Chemical Engineering Research in the US

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Outline

- Overview of Academic ChE Research in the US
- Overview of Research Funding in the US
Outline

- Overview of Academic ChE Research in the US
- Overview of Research Funding in the US
The Paradigms of ChE

- **Unit Operations (1915)**
  - A. D. Little
  - W. H. Walker
  - W. K. Lewis

- **Engineering Science (1950s)**
  - N. Amundson
  - R. Aris
  - J. Prausnitz
  - A. Acrivos
  - R. Sargent

*Transport Phenomena, 1960*
Molecular Engineering

- Incorporation of biotechnology and nanotechnology in the ChE discipline
- Shared with other engineering and science fields, like paradigm 2.
- Growing feasibility to conduct molecular-scale simulations to calculate thermodynamic, transport, and other properties of fluids and materials
- Being applied currently with greater frequency and success for the analysis and design of ChE products and processes.

R. Langer
G. Whitesides
Academia: Shift toward Pure Science

- Significant **growth** in biological engineering and nanotechnology areas
  - In the last 15 years, >50% of young faculty hired in these areas
  - New faculty hires include a significant number of non-ChEs, and a move away from the traditional ChE areas

- Greatly **expands the scope of ChE** and promotes multidisciplinary research

- A significant **shift** toward pure science, away from core ChE areas

- Particularly for younger faculty, goal is to publish in journals such as *Science* and *Nature*, leading to **decreased frequency** of publication in mainstream ChE journals (*AIChE J.*, *Chem Eng Sci*, and *Ind Eng Chem Res*)

- In the long term, this **can adversely affect** future of the ChE discipline.
## Industry-Academia Disconnect

### Ranking by Companies of Relative Importance of Areas

<table>
<thead>
<tr>
<th>Skill</th>
<th>Average relative importance (from 1 to 5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit operations, transport phenomena, thermodynamics, separation processes</td>
<td>4.6</td>
</tr>
<tr>
<td>Reaction engineering, catalysis, kinetics</td>
<td>4.0</td>
</tr>
<tr>
<td>Analysis, modeling, simulation, process control</td>
<td>4.0</td>
</tr>
<tr>
<td>Materials, surface science, polymers</td>
<td>3.2</td>
</tr>
<tr>
<td>Biotechnology, medical and life sciences</td>
<td>2.1</td>
</tr>
<tr>
<td>Nanotechnology and its applications</td>
<td>1.8</td>
</tr>
</tbody>
</table>

### Faculty Increase in Biological Engineering and Unit Operation Areas

<table>
<thead>
<tr>
<th>Rank of Professor</th>
<th>Biological Eng.</th>
<th>Unit Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Professor</td>
<td>22%</td>
<td>-16%</td>
</tr>
<tr>
<td>Associate Professor</td>
<td>26%</td>
<td>-12%</td>
</tr>
<tr>
<td>Assistant Professor</td>
<td>36%</td>
<td>-6%</td>
</tr>
</tbody>
</table>

Session organized by late John Chen, AIChE annual meeting, San Francisco, 2013
Recent Trends in Research

- ChE research in the last decade has been largely dominated by biologically-oriented engineering.
- This trend has been driven largely by research funding, given the increasing importance of biological engineering for addressing advances in healthcare and in the development of biomass-based fuels and chemicals.
- The importance of biotechnology is likely to continue as is research in nanotechnology, given the importance of analyzing physical, chemical, and biological phenomena at the atomic and molecular level, with applications in molecular self-assembly for the development of new materials at the nanoscale to control matter at the atomic scale.
- More recently, energy, sustainability and manufacturing have emerged as significant directions for ChE research.

Outline

- Overview of Academic ChE Research in the US
- Overview of Research Funding in the US
Overview and Funding Level in the U.S.

- **National R&D by Funder, in billion 2017 $**

- **University R&D by Source, in billion 2017 $**

- **Spending by field**
  - Math & computer science: 4.1%
  - Geosciences: 5.1%
  - Chemistry: 2.8%
  - Chemical engineering: 1.4%
  - Materials engineering: 1.4%
  - Other physical sciences: 4.6%
  - Other engineering: 14.5%
  - Life sciences: 60.8%
  - Social sciences: 3.6%
  - Other sciences: 1.7%

**Note:**
- *a* Includes agricultural, biological, medical, and other life sciences.
- *b* Includes astronomy, physics, and other physical sciences.
- *c* Includes psychology.

**Source:**
- NSF, National Science Foundation’s WebCASPAR database, 2015 data
Main Federal Funding Agencies

Main agencies and funding, in billion 2015 $

<table>
<thead>
<tr>
<th>Year</th>
<th>NSF 2015</th>
<th>Engineering 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY13</td>
<td>6,884</td>
<td>814</td>
</tr>
<tr>
<td>FY14</td>
<td>7,172</td>
<td>911</td>
</tr>
<tr>
<td>FY15</td>
<td>7,344</td>
<td>924</td>
</tr>
<tr>
<td>FY16</td>
<td>7,4633</td>
<td>916</td>
</tr>
<tr>
<td>FY17</td>
<td>7,472</td>
<td>1,002</td>
</tr>
</tbody>
</table>

CBET ~ 20% of ENG; ENG ~ 13.4% of NSF

CBET: Chemical, Bioengineering, Environmental, and Transport Systems

Supports discoveries in chemical and biochemical systems; environmental engineering and sustainability; bioengineering and engineering healthcare; and fundamental transport, thermal and fluid phenomena.

In constant $, total Federal R&D unchanged for ~15 years!

U.S. Department of Agriculture (USDA)
U.S. Department of Defense (DOD)
National Aeronautics and Space Administration (NASA)
U.S. Department of Energy (DOE)
National Science Foundation (NSF)
National Institute of Health (NIH)
American Recovery & Reinvestment Act (ARRA) - 2009

Source: 1975-1994 from NSF federal funds survey; remainder from AAAS R&D reports.
National Labs in the U.S.

Established starting in 1930-1940s
Lawrence Berkeley – 1931
Los Alamos – 1943
Oak Ridge – 1943
Argonne - 1946

Typically $0.5-1.5 billion annual budget per lab

Office of Science:
the lead federal agency supporting fundamental scientific research for energy and the Nation’s largest supporter of basic research in the physical sciences

NNSA:
National Nuclear Security Administration

17 Labs from DOE

Office of Science Laboratories
1. Ames Laboratory
   Ames, Iowa

2. Argonne National Laboratory
   Argonne, Illinois

3. Brookhaven National Laboratory
   Upton, New York

4. Fermi National Accelerator Laboratory
   Batavia, Illinois

5. Lawrence Berkeley National Laboratory
   Berkeley, California

6. Oak Ridge National Laboratory
   Oak Ridge, Tennessee

7. Pacific Northwest National Laboratory
   Richland, Washington

8. Princeton Plasma Physics Laboratory
   Princeton, New Jersey

9. SLAC National Accelerator Laboratory
   Menlo Park, California

10. Thomas Jefferson National Accelerator Facility
    Newport News, Virginia

Other DOE Laboratories
1. Idaho National Laboratory
   Idaho Falls, Idaho

2. National Energy Technology Laboratory
   Morgantown, West Virginia

3. Savannah River National Laboratory
   Aiken, South Carolina

4. National Renewable Energy Laboratory
   Golden, Colorado

NNSA Laboratories
1. Lawrence Livermore National Laboratory
   Livermore, California

2. Los Alamos National Laboratory
   Los Alamos, New Mexico

3. Sandia National Laboratory
   Albuquerque, New Mexico

Livermore, California
Role of Centers

- ERCs (Engineering Research Centers), funded by NSF

- ERCs funded by NSF ~ $4 M annually per Center; funding for up to 10 years

- Total ERCs: 74; currently active: 19

- Established in 1985

Note: All centers are multi-university partnerships; university shown is lead institution.
Four new ERCs announced on September 12, 2017

- **Fuels derived from shale gas**
  Center for Innovative and Strategic Transformation of Alkane Resources (CISTAR)
  Purdue (lead); Partners: U. New Mexico, Northwestern U., U. Notre Dame, U. Texas - Austin

- **Therapies based on living cells**
  Center for Cell Manufacturing Technologies (CMaT)
  Georgia Tech (lead); Partners: U. Georgia, U. Wisconsin-Madison, U. Puerto Rico

- **Personalized heart tissue**
  Center for Directed Multiscale Assembly of Cellular Metamaterials (CELL-MET)
  Boston University (lead); Partners: U. Michigan, Florida International U.

- **Health systems for underserved populations**
  Center for Precise Advanced Technologies and Health Systems for Underserved Populations (PATHS-UP)
  Texas A&M (lead); Partners: UCLA, Rice, Florida International U.
Role of Centers

Materials Research Science and Engineering Centers

- University of California at Santa Barbara
  Materials Research Laboratory: An NSF MRSEC

- University of Utah
  Next Generation Materials for Plasmonics and Organic Spintronics

- University of Colorado Boulder
  Soft Materials Research Center

- University of Nebraska
  UNL Materials Research Science and Engineering Center

- University of Minnesota
  UMN Materials Research Science and Engineering Center

- University of Wisconsin-Madison
  Materials Research Science and Engineering Center on Structured Interfaces

- Princeton University
  Princeton Center for Complex Materials

- University of Chicago
  Materials Research Center

- Northwestern University
  Northwestern University Materials Research Science and Engineering Center

- Cornell University
  Cornell Center for Materials Research

- Ohio State University
  Center for Emergent Materials

- Columbia University
  Center for Precision Assembly of Superstratic and Superatomic Solids

- University of Michigan
  Center for Photonic and Multiscale Nanomaterials

- New York University
  NYU Materials Research Science and Engineering Center

- Yale University
  CRISP: Center for Research on Interface Structures and Phenomena

- Brandeis University
  The Bioinspired Soft Materials Center

- Harvard University
  Harvard Materials Research Center

- Massachusetts Institute of Technology
  Center For Materials Science and Engineering

- Pennsylvania State University
  Center for Nanoscale Science

- Duke/NC State/UNC Chapel Hill/NCU
  Research Triangle MRSEC

- University of Pennsylvania
  The Laboratory for Research on the Structure of Matter

Established in 1994

Total MRSECs # 21

Funding: $1.5-3.5 M per year
Role of Centers

- Energy Frontier Research Centers (EFRCs), funded by DOE

Established in 2009

36 EFRCs in 34 States + D.C.

- $2 to 4 Million per year per center
- ~ 595 Senior Investigators
- ~ 1630 students, postdoctoral fellows, and technical staff
- ~ 110 Institutions
Role of Centers

BioEnergy Research Centers (BERCs), funded by DOE

DOE Joint BioEnergy Institute
Lawrence Berkeley National Laboratory
Berkeley, California
- Carnegie Institution for Science at Stanford University
  Palo Alto, California
- Lawrence Livermore National Laboratory
  Livermore, California
- Sandia National Laboratories
  Albuquerque, New Mexico
- Sandia National Laboratories
  Livermore, California
- University of California
  Berkeley
- University of California
  Davis

DOE Great Lakes Bioenergy Research Center
University of Wisconsin
Madison
- Cornell University
  Ithaca, New York
- Illinois State University
  Normal
- Iowa State University
  Ames
- Lucigen Corporation
  Middleton, Wisconsin
- Michigan State University
  East Lansing
- Oak Ridge National Laboratory
  Oak Ridge, Tennessee
- Pacific Northwest National Laboratory
  Richland, Washington
- University of Minnesota
  St. Paul
- University of Missouri
  Columbia
- University of Toledo
  Toledo, Ohio

DOE BioEnergy Science Center
Oak Ridge National Laboratory
Oak Ridge, Tennessee
- ArborGen
  Summerville, South Carolina
- Brookhaven National Laboratory
  Upton, New York
- Ceres
  Thousand Oaks, California
- Cornell University
  Ithaca, New York
- Dartmouth College
  Hanover, New Hampshire
- Georgia Institute of Technology
  Atlanta
- Mascoma Corporation
  Boston, Massachusetts
- National Renewable Energy Laboratory
  Golden, Colorado
- North Carolina State University
  Raleigh
- The Samuel Roberts Noble Foundation
  Ardmore, Oklahoma
- University of California
  Los Angeles
- University of California
  Riverside
- University of Georgia
  Athens
- University of Minnesota
  St. Paul
- University of Tennessee
  Knoxville
- Verenium Corporation
  Cambridge, Massachusetts
- Virginia Polytechnic Institute and State University
  Blacksburg
- Washington State University
  Pullman
- West Virginia University
  Morgantown

Established in 2007
Three Centers until 2016
FY13 - FY17, $25 M per Center
Since FY18, $10 M per Center

New: Center for Advanced Bioenergy and Bioproducts Innovation (established in 2017) - University of Illinois at Urbana-Champaign
### Chemical Industry R&D investments, $M – 18 major companies

<table>
<thead>
<tr>
<th>Company</th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>% of Sales 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>3M</td>
<td>1,570</td>
<td>1,634</td>
<td>1,715</td>
<td>1,770</td>
<td>1,763</td>
<td>5.8</td>
</tr>
<tr>
<td>Air Products</td>
<td>119</td>
<td>126</td>
<td>134</td>
<td>141</td>
<td>139</td>
<td>1.4</td>
</tr>
<tr>
<td>Albemarle</td>
<td>77</td>
<td>79</td>
<td>82</td>
<td>88</td>
<td>103</td>
<td>2.8</td>
</tr>
<tr>
<td>Arkema</td>
<td>147</td>
<td>164</td>
<td>166</td>
<td>172</td>
<td>232</td>
<td>2.7</td>
</tr>
<tr>
<td>Ashland</td>
<td>89</td>
<td>137</td>
<td>178</td>
<td>114</td>
<td>110</td>
<td>2.0</td>
</tr>
<tr>
<td>BASF</td>
<td>1,781</td>
<td>1,937</td>
<td>2,036</td>
<td>2,090</td>
<td>2,167</td>
<td>2.8</td>
</tr>
<tr>
<td>Cabot</td>
<td>66</td>
<td>73</td>
<td>74</td>
<td>60</td>
<td>58</td>
<td>2.0</td>
</tr>
<tr>
<td>Celanese</td>
<td>96</td>
<td>102</td>
<td>85</td>
<td>86</td>
<td>119</td>
<td>2.1</td>
</tr>
<tr>
<td>Clariant</td>
<td>183</td>
<td>182</td>
<td>188</td>
<td>221</td>
<td>212</td>
<td>3.5</td>
</tr>
<tr>
<td>Dow Chemical</td>
<td>1,646</td>
<td>1,708</td>
<td>1,747</td>
<td>1,647</td>
<td>1,598</td>
<td>3.3</td>
</tr>
<tr>
<td>DuPont</td>
<td>1,956</td>
<td>2,067</td>
<td>2,153</td>
<td>2,067</td>
<td>1,898</td>
<td>7.6</td>
</tr>
<tr>
<td>Eastman</td>
<td>158</td>
<td>198</td>
<td>193</td>
<td>227</td>
<td>251</td>
<td>2.6</td>
</tr>
<tr>
<td>Evonik Industries</td>
<td>405</td>
<td>436</td>
<td>437</td>
<td>458</td>
<td>482</td>
<td>3.2</td>
</tr>
<tr>
<td>FMC</td>
<td>105</td>
<td>118</td>
<td>118</td>
<td>129</td>
<td>144</td>
<td>4.4</td>
</tr>
<tr>
<td>W.R. Grace</td>
<td>69</td>
<td>65</td>
<td>65</td>
<td>80</td>
<td>70</td>
<td>2.3</td>
</tr>
<tr>
<td>Huntsman Corp.</td>
<td>166</td>
<td>152</td>
<td>140</td>
<td>158</td>
<td>160</td>
<td>1.6</td>
</tr>
<tr>
<td>Praxair</td>
<td>90</td>
<td>98</td>
<td>98</td>
<td>96</td>
<td>93</td>
<td>0.9</td>
</tr>
<tr>
<td>Solvay</td>
<td>173</td>
<td>290</td>
<td>333</td>
<td>274</td>
<td>307</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Total and Average</strong></td>
<td><strong>8,896</strong></td>
<td><strong>9,566</strong></td>
<td><strong>9,942</strong></td>
<td><strong>9,878</strong></td>
<td><strong>9,906</strong></td>
<td><strong>3.4</strong></td>
</tr>
</tbody>
</table>

Total 2015 R&D ~$9.9 billion

*Chemical & Engineering News, 94 (16), 18-20 (2016)*
### Univ R&D Expenditures - ChE, $M

<table>
<thead>
<tr>
<th>Institution</th>
<th>2015</th>
<th>2014</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>U of Texas, Austin</td>
<td>51.9</td>
<td>48.9</td>
<td>14.0</td>
</tr>
<tr>
<td>Texas A&amp;M U</td>
<td>38.1</td>
<td>21.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Massachusetts Inst. of Technology</td>
<td>33.2</td>
<td>32.8</td>
<td>13.7</td>
</tr>
<tr>
<td>Georgia Tech</td>
<td>32.7</td>
<td>31.1</td>
<td>13.8</td>
</tr>
<tr>
<td>California Inst. of Technology</td>
<td>27.7</td>
<td>14.3</td>
<td>5.9</td>
</tr>
<tr>
<td>North Carolina State U</td>
<td>24.7</td>
<td>29.5</td>
<td>15.2</td>
</tr>
<tr>
<td>U at Buffalo</td>
<td>23.8</td>
<td>24.4</td>
<td>2.0</td>
</tr>
<tr>
<td>U of Minnesota</td>
<td>20.8</td>
<td>16.6</td>
<td>8.7</td>
</tr>
<tr>
<td>U of Colorado</td>
<td>17.6</td>
<td>14.6</td>
<td>6.3</td>
</tr>
<tr>
<td>U of Delaware</td>
<td>15.0</td>
<td>17.8</td>
<td>7.2</td>
</tr>
<tr>
<td>U of Tulsa</td>
<td>14.3</td>
<td>17.1</td>
<td>3.8</td>
</tr>
<tr>
<td>U of Michigan</td>
<td>13.4</td>
<td>13.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Pennsylvania State U</td>
<td>12.9</td>
<td>12.4</td>
<td>17.4</td>
</tr>
<tr>
<td>Purdue U</td>
<td>12.2</td>
<td>14.6</td>
<td>5.5</td>
</tr>
<tr>
<td>U of Oklahoma</td>
<td>11.8</td>
<td>10.4</td>
<td>4.4</td>
</tr>
<tr>
<td>Johns Hopkins U</td>
<td>11.7</td>
<td>10.8</td>
<td>9.7</td>
</tr>
<tr>
<td>Iowa State U</td>
<td>11.6</td>
<td>11.3</td>
<td>3.6</td>
</tr>
<tr>
<td>U of California, Santa Barbara</td>
<td>11.5</td>
<td>9.8</td>
<td>7.2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>384.9</strong></td>
<td><strong>351.2</strong></td>
<td><strong>159.4</strong></td>
</tr>
</tbody>
</table>

**Note:** Total 2015 academic ChE R&D ~$895 million

**Top 18 academic ChE programs by R&D $**
Conclusions

- **Significant growth in biological engineering and nanotechnology areas**
  - In the last 15 years, >50% of young faculty hired in these areas, including a significant number of non-ChEs
  - Greatly expands the scope of ChE and promotes multidisciplinary research
  - More recently, energy, sustainability and manufacturing have emerged as significant directions for ChE research

- In academia, a significant **shift** toward pure science, away from core ChE areas

- **A disconnect** in faculty hiring vs industry needs

- **Federal government is the largest source for academic R&D**
  - NIH, DoE, DoD, NSF, NASA, …

- In constant $, total federal R&D funds essentially **constant for ~15 years**

- Important role of **Centers** – ERCs, MRSECs, EFRCs, BERCs

- Important role of **DoE labs**

- Major chemical companies invest ~3.4% of sales on R&D