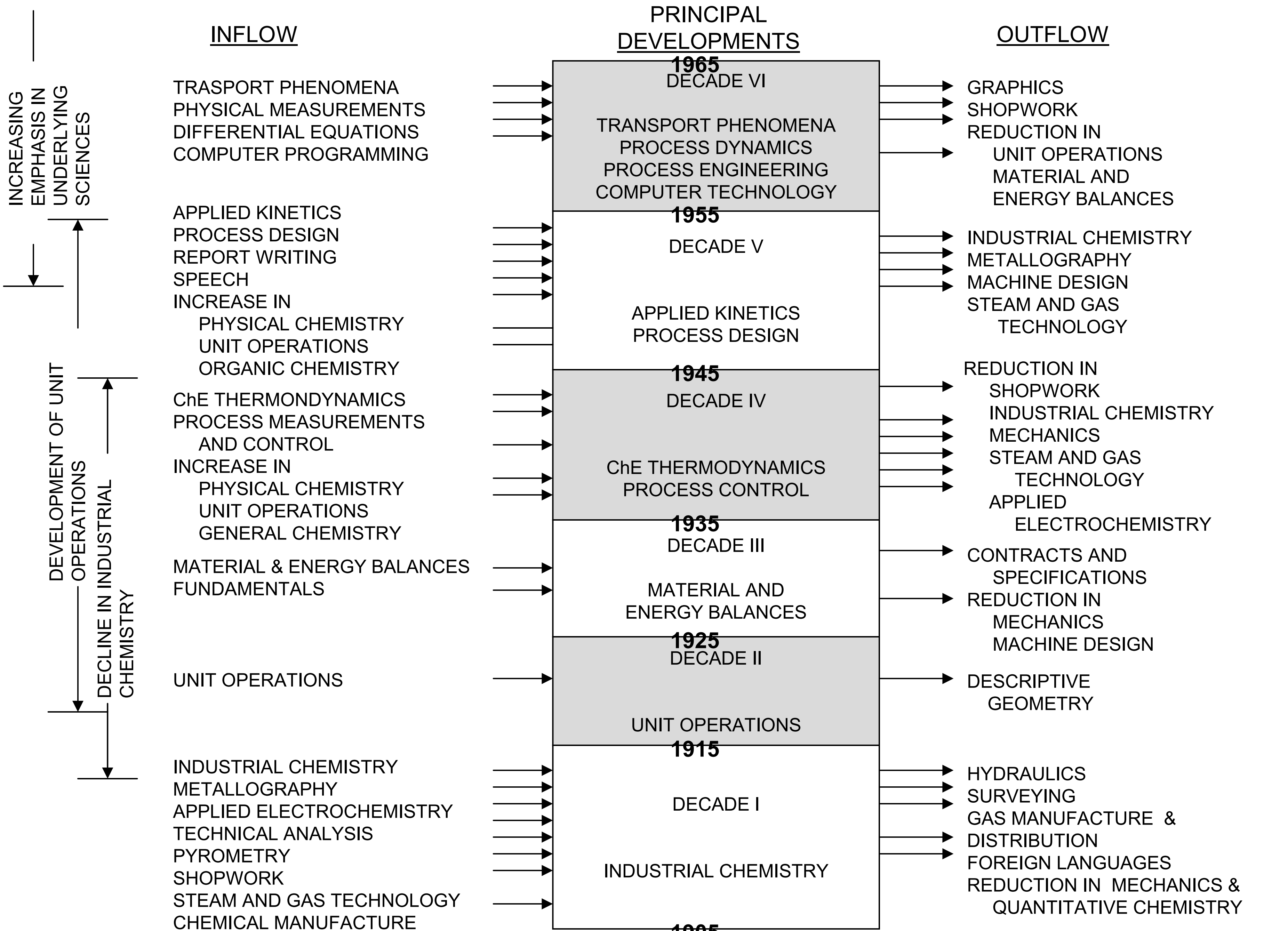
New Directions and Opportunities – Creating the Future

CCR/NSF Discipline Wide Curriculum Workshops

The Path Forward

Summary

- It has been 40+ years since chemical engineering curriculum underwent major change
- During this period the profession has experienced major change
- Mechanisms to change are different today than in the past
- We must work as leaders of the discipline to encourage and facilitate this process
  - Allocation of resources
  - Assignment of credit



Changes in a typical undergraduate chemical engineering curriculum during 60 years. The initial curriculum in 1905 consisted of separate courses in chemistry and conventional engineering.

Changing Nature of Chemical Engineering

- Our industry
- Career paths
- Research opportunities
- Underlying science

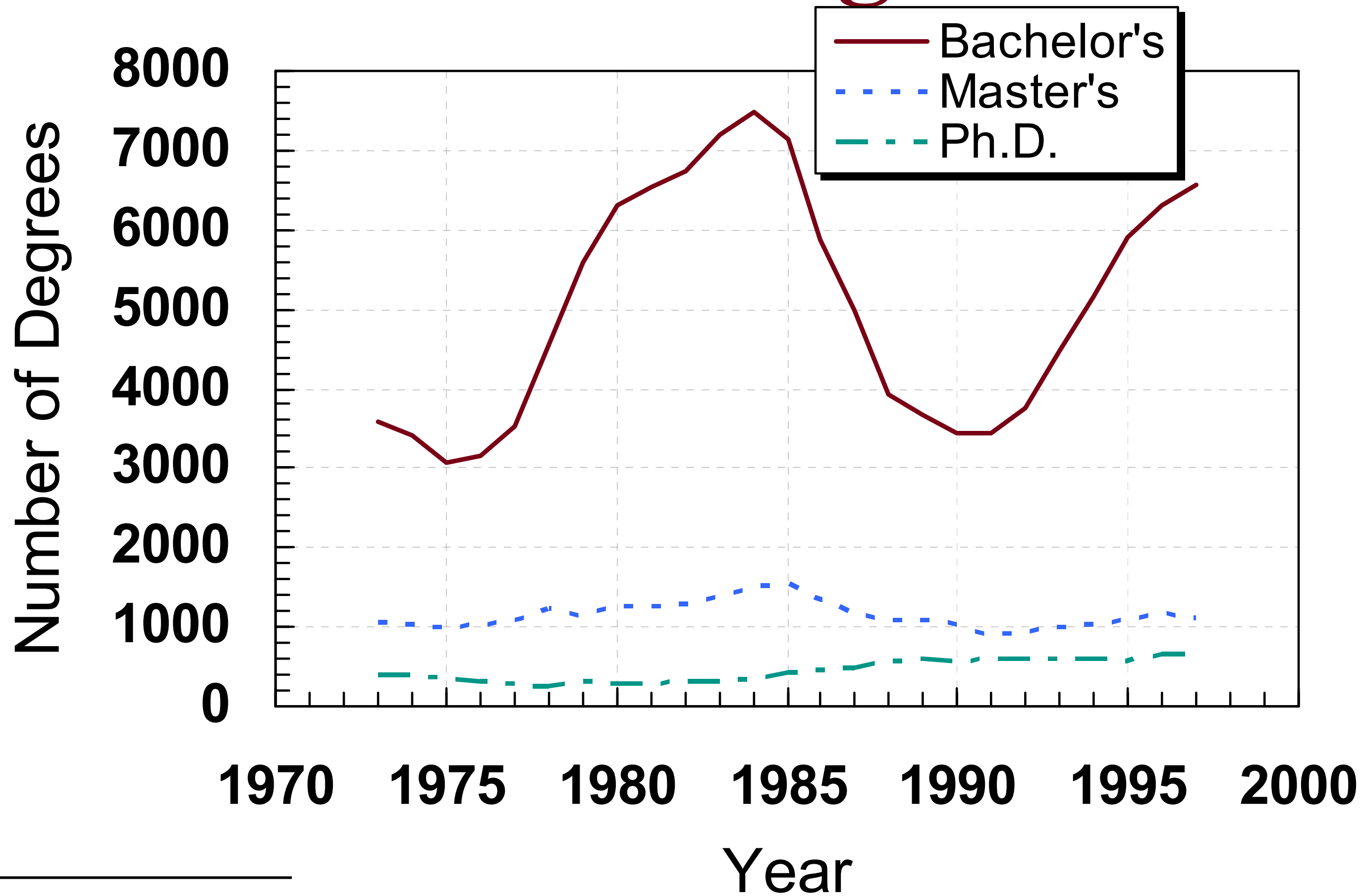
Chemical Industry Trends

- The chemical industry is cyclical
- The industry is becoming increasingly global
- Mergers of companies and product lines
- Chemical companies are becoming life science companies and spinning off chemical units
- Virtual companies - out-sourcing of services - incl. research
- Chemical engineering no longer is dominated by petrochemicals/bulk chemicals
- Time to market for new products has dramatically decreased
- Graduates can expect to have multiple professional jobs
- Chemical engineering graduates go into a broad range of careers:
  - Chemicals, biochemical, materials, consumer products, …….
  - Teaching

Manpower Issues

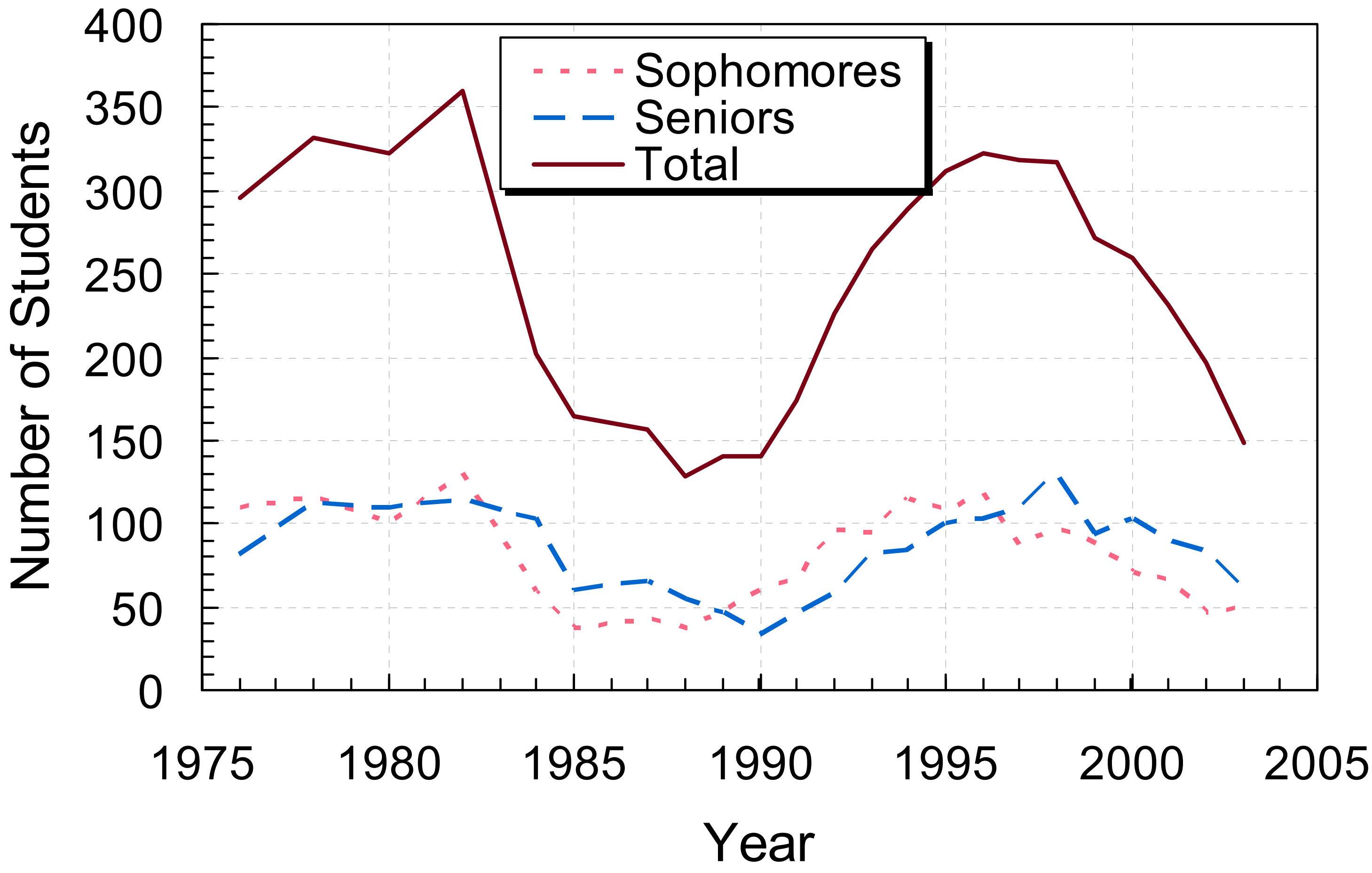
- Public perception of "chemical" is negative
- Consumers (potential students) do not know what we do in emerging technologies such as biotechnology and nanotechnology
- Enrollments are small relative to other engineering disciplines
  - Not necessarily bad, but we want the best
- Enrollments appear to be cyclic
  - Are they really?
  - Do they need to be?
- Employment opportunities are diverse
  - Reflects research opportunities in our departments
- Other disciplines are beginning to recognize the importance of molecules/molecular engineering
- We are currently dealing individually with these issues, particularly the response to opportunities with molecular biology

U.S. Chemical Engineering Degrees 1973-97

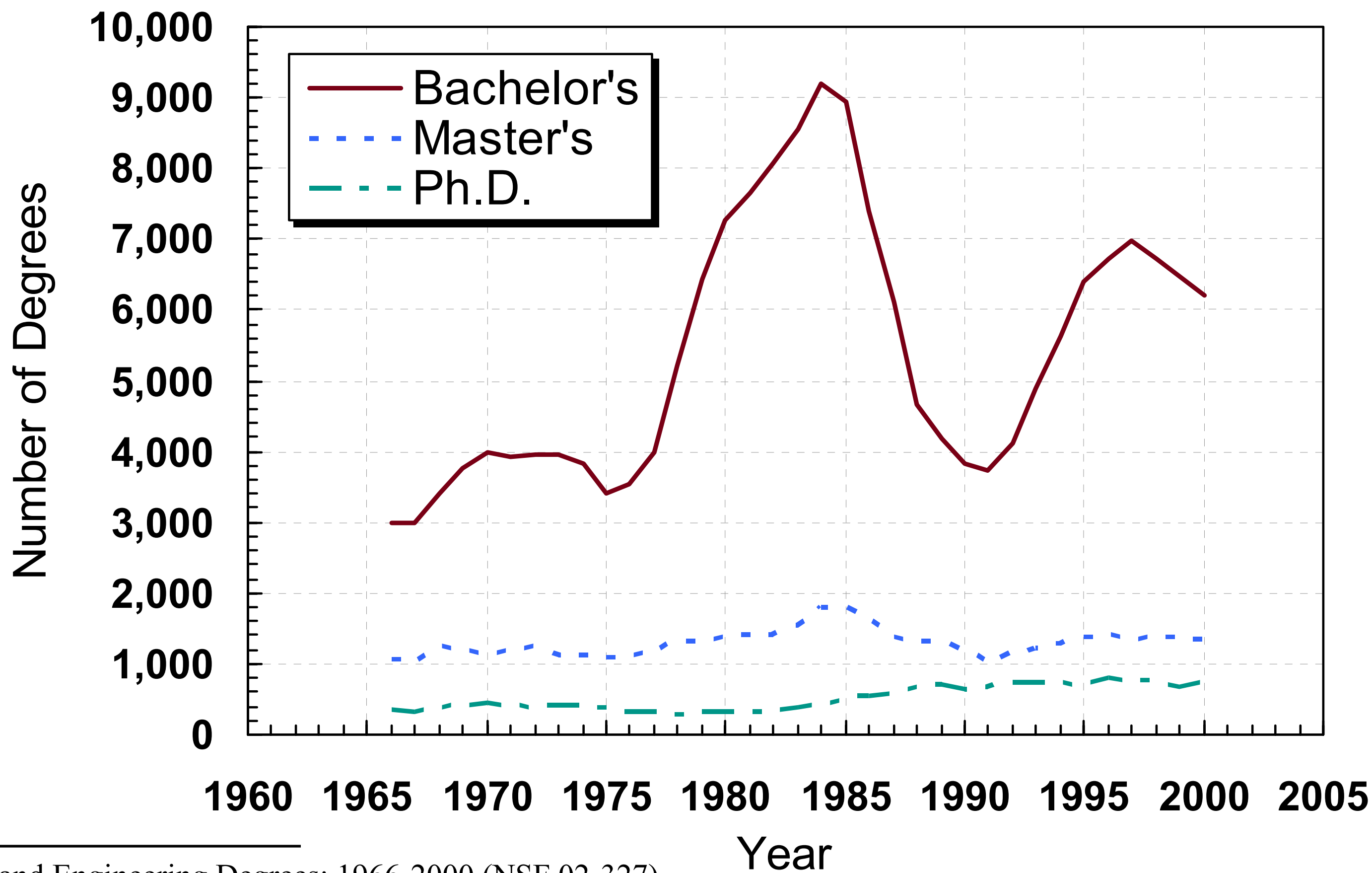


Chemical & Engineering News

MIT Undergraduate Class Size

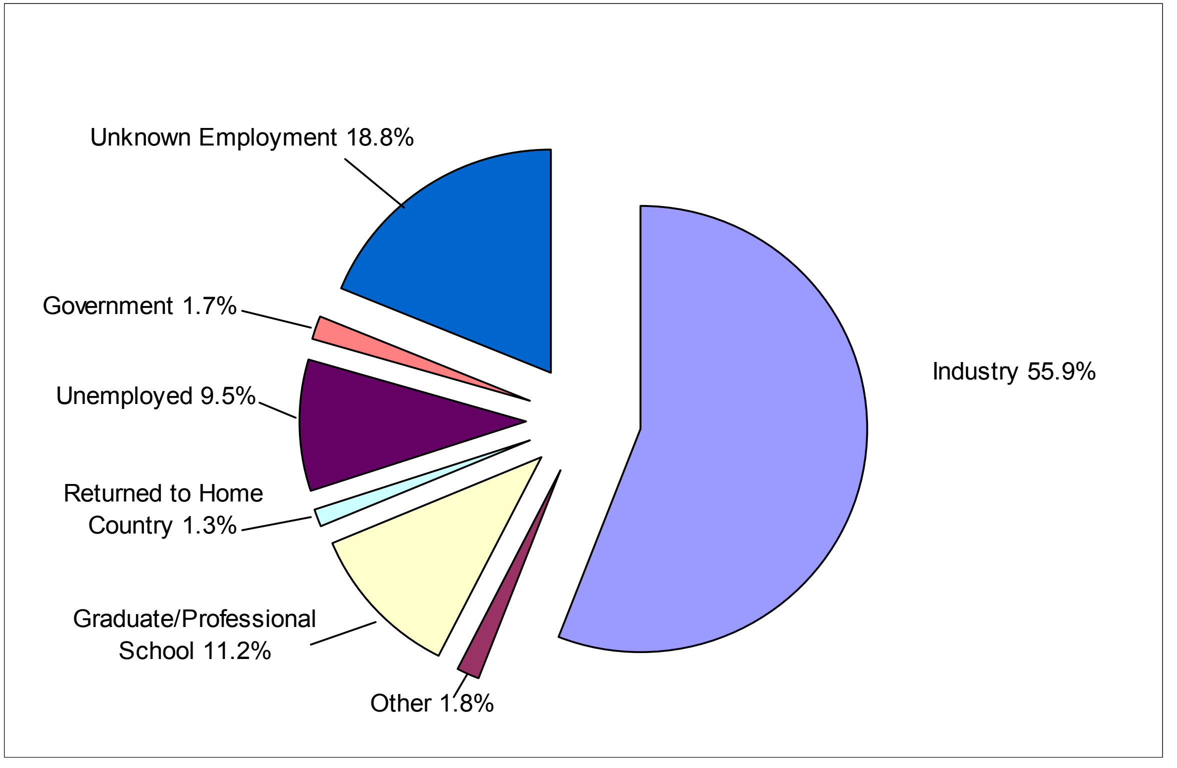


U.S. Chemical Engineering Degrees 1966-2000



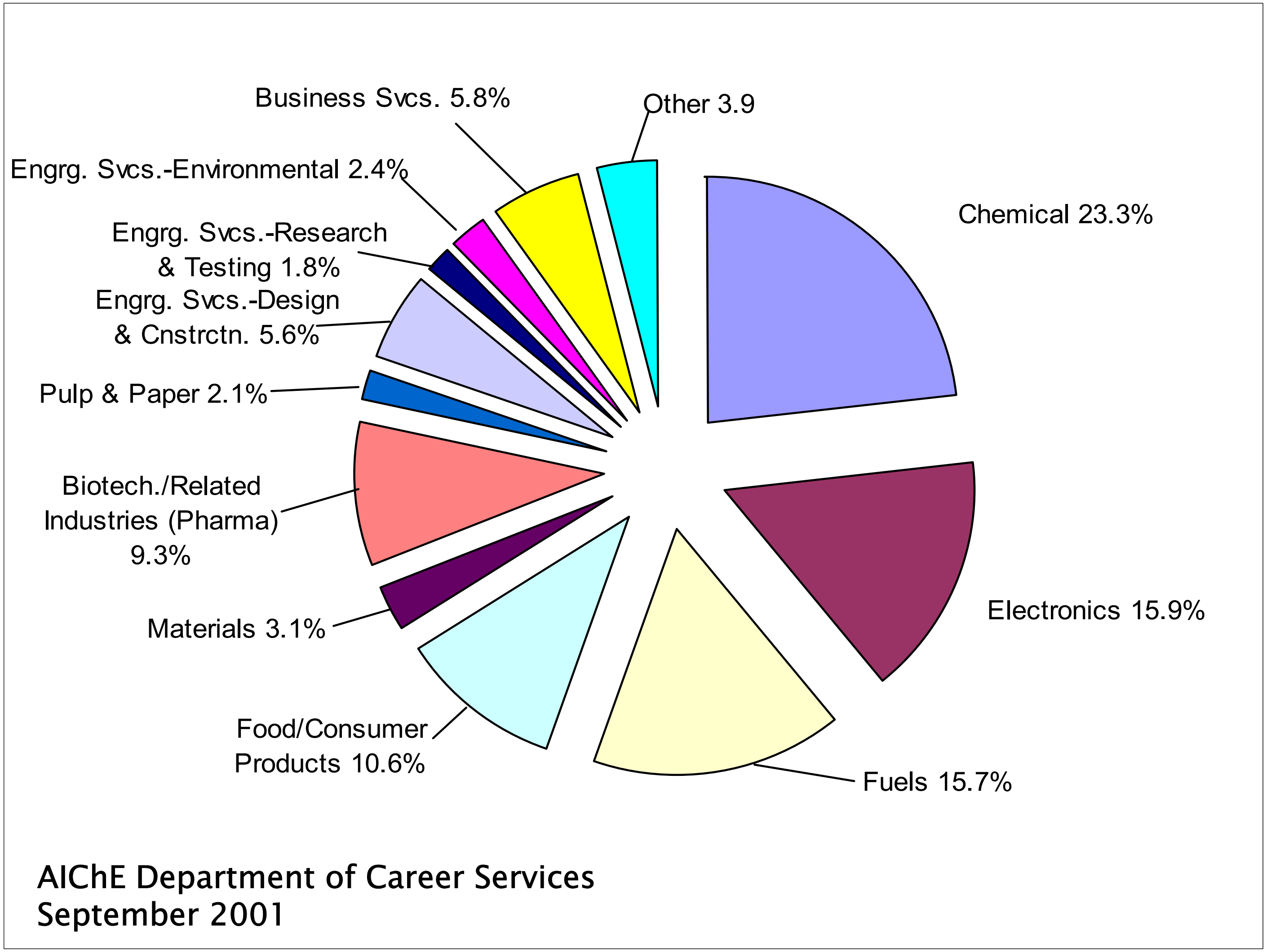
Science and Engineering Degrees: 1966-2000 (NSF 02-327)

Initial Placement for BS 00-01

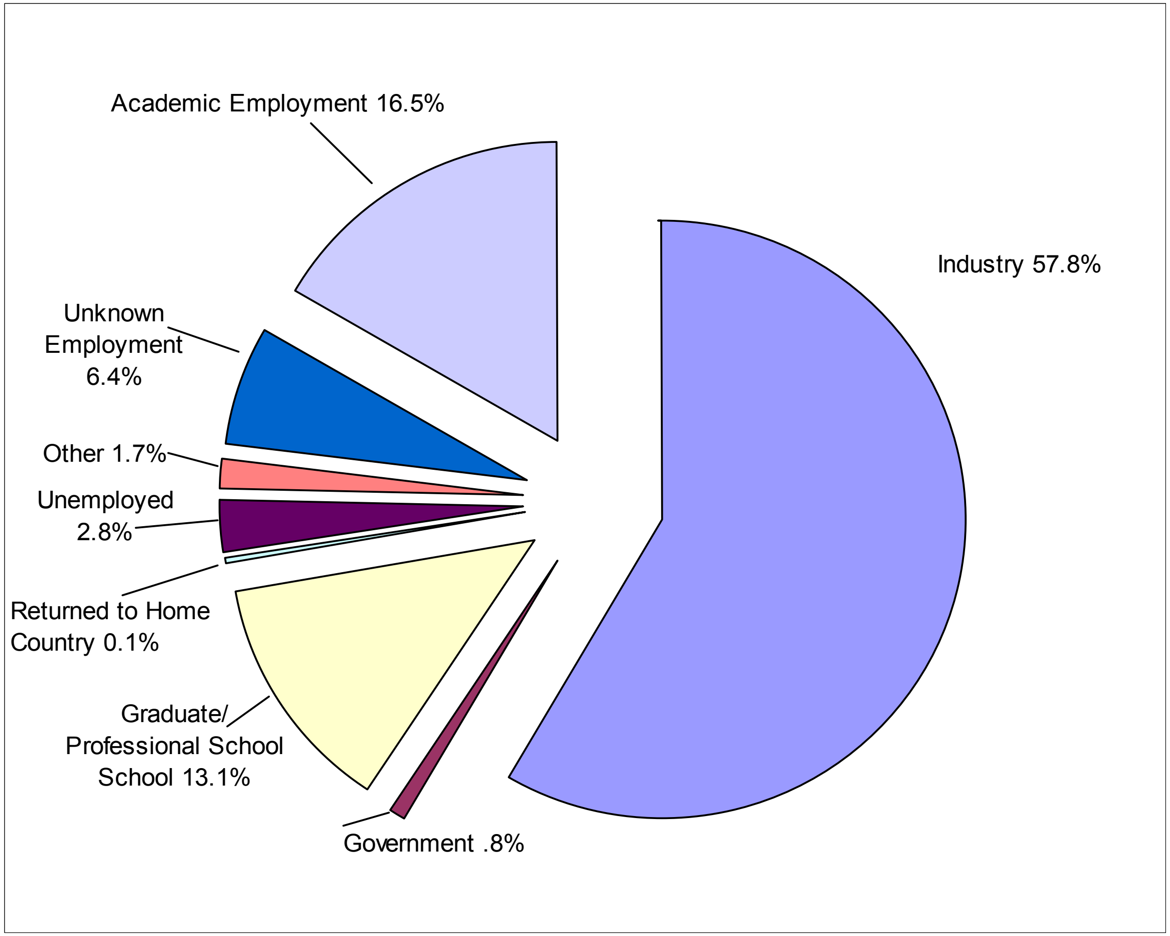


AIChE Department of Career Services
September 2001

Industrial Employment for BS

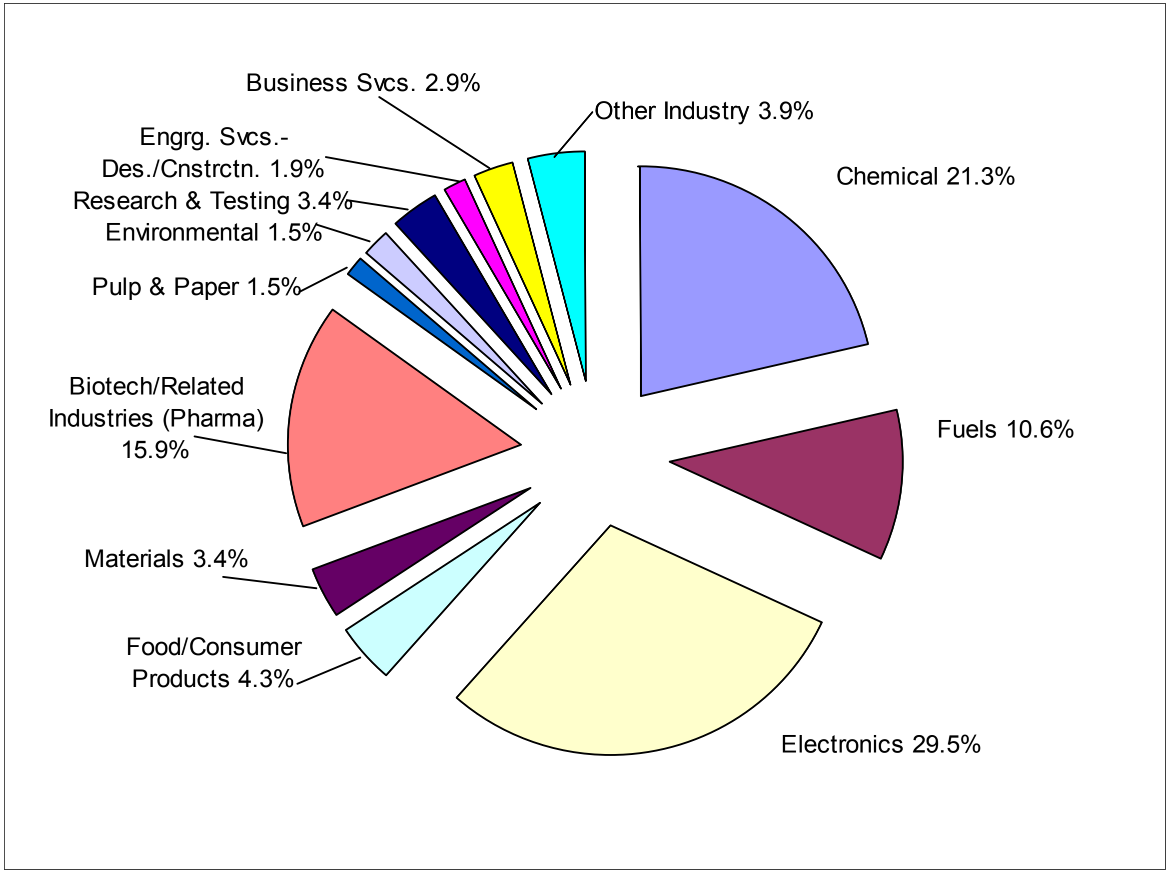


Initial Placement for PhD 00-01



AIChE Department of Career Services
September 2001

Industrial Employment for PhDs



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BS Starting Salaries*

Chemical engineering leads all fields

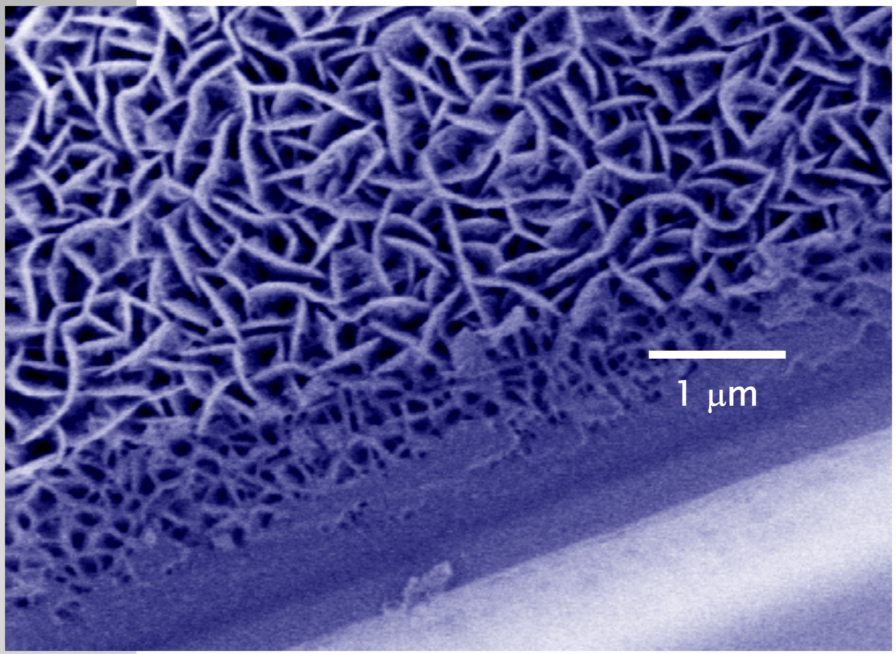
Field	Starting salary	Pct change from 2002
Business administration	$36,515	3.7
General accounting	$41,360	2.6
Marketing	$35,822	1.3
Computer science	$46,536	- 7.6
Information science and systems	$39,800	- 3.9
Civil engineering	$41,067	0.5
Electrical engineering	$50,566	0.4
Chemical engineering	$52,169	1.8
Liberal arts	$29,543	3.1

*Boston Globe, April 25, 2003, p. C1.

Opportunities

- Chemical engineering is a uniquely positioned at the interface between molecular sciences and engineering with many exciting opportunities, including:
  - Life sciences (genetics, pharmaceuticals ….)
  - Energy - fuel cells, catalysis,
  - Sustainable systems
  - Molecular control of processes and devices
  - …
- Other disciplines have opportunities in these areas as well and are beginning to have interest in process, synthesis, analysis issues traditionally addressed within chemical engineering
- *We need to have a clear vision of chemical engineering in order to function effectively in multidisciplinary research*

Hot-Filament Chemical Vapor



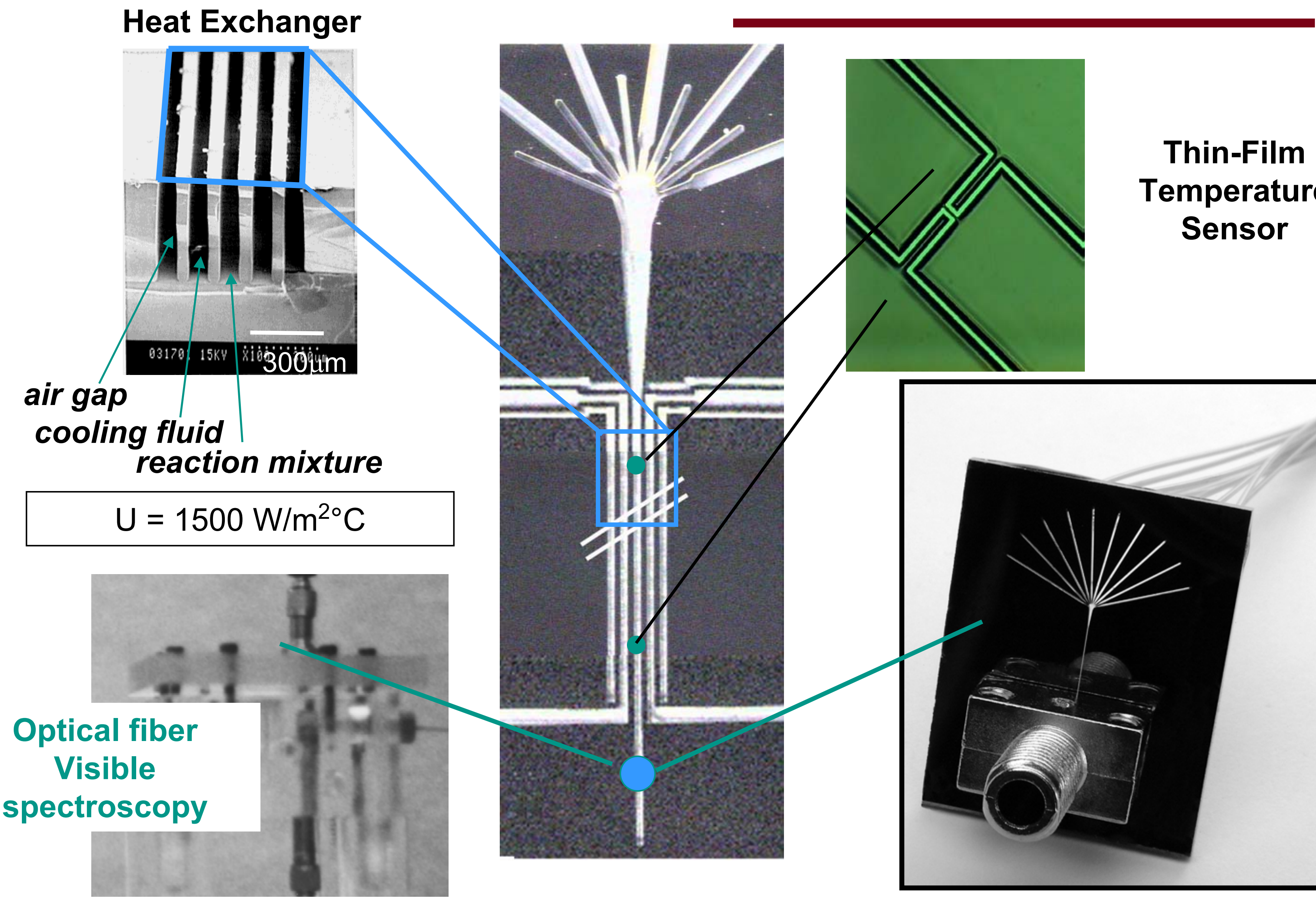
- Thin conformal films of PTFE and other polymers
- Applicable to temperature sensitive substrates
- Creation of mesoscale porosity

ultra-hydrophobic cotton cloth (retains breathability)

US Patent Nos. 5,888,591, 6,045,877, and 6,153,269

Karen K. Gleason

Microreactor for Liquid Phase Chemistry: Integrated Heat Exchangers and Temperature Sensors

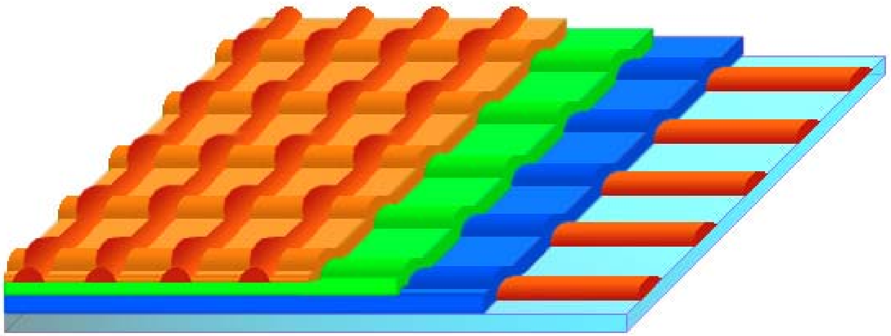


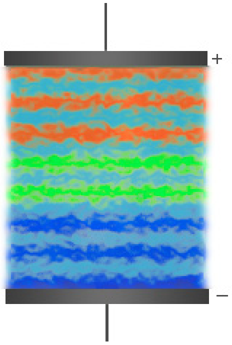
Chemotherapy Drug Delivery Wafers in Brain Cavity

Functionality in Multilayer Systems for Microdevices, Coatings

- LBL is the perfect tool to design
  - Electrochromic systems: electronic ink, plastic displays, smart windows and coatings
  - Ion conducting films: batteries, fuel cells, micropower
  - Photovoltaic films: power storage
  - Direction: move to flexible substrates, textiles, responsive thin films

Result: Patterned Device

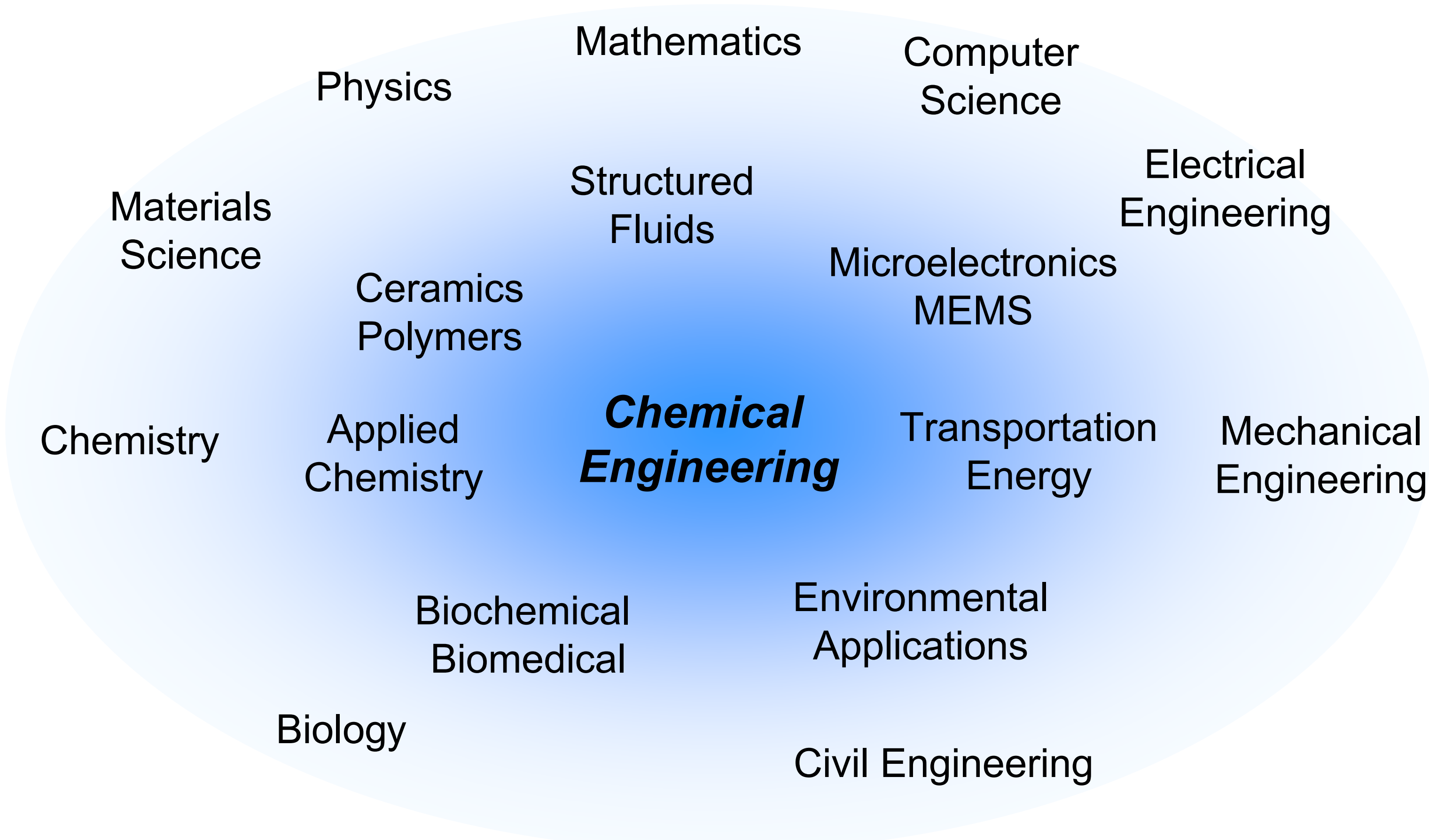




Vision

- Chemical engineering is a vibrant discipline with a central role in many new and emerging technologies - specifically in the translation of molecular information and discovery into products and processes
- We have evolved from a discipline closely tied to a single industry, the petrochemical industry, to one which interacts with many different industries across a broad spectrum of biological and chemical applications
- We must continue to hold a well defined core that defines the discipline and provides the basis for quantification, integration, and relevance in problem solutions
- A close, broad coupling to sciences – physics, chemistry, and biology – is essential to the discipline, enabling the chemical engineer to impact across all scales - systems, processes, products, and molecules - at different levels of focus and providing interdisciplinary perspectives on technology innovation and development

Chemical Engineering at the Center



Chemical engineering has a unique position at the interface between molecular sciences and engineering

Challenges for Our Curriculum

- Need to balance the tension between diversity in research application areas and a coherent, strong core
  - Molecular transformations, multiscale analysis, systems treatment
- Need to balance the desire to teach many specific topics vs. using these to educate students for the future
- Need to balance applications with fundamental knowledge, synthesis with analysis
- Need to integrate biology appropriately as a basic science for our discipline
- Need to attract the best and brightest young minds into our discipline
  - Need to project an accurate, exciting image of our discipline to students/employers
  - Reconnect education with research advances

NSF/CCR Curriculum Workshops

- A series of three planning workshops have led to a vision and model for a dramatic change in undergraduate chemical engineering education
- Why discipline wide?
  - The opportunities/frontiers are too broad for any one or several departments to address effectively
  - The costs – time and money – of developing new educational materials are too high for any of us to absorb alone
  - The coherence resulting for a joint effort will serve the discipline well
    - Maintain clear identify to the world (potential students, industry, government)
    - Ensure good manpower supply to industry and to our graduate programs
    - Ensure that curriculum developments are used

Basic Vision of the New Curriculum

- Changes in science and the marketplace call for extensive changes to the chemical engineering curriculum
- The enabling sciences are: biology, chemistry, physics, math
- There is a core set of organizing chemical engineering principles
  - Molecular transformations, multi-scale analysis, systems
    - Molecular level design is a new core organizing principle
- Chemical engineering contains both product and process design
- There is agreement on the general attributes of a chemical engineer

Ingredients of the New Curriculum

- The curriculum should integrate all organizing principles and basic supportive sciences throughout the educational sequence
- All organizing principles should be operative in the curriculum throughout the sequence and should move from simple to complex
- The curriculum should be consistently infused with relevant and demonstrative laboratory experiences
- Opportunities for teaming experiences and use of communications skills (written and oral) should be included throughout the curriculum

Ingredients of the New Curriculum

- The curriculum should address different learning styles
- The curriculum should be consistently infused with relevant and demonstrative examples
  - open-ended problems and case studies
  - challenges of engineering practice: safety, economics, ethics, regulation, IP, market/social needs
- The curriculum should include a first year chemical engineering experience

Integration of the Curriculum: New Core Organizing Principles

- Molecular Scale Transformations
  - chemical & biological
  - physical: phase change, adsorption, etc
- Multi-Scale Descriptions
  - from sub-molecular through “super-macro”
  - for physical, chemical and biological processes
- Systems Analysis & Synthesis
  - at all scales
  - tools to address dynamics, complexity, uncertainty, external factors

Old core does not integrate molecular concepts

Old core covers only macro to continuum, physical and chemical

Old core primarily tied to large scale chemical processes

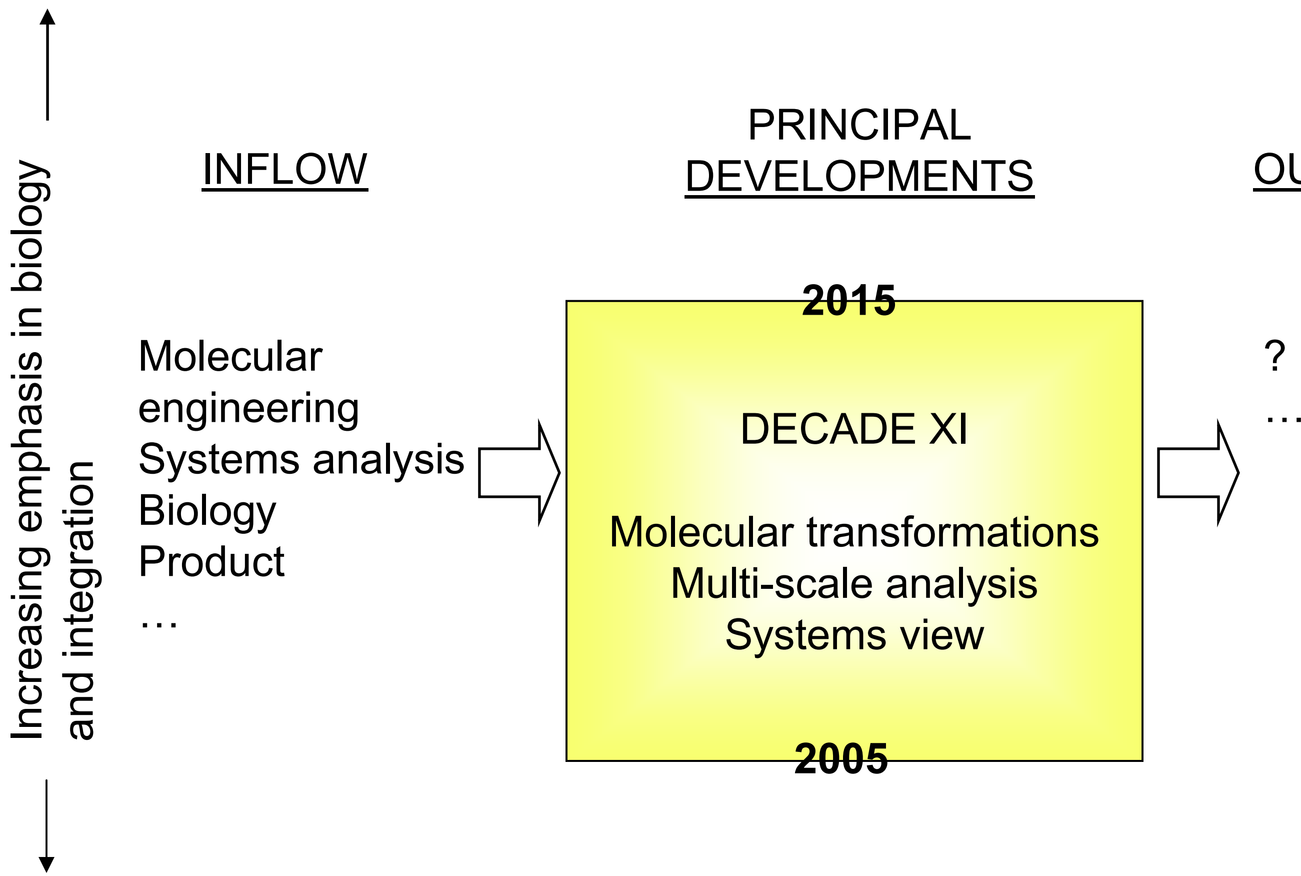
Creation of the New Curriculum: Essential Elements

- Case Studies and Examples
  - Diverse
  - Relevant and topical
  - Integrated into curriculum
    - horizontal integration (over time)
    - vertical integration (between classes at same time)
  - Provide real world context
    - safety, economics, ethics, regulation, IP, market/social needs
  - Provide real world challenge
    - open-ended, complex, incomplete data, rapid generation, and pruning alternatives
  - Reopen the flow of ideas from graduate research to the undergraduate curriculum

The Spectrum of Curriculum Change: from “Tweaks” to “Complete Overhaul”

- The consensus is that we seek large change
  - the science base has dramatically increased
  - this creates new economic opportunity
  - some discipline will emerge to address these new opportunities
  - chemical engineering is well positioned to be this new discipline...
  - …but it will require a large change to the undergraduate curriculum
- This change will likely require a 10 year investment
- We must accommodate a diversity of universities

The Frontier



A “First Draft” Curriculum

Supporting Courses from Other Departments

- Physics
  - Introductory mechanics, E&M, biophysics, solid state
- Chemistry
  - General chemistry + 1 semester organic chemistry
  - Physical chemistry: quantum, spectroscopy, analytical techniques
- Biology
  - Biochemistry, molecular & cellular biology
- English/humanities: communications skills, ethics
- Math: calculus, linear algebra, ODE’s
- Materials science
- Management/ business

The Freshman "Experience"

- Molecular transformations
  - Introduction to molecular structure-property correlations
- Multi-scale analysis
  - Scaling laws
  - Dimensional analysis
  - Impact of micro events on macro phenomena
- Systems
  - Plant-wide and product viewpoints
  - Degrees of freedom analysis
- Laboratories
  - Spheres of different sizes and densities falling through fluid (dimensional analysis)
  - Hydrophobic vs. hydrophilic coating on sphere surface, solutes that affect viscosity
  - Numerically model, optimize, and make a sphere that will drop in specified time

Molecular Transformations

- Molecular transformations: the molecular basis of chemical engineering
  - goals: students recognize that properties can be changed by changing structure via qualitative and quantitative computation
- Molecular basis of thermodynamics (sophomore)
  - introductory quantum & stat mech, ideal gas heat capacities, molecular/stat mech basis of entropy, equilibria, 1st law, 2nd law, equations of state, heat of vaporization, phase transitions
- Classification of molecules (sophomore)
  - qualitative concepts (“hydrophilic”, “hydrophobic”), quantitative structure-property correlations, different types of molecules, macromolecules, high-specificity biological interactions
- Molecular basis of reaction rates (sophomore or junior)
- Molecular basis of other properties & constitutive equations (junior)
  - transport properties, effects of polymer/biomolecular conformations, mixture properties, some elements of molecular biology
- Special topics (junior/senior electives)
  - interfacial phenomena, nucleation/growth, material props, directed evolution

Multi-Scale Analysis

- Multi-scale analysis: Application of chemical engineering principles over many scales of length and time
- Interfaces and assemblies (sophomore)
  - adsorption, extraction, interfaces, Brownian motion, DLVO, nucleation, colloidal interactions, molecular assemblies
- Homogeneous reactor engineering (sophomore)
  - PFR and CSTR
- Multi-scale descriptions of reactive systems (junior)
  - Integrated approach to continuum momentum, heat and mass transfer with reactivity
  - stochastic processes
  - heterogeneous systems and interfacial phenomena
  - separations
  - advanced assemblies
- Beaker-to-plant: implementation of multi-scale principles for product and process design (senior)
  - design of a product and process to make the product: polymer, drug delivery system (includes lab component for making of prototype)
  - tie-in with “Systems and the Marketplace”?

Systems

- Systems: tools for synthesis, analysis and design of processes, units and collections thereof
- Introduction to Systems (Sophomore)
  - conservation laws for simple dynamic and steady state systems, build model for experimental dynamic system, collect and analyze lab data, build numerical simulation, parameter estimation (exposure to complexity and uncertainty), construct equipment/sensor
- Introduction to Molecular Systems (Junior)
  - stochastic systems and molecular level reactions as systems
  - simulation as an enabling technology
  - optimization principles for design, parameter estimation and decision-making
  - examples from microelectronics, catalysis, systems biology, stochastic kinetics
- Systems and the Marketplace (Senior)
  - multi-scale systems: separation and resolution of time and length scales
  - design and analysis of feedback
  - monitoring, fault detection and sensitivity analysis
  - design experience: economics/business skills, safety, marketing, environmental impact, life cycle analysis, ethics, globalization, IP

Laboratory

- Includes VLAB, ILAB and hands-on
- Will teach:
  - teamwork & communication skills
  - ability to handle real (i.e.messy) problems and data
  - open-ended problem solving
  - safety
  - environmental & regulatory issues
  - reinforcement and visualization of concepts from courses
- Can also teach
  - experimental design
  - new concepts
  - basic lab techniques and instrumentation

Integrated Curriculum

Freshman | Soph | Junior | Senior

Enabling Courses
- Physics
- Chemistry
- Biology
- Math
- Mat'ls Sci
- Eng/Comm
- Bus/Mgt

Chem Eng: The Frosh Experience

Molecular-Scale Transformations

Molecular Basis of Thermo
Classfctn of Molecules

Molecular Basis of Reactions
Molecular Basis of Properties and Constitutive Eqns

Special Topics (Electives)

⇕

Multi-Scale Analysis

Interfaces and Assemblies
Homogeneous Reactor Eng

Multi-Scale Descriptions of Reactive Systems

Beaker to Plant: Principles of Product & Process Des.

⇕

Systems

Intro to Systems

Intro to Molecular Systems

Systems & The Marketplace

Final Workshop Thoughts

- The "frontiers in chemical engineering education" workshops have taken the participants on an introspective "journey"
  - We have asked and answered: What is an education in chemical engineering? Why is it important? What value does it add?
- We have been willing to look ahead and develop a new and creative vision for our future students
- We have demonstrated the ability to work together as a broad community on the curriculum
- The consensus for this framework for change is strong
- We should be bold in implementation

Concluding Questions/Issues for Department Heads

- Do you want to take this on? Can you afford not to?
- How do we provide resources to accomplish this?
- How do we reward those who contribute?
  - Professional recognition
- What is the value to departments for being known for creating "textbooks" for the future
  - How do we balance this against focus on research metrics?
- What would be helpful to you for engaging your department, dean, etc...?

Appendix

Sophomore Year

- Molecular Transformations: Molecular Basis of Thermodynamics
  - intro quantum & stat mech, ideal gas heat capacities, molecular/stat mech basis of entropy, equilibria, 1st Law, 2nd Law, equations of state, heat of vaporization, phase transitions
- Molecular Transformations: Classification of Molecules
  - qualitative concepts (“hydrophilic”, “hydrophobic”), quantitative structure-property correlations, different types of molecules, macromolecules, high-specificity biological interactions
- Molecular Transformations: Molecular Basis of Reaction Rates
- Multi-Scale: Interfaces and Assemblies
  - adsorption, extraction, interfaces, Brownian motion, DLVO, nucleation, colloidal interactions, molecular assemblies
- Multi-Scale: Homogeneous Reactor Engineering
  - PFR and CSTR
- Systems: Introduction to Systems
  - conservation laws for simple dynamic and steady state systems, build model for experimental dynamic system, collect and analyze lab data, build numerical simulation, parameter estimation (exposure to complexity and uncertainty), construct equipment/sensor

Junior Year

- Molecular Transformations: Molecular Basis of Reaction Rates
- Molecular Transformations: Molecular Basis of Other Properties & Constitutive Equations
  - transport properties, effects of polymer/biomolecular conformations, mixture properties, some elements of molecular biology
- Multi-scale: Descriptions of reactive systems
  - Integrated approach to continuum momentum, heat and mass transfer with reactivity
  - stochastic processes
  - heterogeneous systems and interfacial phenomena
  - Separations
  - advanced assemblies
- Systems: Introduction to Molecular Systems
  - stochastic systems and molecular level reactions as systems
  - simulation as an enabling technology
  - optimization principles for design, parameter estimation and decision-making
  - examples from microelectronics, catalysis, systems biology, stochastic kinetics

Senior Year

- Molecular Transformations: Special Topics (electives)
  - interfacial phenomena, nucleation/growth, material props, directed evolution
- Multi-Scale: Beaker-to-Plant- Implementation of Multi-scale Principles for Product and Process Design
  - design of a product and process to make the product: polymer, drug delivery system (includes lab component for making of prototype)
  - tie-in with "Systems and the Marketplace"?
- Systems and the Marketplace
  - multi-scale systems: separation and resolution of time and length scales
  - design and analysis of feedback
  - monitoring, fault detection and sensitivity analysis
  - design experience: economics/business skills, safety, marketing, environmental impact, life cycle analysis, ethics, globalization, IP

Multi-Scale Analysis

Dimension/Year	Freshman	Sophomore	Junior	Senior
What's taught	Scaling laws Dimensional Analysis Impact of Micro events on macro-phenomena	Interfaces and Assemblies - Adsorption & Extraction - Interfaces - Brownian Motion - DLVO - Nucleation theory - Colloidal interactions - Molecular Assemblies Homogeneous Reactor Engineering - incl PFR, CSTR	Multi-Scale Descriptions for Reactive Systems - Continuum: integrated approach to continuum momentum, heat and mass phenomena for chemically reactive systems - Micro-Macro/Stochastic - Heterogeneous systems - interfacial transport - Advanced assemblies	Beaker to Plant: Implementation of Multi-scale Principles for Product and Process Design
What's brought in	Simple conservation laws	Molecular interactions Physical Property Estimation	Molecular reactivity	
Types of problems	Wave speed on ocean Pendulum swing Settling velocity of sphere and influence of scale Swimming organisms Impact of scale on epidemics and their impacts on populations (native Americans)	RSA "Migration" - Electrophoresis - Chemotaxis - Blots Liposomes Rou Laux (blood cell aggregate) Atmospheric aerosols Cells Atmosphere Atmospheric totality Microelectronics	Complex flows w/ & w/out reaction Catalytic reactor design - Chemical - enzymatic Cell culture and Fermentation Microelectronics fabrication Staged operations - distillation, chromatography, etc	Design and Delivery of a Drug Polymer Product and Process Design
Lab Expts	Settling of a sphere in a tube - fluids - drag-reducing fluids Sexy expt (TBA: Lab Group)	Micro-reactor Flocculation Nano-particles for Drug Delivery	CFD Enzyme reactor Flow Visualization	Making the Product