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Chemical Engineering Research in the US

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Barcelona, Spain
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Outline

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

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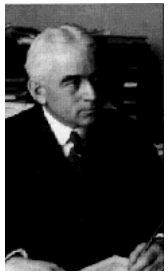
The Paradigms of ChE

- **Unit Operations (1915)**

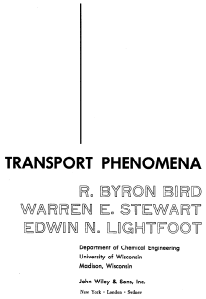
A. D. Little



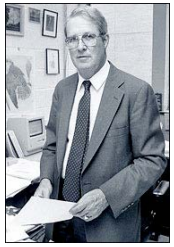
W. H. Walker

W. K. Lewis

- **Engineering Science (1950s)**



N. Amundson



R. Aris

J. Prausnitz

A. Acrivos

R. Sargent

Transport Phenomena, 1960

Molecular Engineering - The Current Paradigm

❑ 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

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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.

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Industry-Academia Disconnect

❑ Ranking by Companies of Relative Importance of Areas

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

❑ Faculty Increase in Biological Engineering and Unit Operation Areas

Rank of Professor	Biological Eng.	Unit Operations
Professor	22%	-16%
Associate Professor	26%	-12%
Assistant Professor	36%	-6%

Session organized by late John Chen, AIChE annual meeting, San Francisco, 2013

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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.

A. Varma & I. E. Grossmann, Perspective Article, *AIChE Journal,* 60, 3692 (2014)

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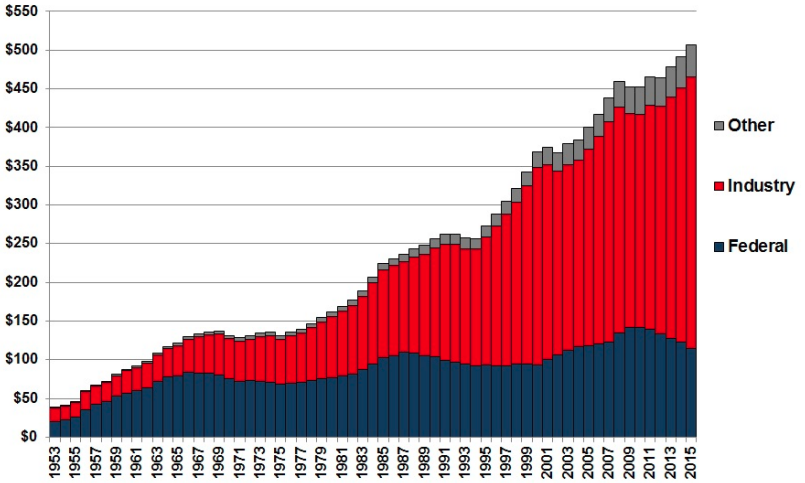
- **Overview of Research Funding in the US**

Overview and Funding Level in the U.S.

❑ National R&D by Funder, in billion 2017 $



Source: NSF, *National Patterns of R&D Resource series*, http://www.nsf.gov/statistics/natlpatterns/

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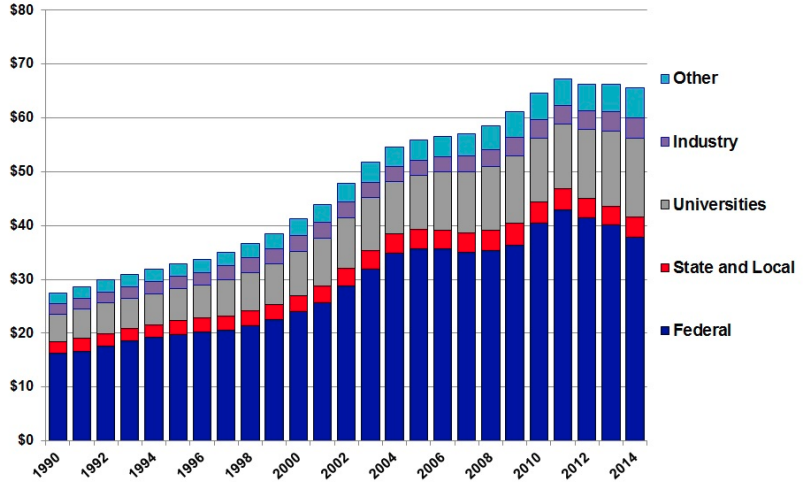
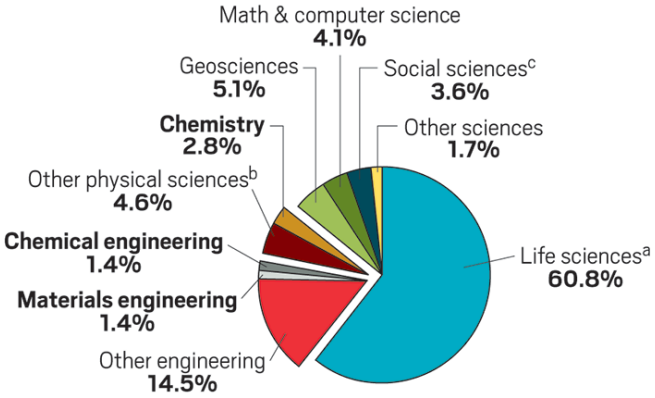
❑ University R&D by Source, in billion 2017 $



Source: NSF, National Center for Science and Engineering Statistics, *Higher Education R&D series*. Includes ARRA funding,

❑ Spending by field



Academic R&D spending, FY 2015 = $63.9 billion

❑ Total ChE academic R&D ~$895 million

Note: **a** Includes agricultural, biological, medical, and other life sciences.

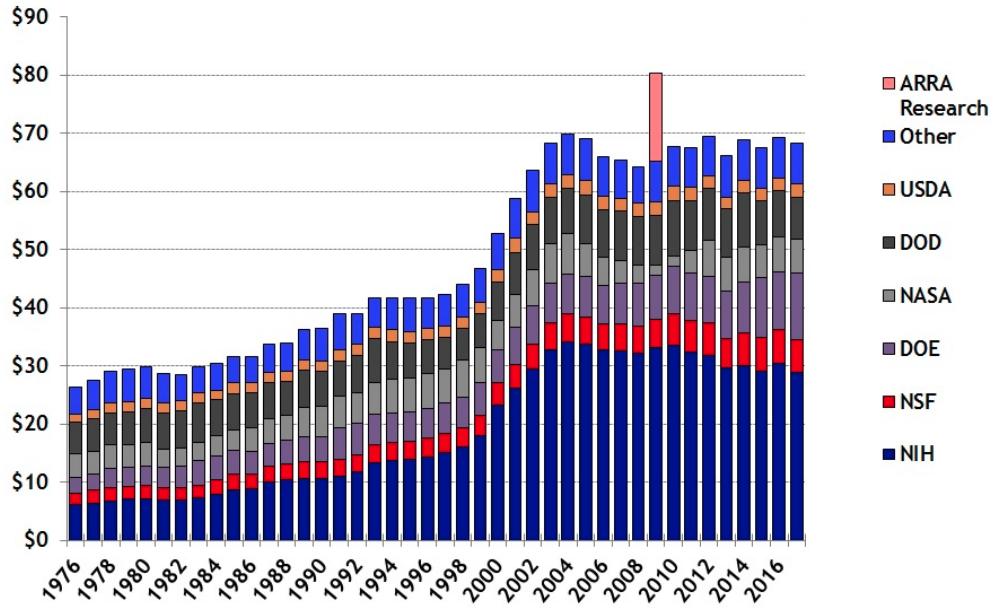
b Includes astronomy, physics, and other physical sciences.

c Includes psychology.

Source: National Science Foundation's WebCASPAR database, 2015 data

Main Federal Funding Agencies

- **Main agencies and funding, in billion 2015 $**



Source: 1975-1994 from NSF federal funds survey; remainder from AAAS R&D reports.

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

- **National Science Foundation (NSF), in million $**

	FY13	FY14	FY15	FY16	FY17
NSF	6,884	7,172	7,344	7,4633	7,472
Engineering	814	911	924	916	1,002
CBET	167	172	180	184	198

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.

National Labs in the U.S.

17 Labs from DOE

Office of Science Laboratories

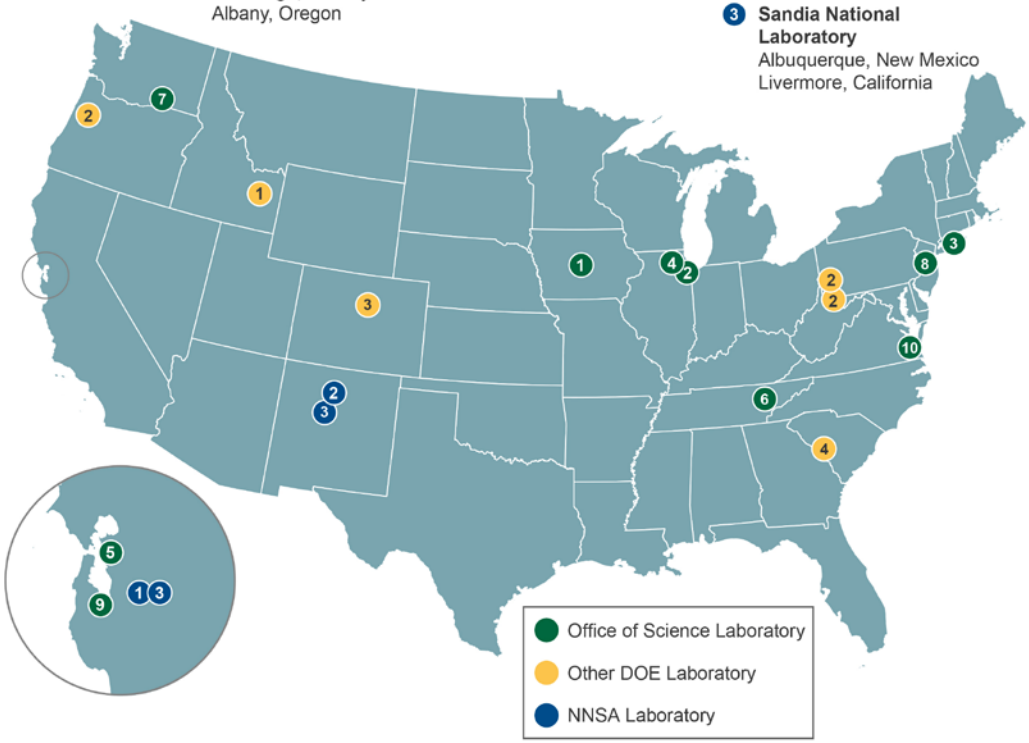
1. **Ames Laboratory**
   Ames, Iowa
2. **Argonne National Laboratory**
   Argonne, Illinois
3. **Brookhaven National Laboratory**
   Upton, New York
4. **Fermi National Accelerator Laboratory**
   Batavia, Illinois
5. **Lawrence Berkeley National Laboratory**
   Berkeley, California
6. **Oak Ridge National 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
   Pittsburgh, Pennsylvania
   Albany, Oregon
3. **National Renewable Energy Laboratory**
   Golden, Colorado
4. **Savannah River National Laboratory**
   Aiken, South Carolina

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



Established starting in 1930-1940s

- Lawrence Berkeley – 1931
- Los Alamos – 1943
- Oak Ridge – 1943
- Argonne - 1946

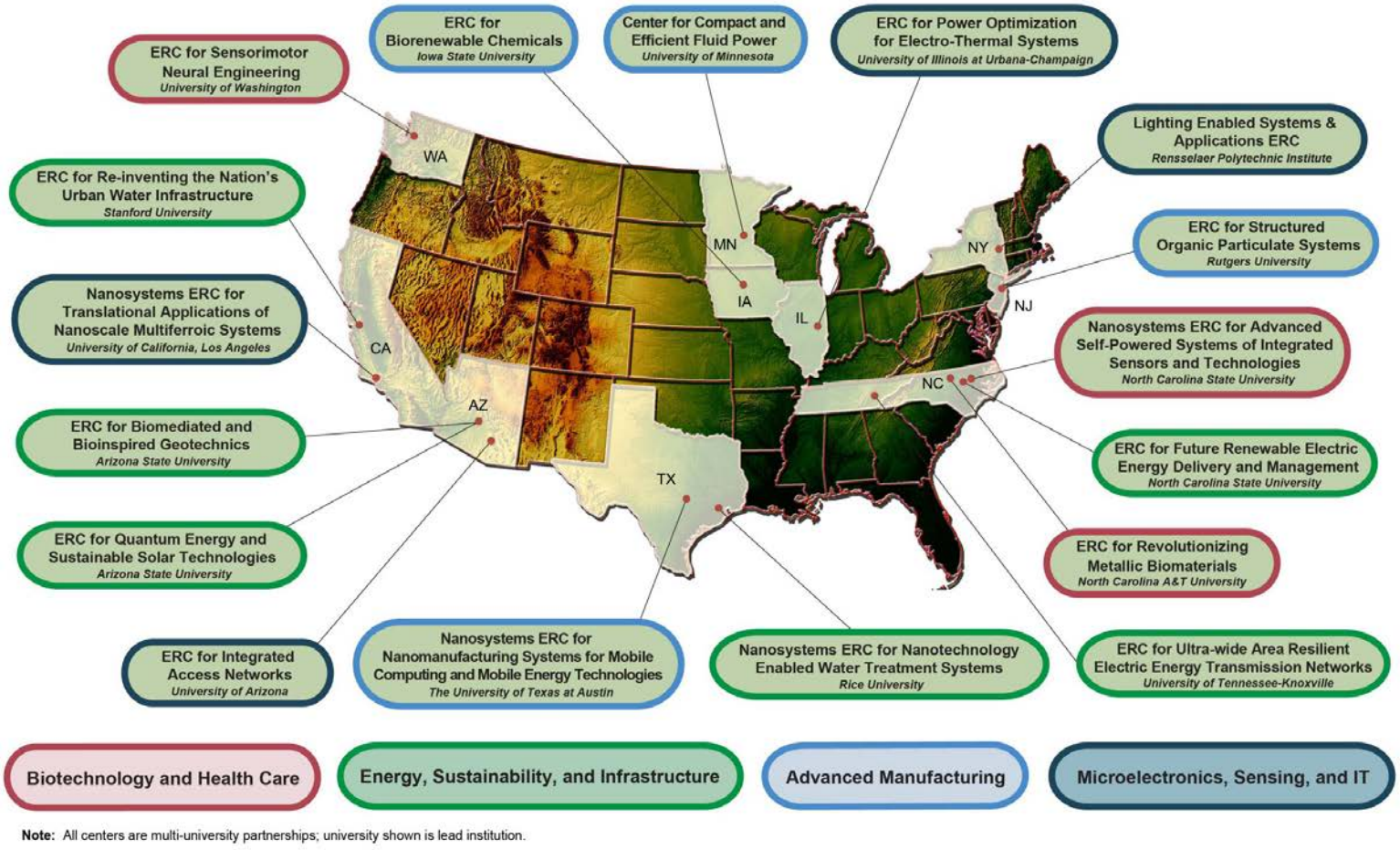
Typically $ 0.5-1.5 billion annual budget per lab

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

Role of Centers

- **ERCs (Engineering Research Centers), funded by NSF**



Note: All centers are multi-university partnerships; university shown is lead institution.

Established in 1985

Total ERCs # 74; currently active #: 19

~ $ 4 M annually per Center; funding for up to 10 years

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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.

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Role of Centers

NATIONAL SCIENCE FOUNDATION MRSEC MATERIALS RESEARCH SCIENCE & ENGINEERING 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

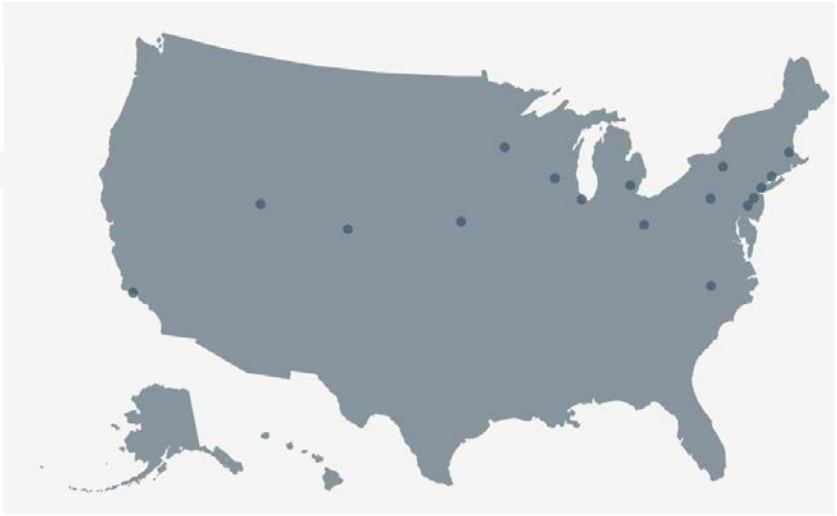
University of Michigan
Center for Photonic and Multiscale Nanomaterials

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

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/NCCU
Research Triangle MRSEC

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

Established in 1994

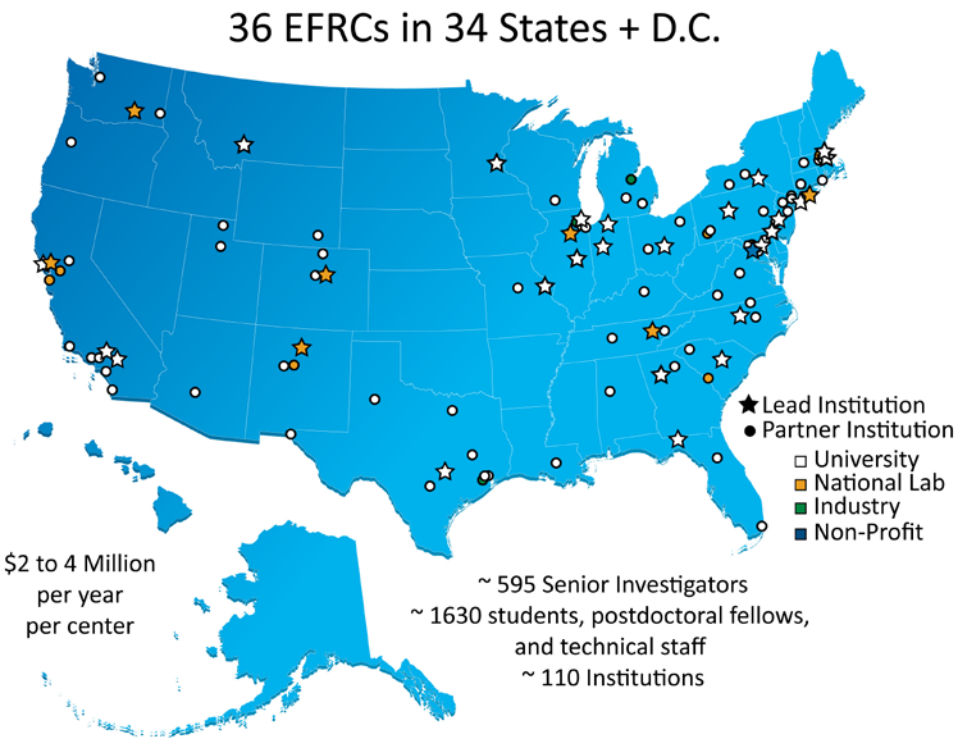
Total MRSECs # 21

Funding: $1.5-3.5 M per year

Role of Centers

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

Light-Material Interactions in Energy Conversion (LMI)
Center for Nanoscale Controls on Geologic CO2 (NCGC)
Center for Gas Separations Relevant to Clean Energy Technologies (CGS)
Spins and Heat in Nanoscale Electronic Systems (SHINES)
Center for Next Generation of Materials by Design: Incorporating Metastability (CNGMD)
Catalysis Center for Energy InnInnovation (CCEI)
Energy Frontier Research in Extreme Environments (EFree)
Center for Actinide Science & Technology (CAST)
Center for Understanding and Control of Acid Gas-induced Evolution of Materials for Energy (UNCAGE-ME)
Center for Electrochemical Energy Science (CEES)
Center for Bio-Inspired Energy Science ((CBES) Northwestern University
Argonne-Northwestern Solar Energy Research Center (ANSER)
Center for Geologic Storage of CO2 (GSCO2)
Center for Direct Catalytic Conversion of Biomass to Biofuels (C3Bio)
Materials Science of Actinides (MSA)
Nanostructures for Electrical Energy Storage (NEES)
Integrated Mesoscale Architectures for Sustainable Catalysis (IMASC)
Center for Excitonics (CE)
Solid-State Solar-Thermal Energy Conversion Center (S3TEC)
Inorganometallic Catalyst Design Center (ICDC)
Photosynthetic Antenna Research Center (PARC)
Center for Biological Electron Transfer and Catalysis (BETCy)
Center for Advanced Solar Photophysics (CASP)
NorthEast Center for Chemical Energy Storage (NECCES)
Center for Emergent Superconductivity (CES)
Center for Mesoscale Transport Properties (m2m)
Center for Solar Fuels (UNC)
Center for Performance and Design of Nuclear Waste Forms and Containers (WastePD)
Center for Lignocellulose Structure and Formation (CLSF)
Center for the Computational Design of Functional Layered Materials (CCDM)
Center for Hierarchical Waste Form Materials (CHWM)
Fluid Interface Reactions, Structures and Transport Center (FIRST)
Energy Dissipation to Defect Evolution (EDDE)
Center for Frontiers of Subsurface Energy Security (CFSES)
Center for Molecular Electrocatalysis (CME)
Interfacial Dynamics in Radioactive Environments and Materials (IDREAM)



Established in 2009

Role of Centers

❑ BioEnergy Research Centers (BERCs), funded by DOE

DOE Bioenergy Research Centers

Established in 2007

Three Centers until 2016

FY13 - FY17, $25 M per Center

Since FY18, $10 M per Center

DOE Joint BioEnergy Institute
Lawrence Berkeley National Laboratory
Berkeley, California

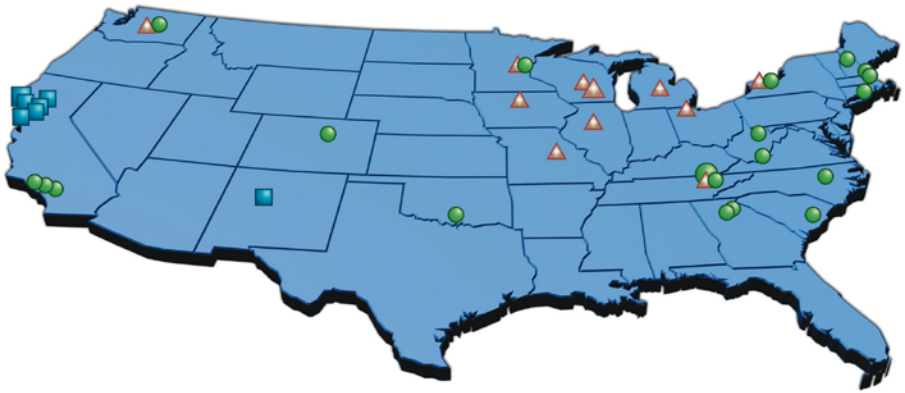
- Carnegie Institution for Science at Stanford University, Palo Alto, California
- Lawrence Livermore National Laboratory, Livermore, California
- Sandia National Laboratories, Albuquerque, New Mexico
- Sandia National Laboratories, Livermore, California
- University of California, Berkeley
- University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



New: **Center for Advanced Bioenergy and Bioproducts Innovation**
(established in 2017) - University of Illinois at Urbana-Champaign

Chemical Industry – R&D

Chemical Industry R&D investments, $M – 18 major companies

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

Total 2015 R&D ~$9.9 billion

***Chemical & Engineering News*, 94 (16), 18-20 (2016)**

Univ R&D Expenditures - ChE, $M

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

Top 18 academic ChE programs by R&D $

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

***Chemical & Engineering News*, 95, 22-23 (2017)**

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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