Engineering for the 21st Century – A Perspective from the National Science Foundation

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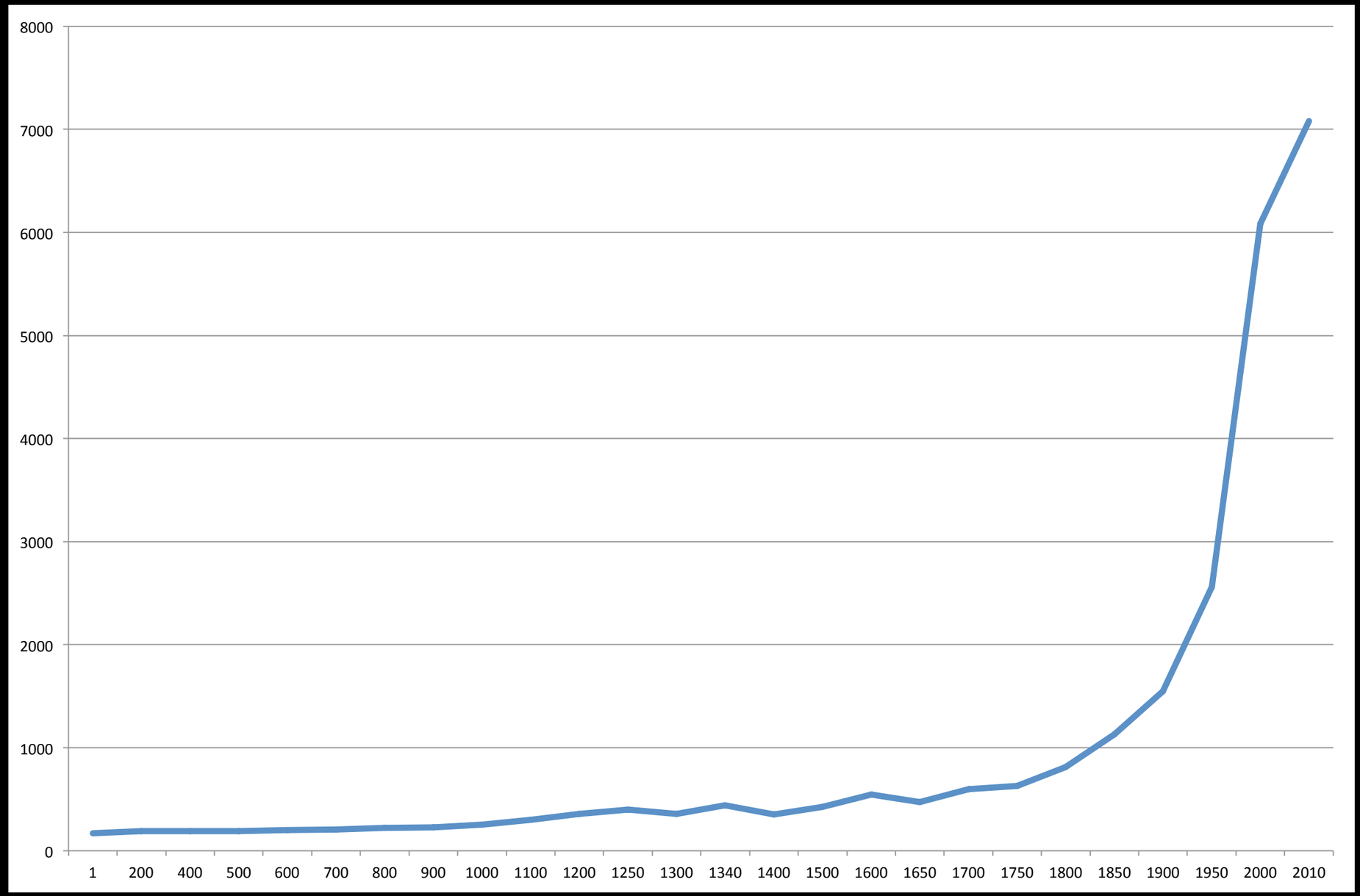
Assistant Director for Engineering
National Science Foundation

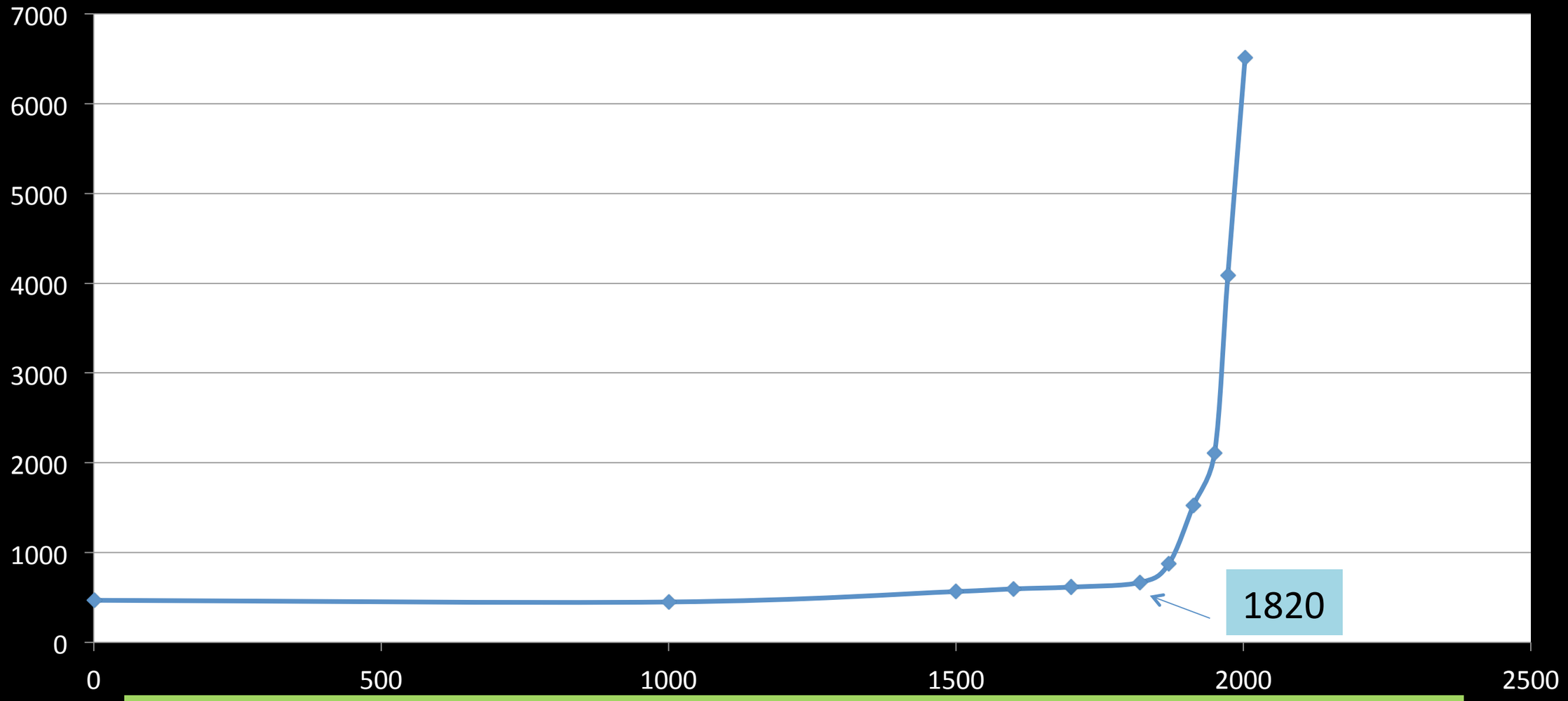
William R. and Erlyn J. Gould Distinguished Lecture
University of Utah
November 10, 2015

World Population (millions)



Source: US Census Bureau

World GDP per capita (1 – 2003)



Source: A. Maddison, World Economy, 2007

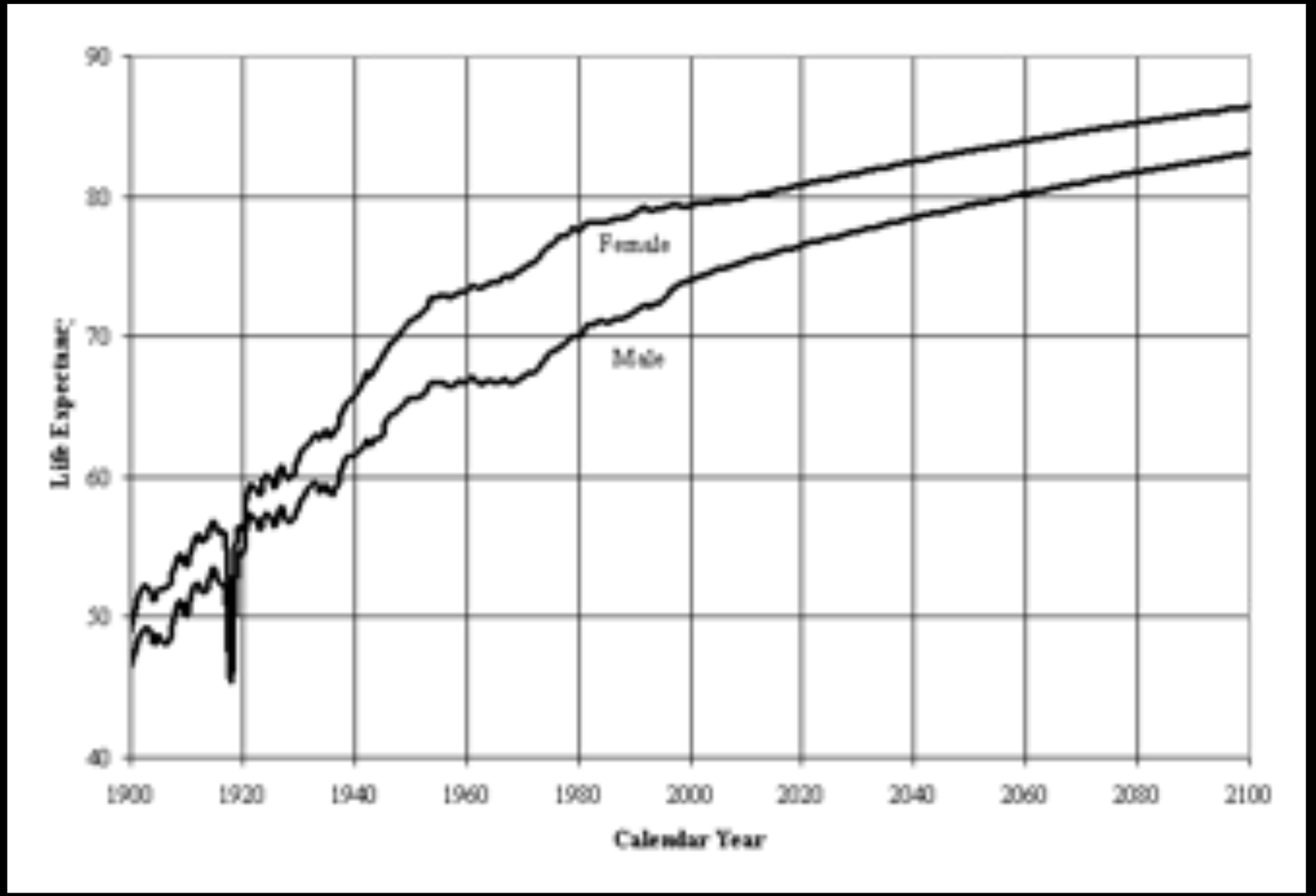
"Hockey-stick" growth starting with the industrial revolution

Top Engineering Achievements of the 20th Century

1. Electrification
2. Automobile
3. Airplane
4. Water Supply and Distribution
5. Electronics
6. Radio and Television
7. Agricultural Mechanization
8. Computers
9. Telephone
10. Air Conditioning and Refrigeration
11. Highways
12. Spacecraft
13. Internet
14. Imaging
15. Household Appliances
16. Health Technologies
17. Petroleum and Petrochemical Technologies
18. Laser and Fiber Optics
19. Nuclear Technologies
20. High-performance Materials

Source: National Academy of Engineering

Life Expectancy has Gone Up!



Source: SSA

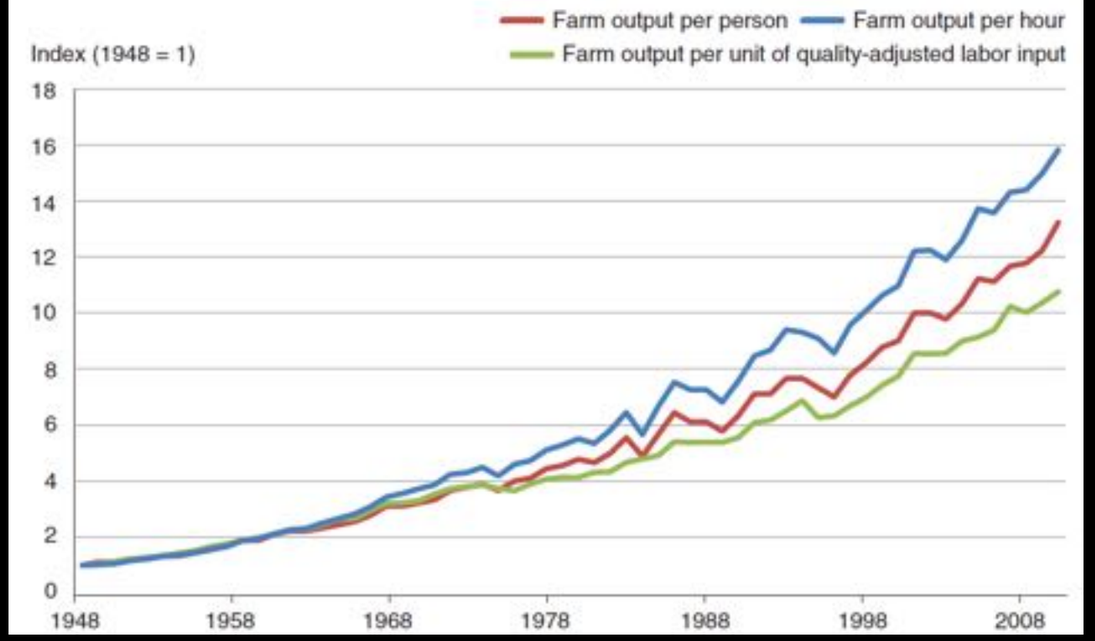
Earth at Night

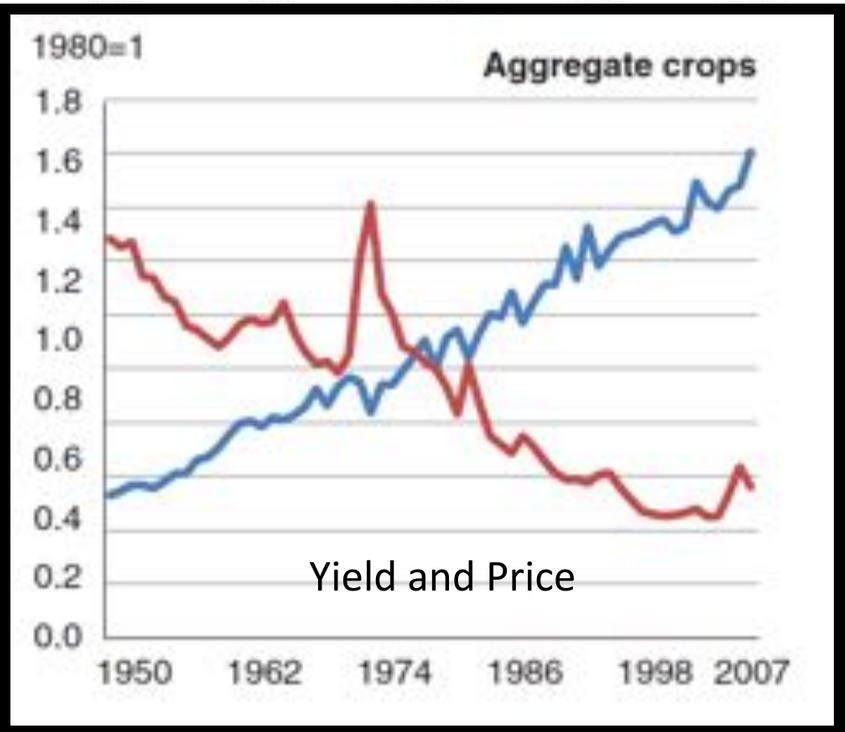
Imagine a world without electricity

Source: NASA/NOAA

Figure 18

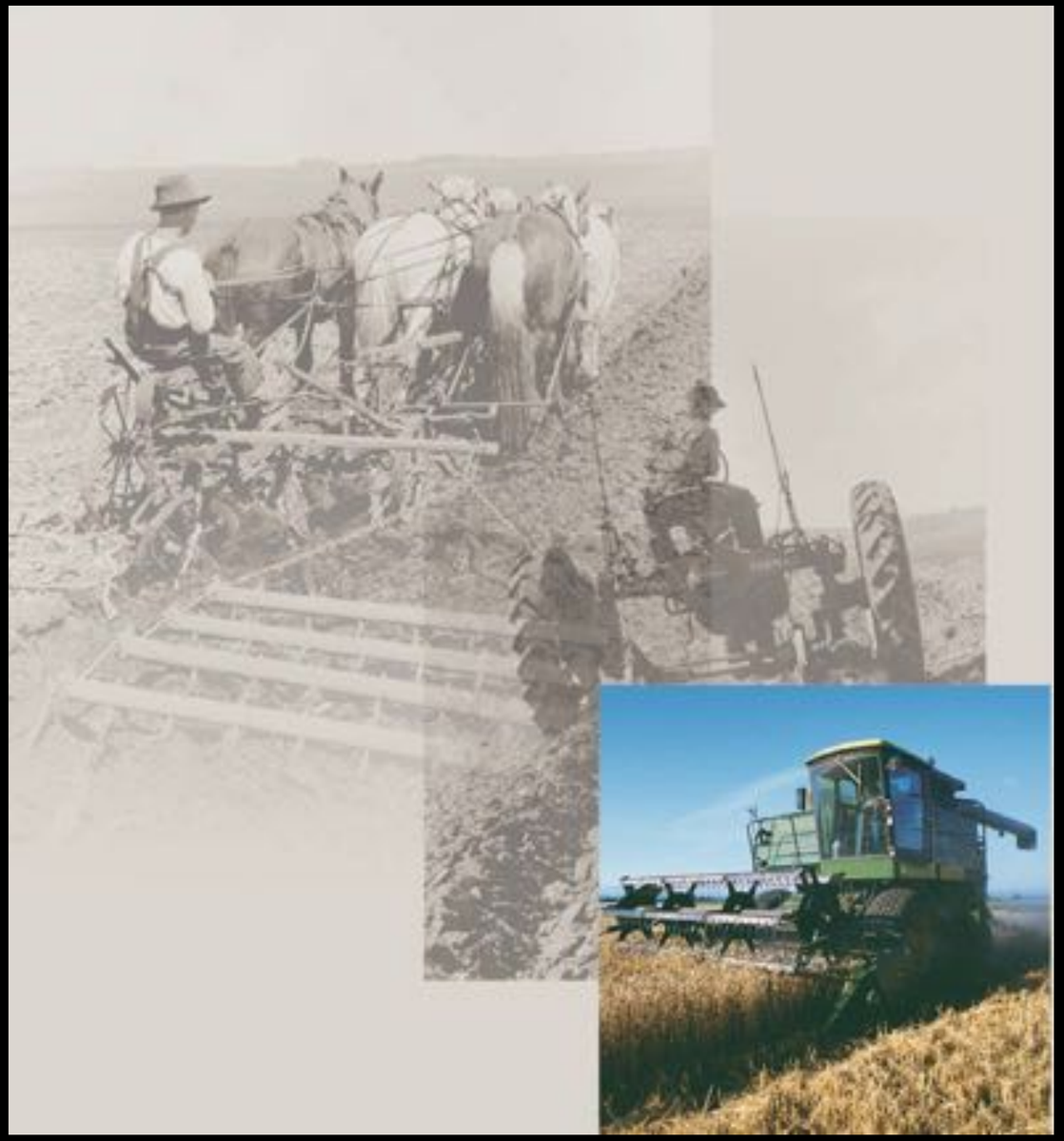
U.S. agricultural labor productivity has risen over the past 60 years





Yield and Price

Source: USDA ERR189



Source: The 20th Century Transformation of U.S. Agriculture and Farm Policy, USDA

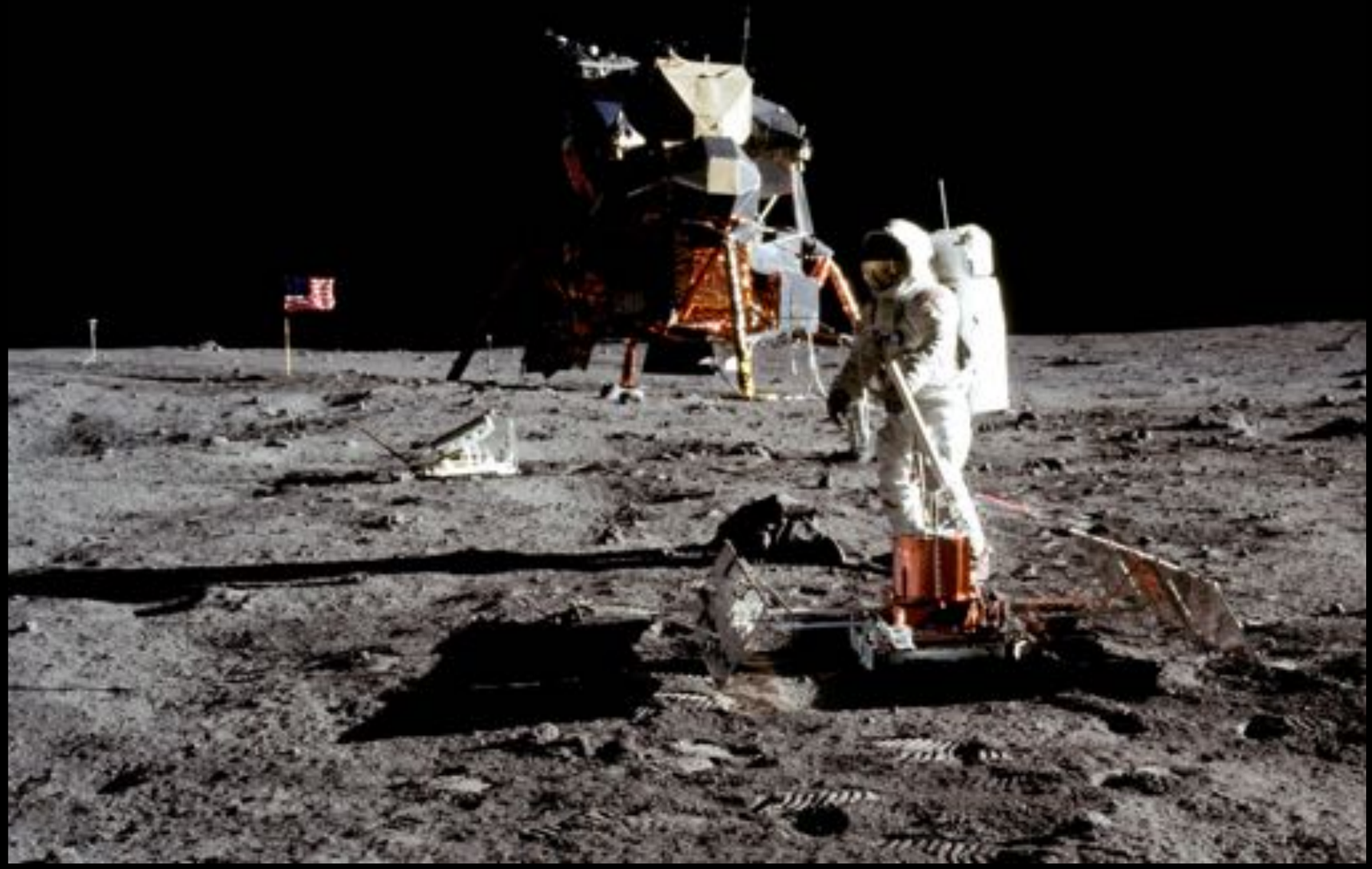
Lincoln Monument, Union Square, Decoration Day, 1876

Source: Library of Congress

San Ysidro Port, 2012

Photo Credit: Josh Denmark, USCBP

July 20, 1969: One Giant Leap For Mankind



Source: NASA

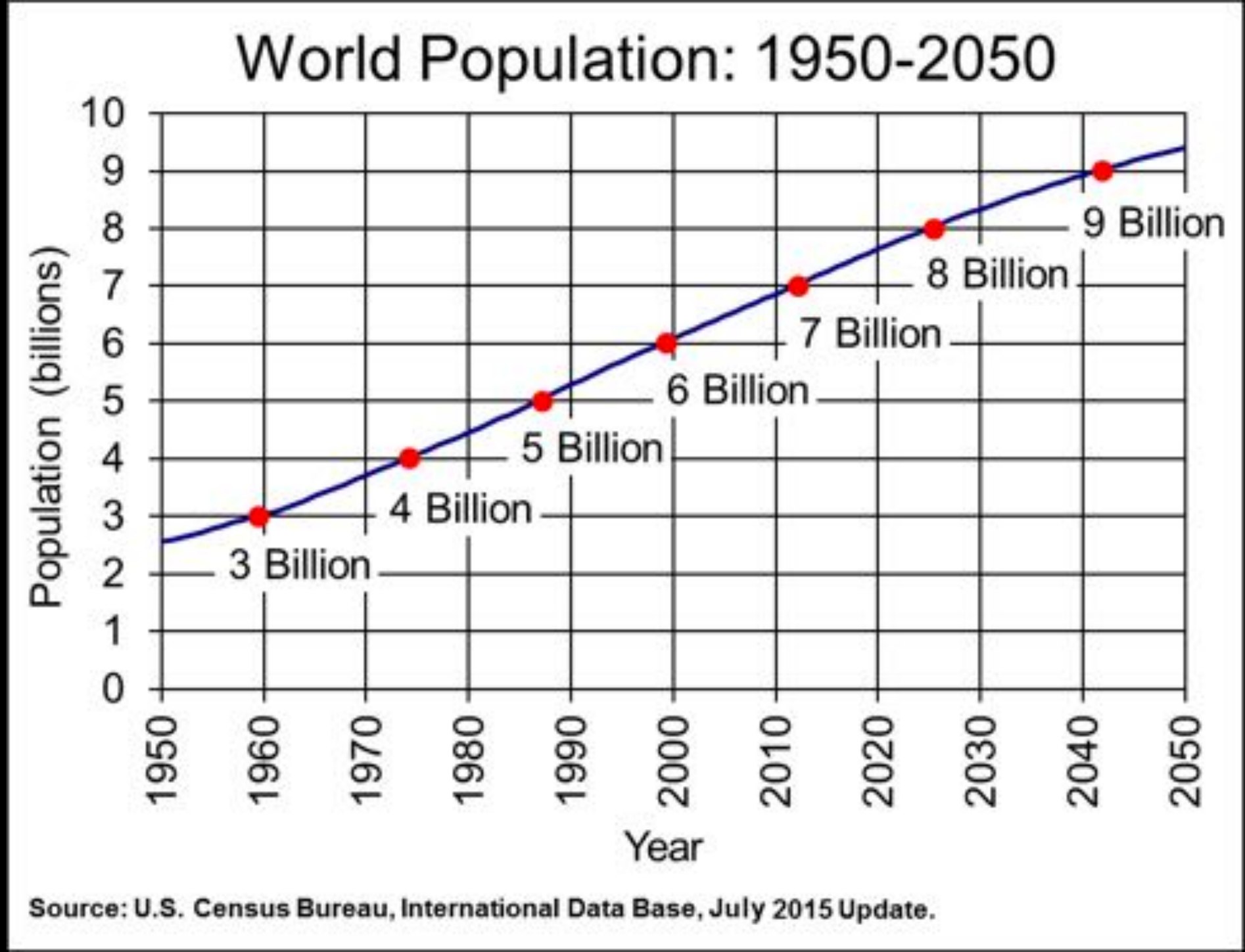
Visualization of the Internet

Credit: Map by Zina Deretsky, National Science Foundation, adapted from maps by Chris Harrison, Human-Computer Interaction Institute at Carnegie Mellon University (http://www.chrisharrison.net).

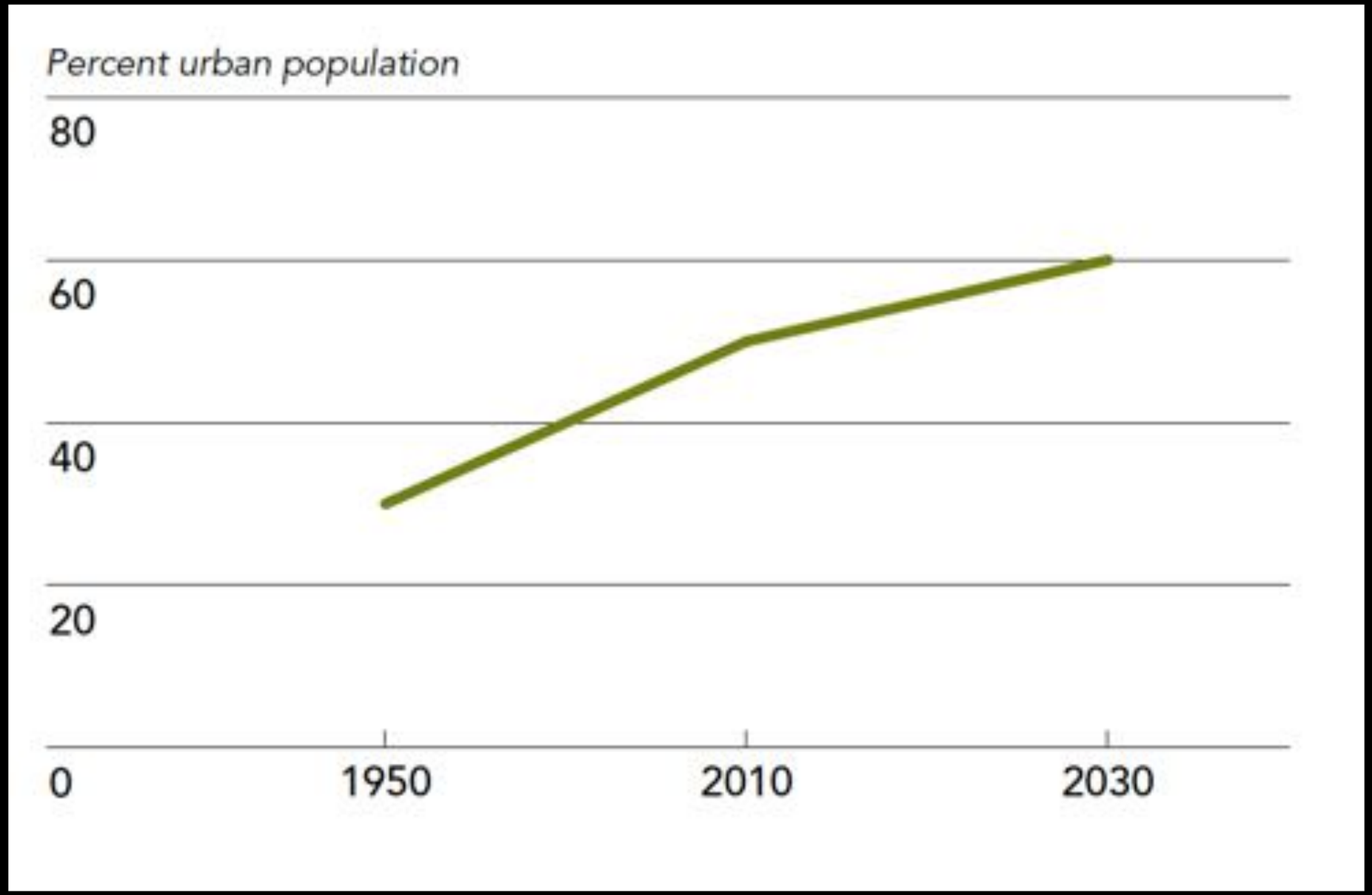
What will the 21st Century Look Like?

In 2050
9.6 Billion in the world
400 Million in US

Living in an increasingly interconnected, interdependent world

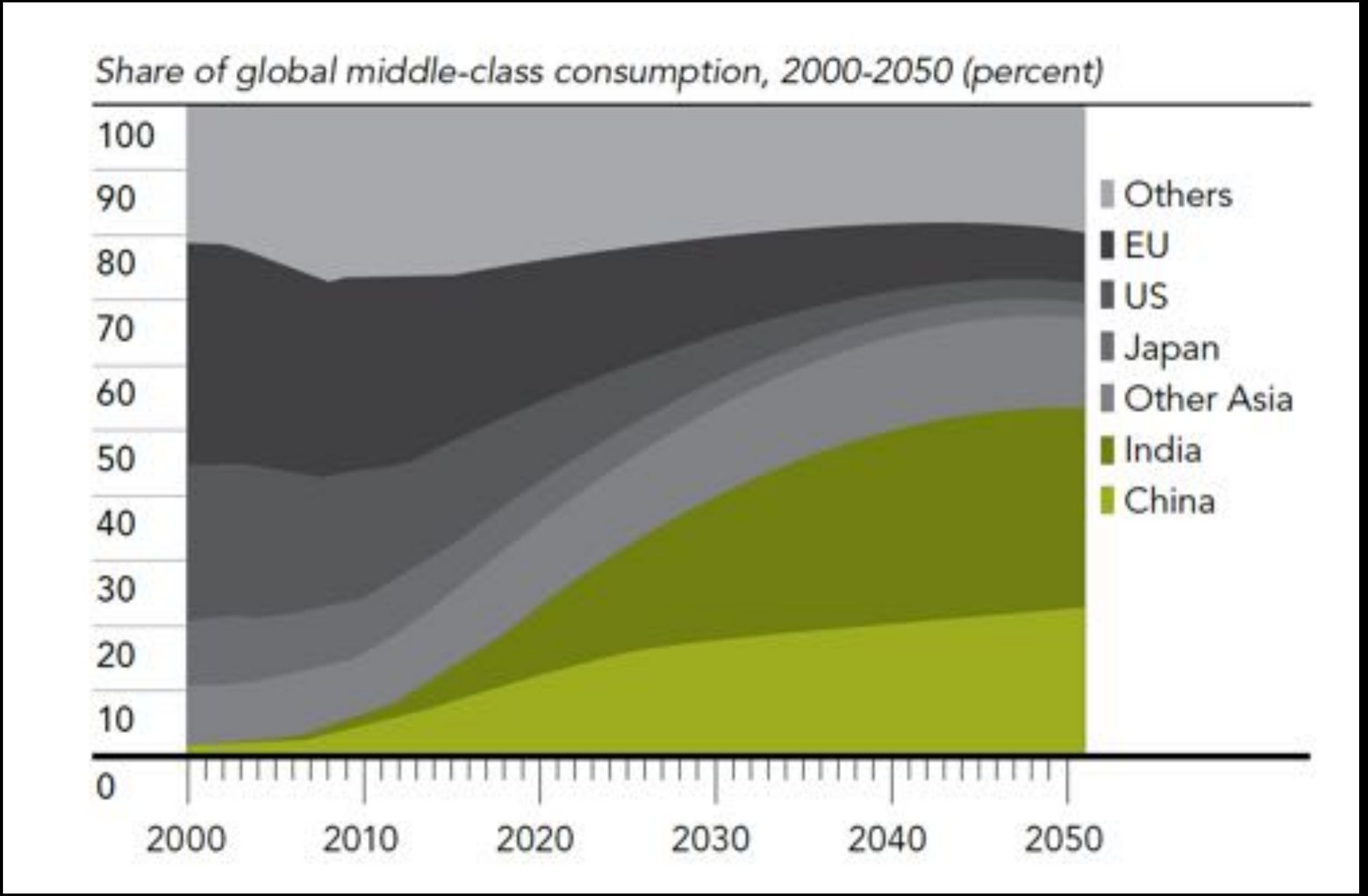


An Urbanizing World



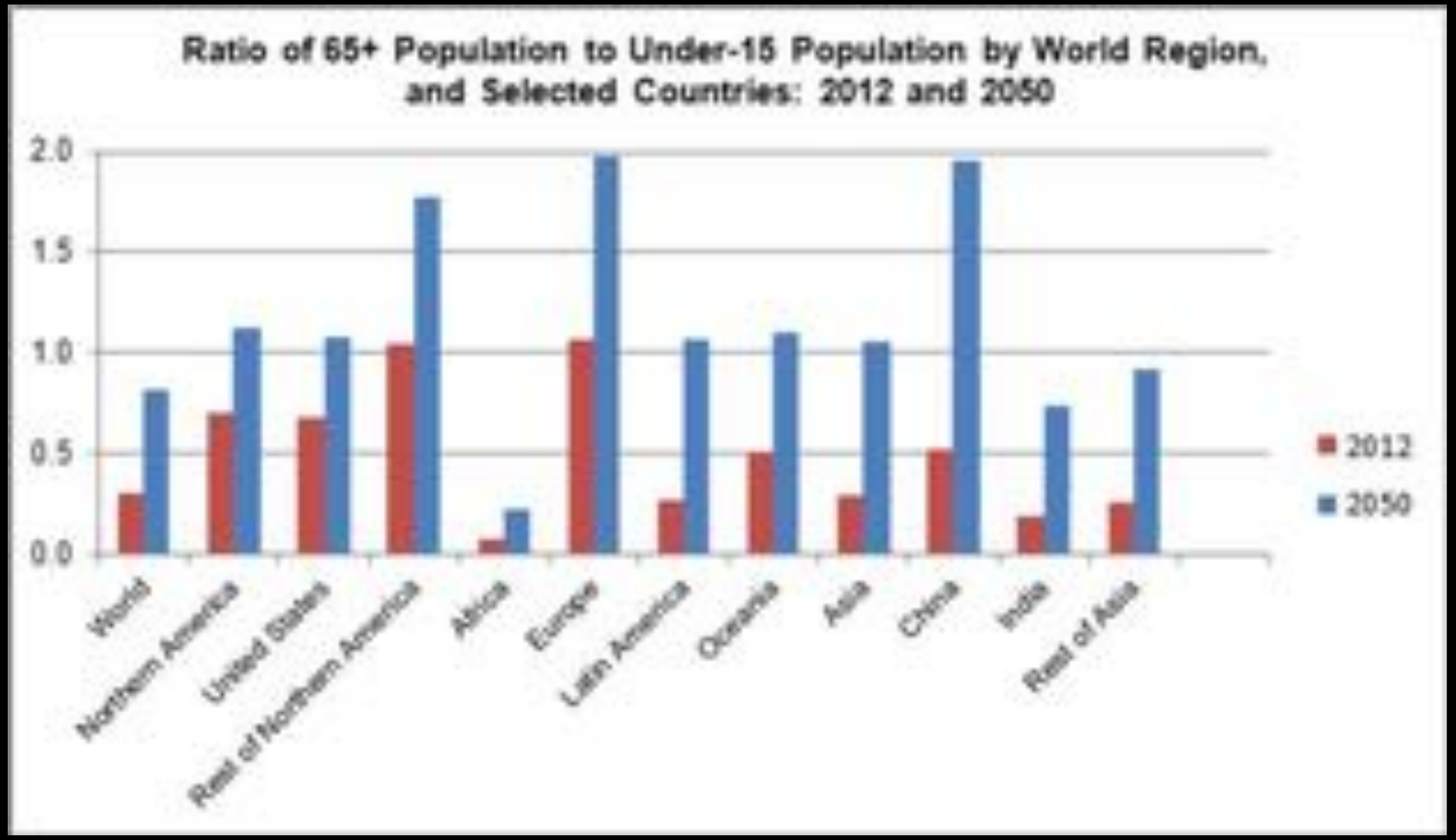
Source: Global Trends 2030, National Intelligence Council

With a Growing Global Middle Class



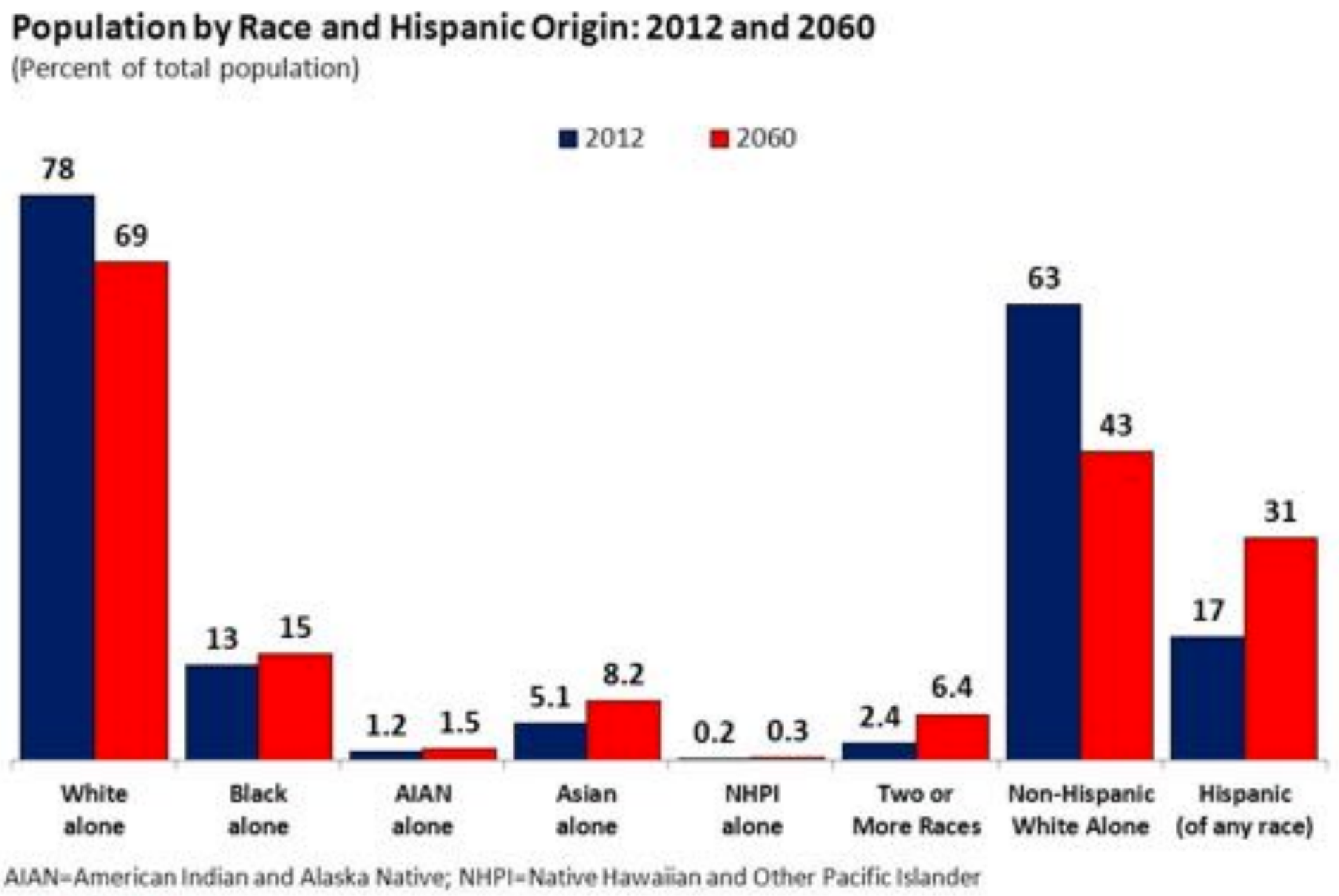
Source: Global Trends 2030, National Intelligence Council

But it is a Graying World!



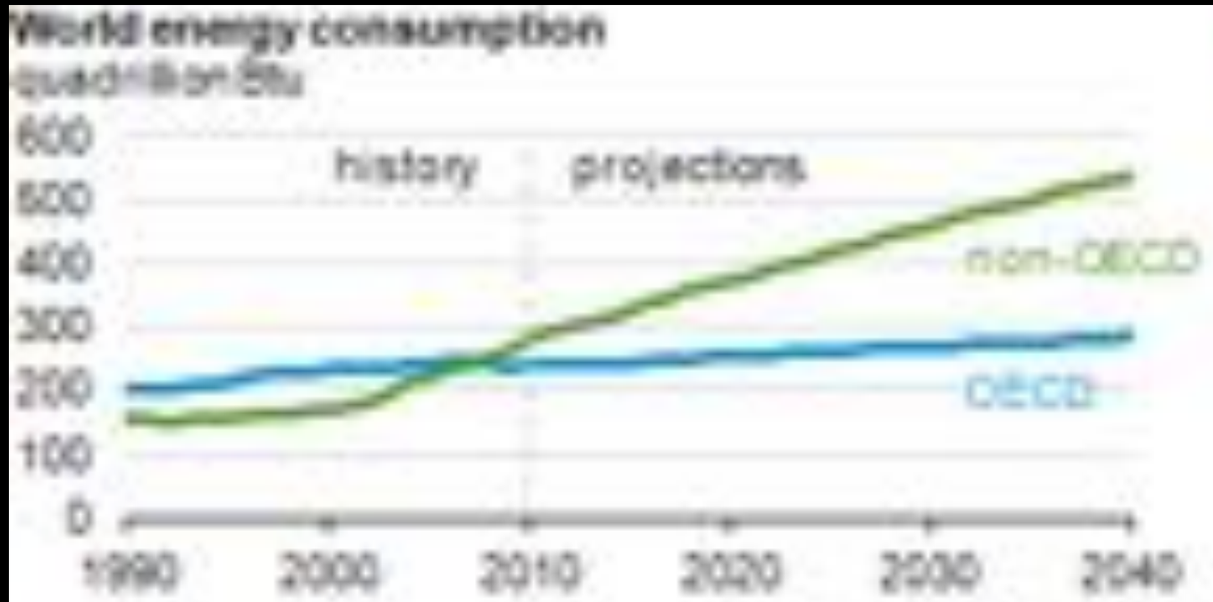
Source: Census Bureau

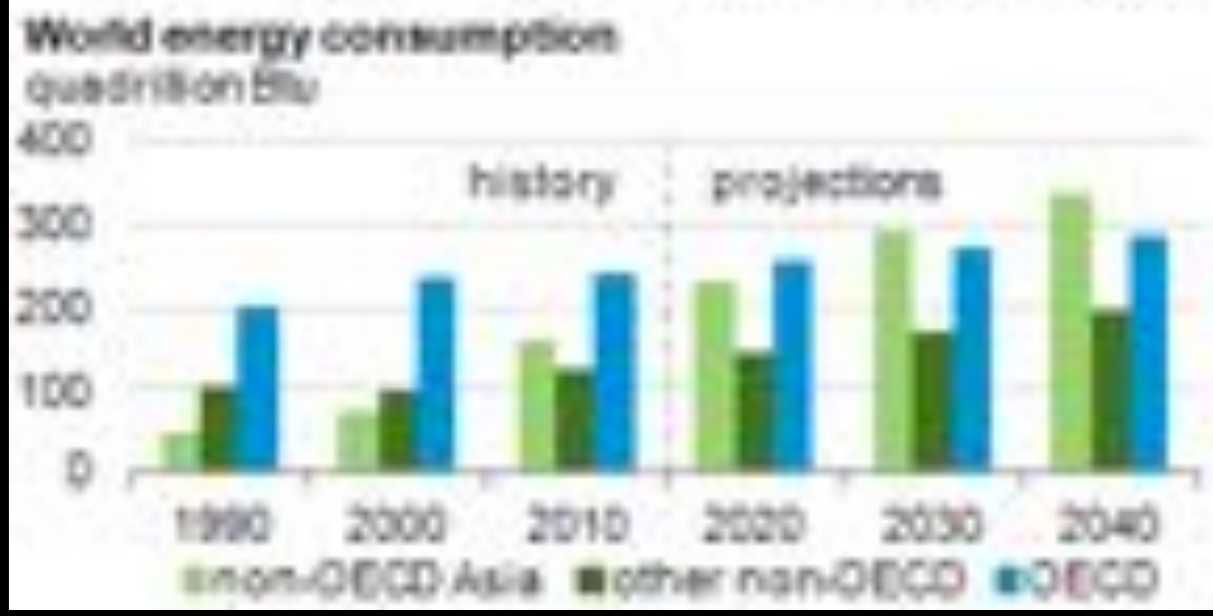
A More Diverse USA

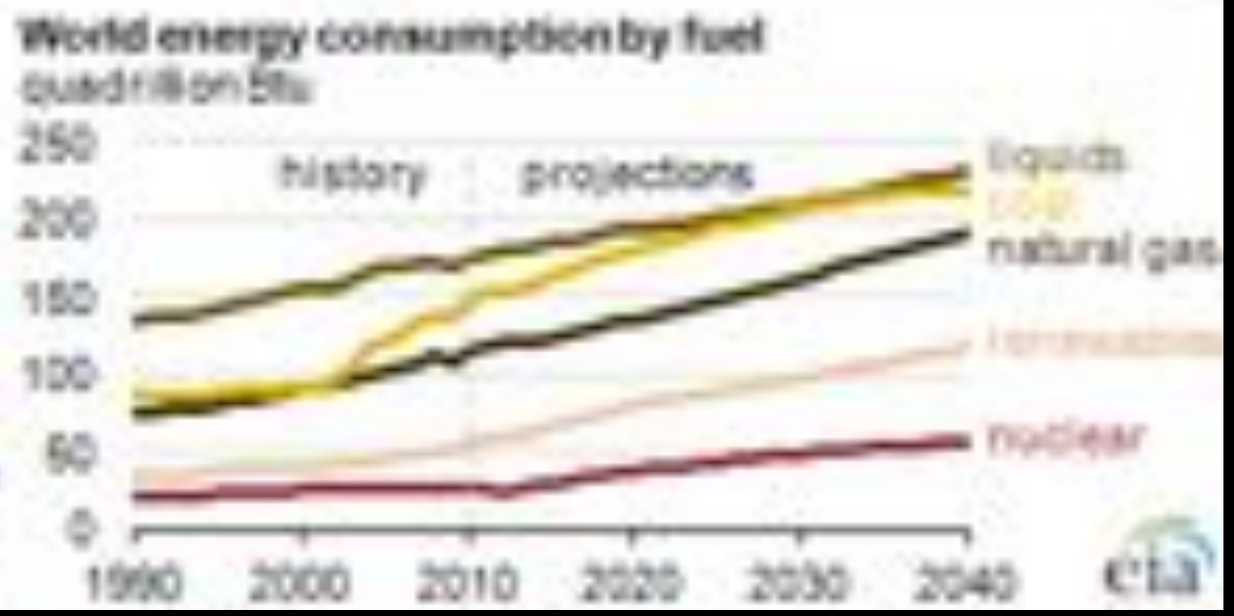


Source: Census Bureau

With Increasing Energy Consumption

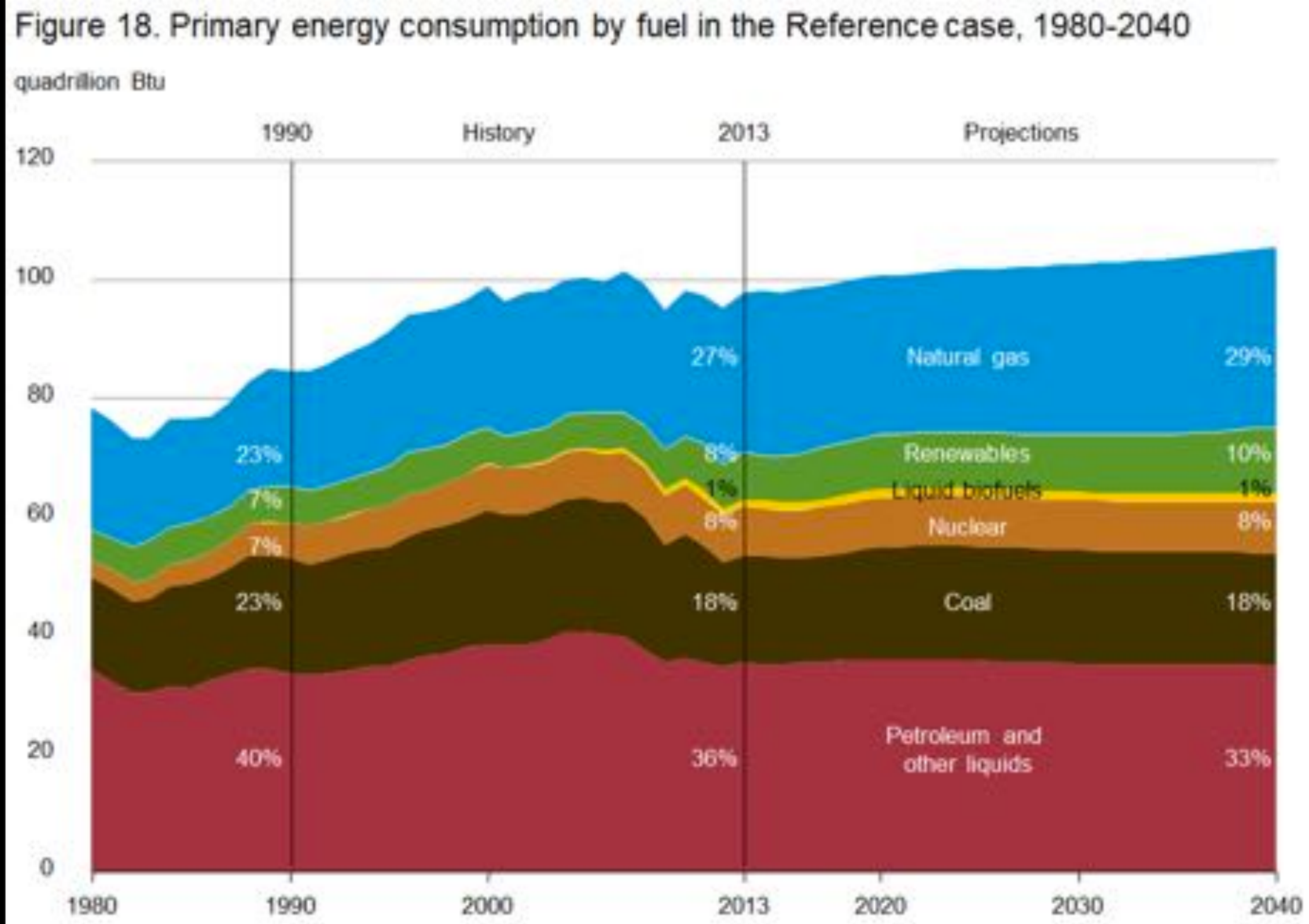




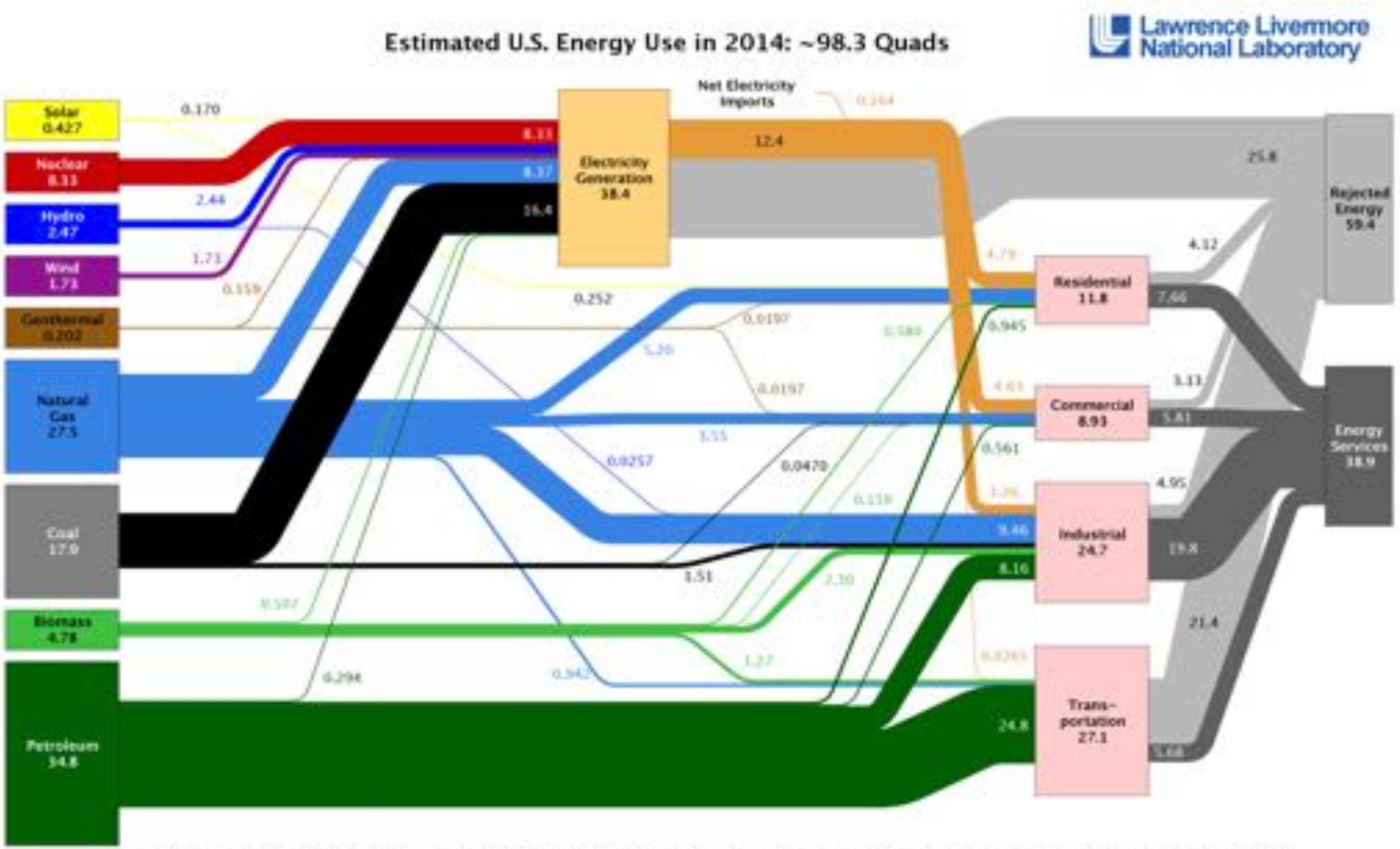


Source: US Energy Information Association, 2013

US Energy Consumption

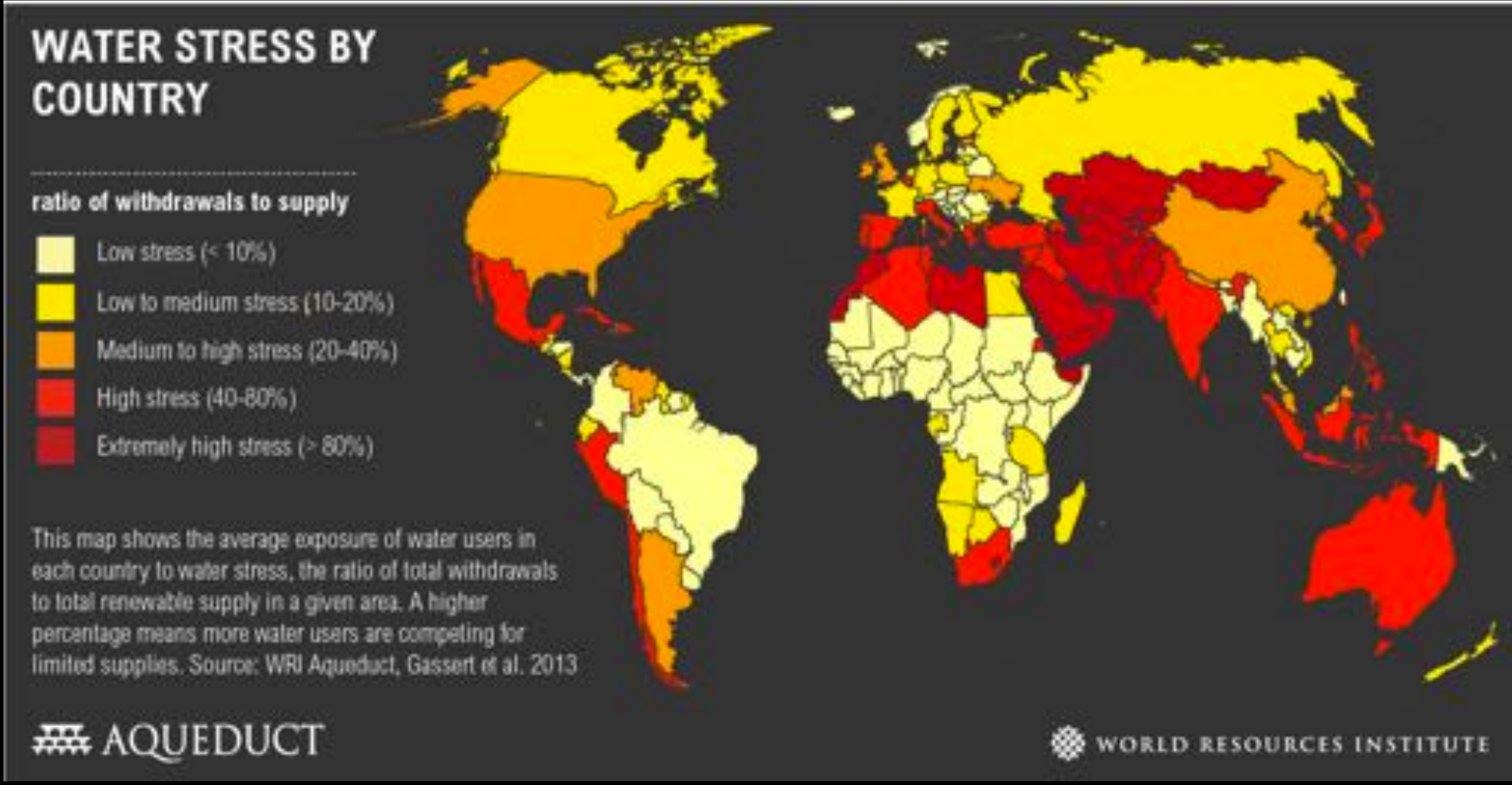


Source: US Energy Information Administration, 2015



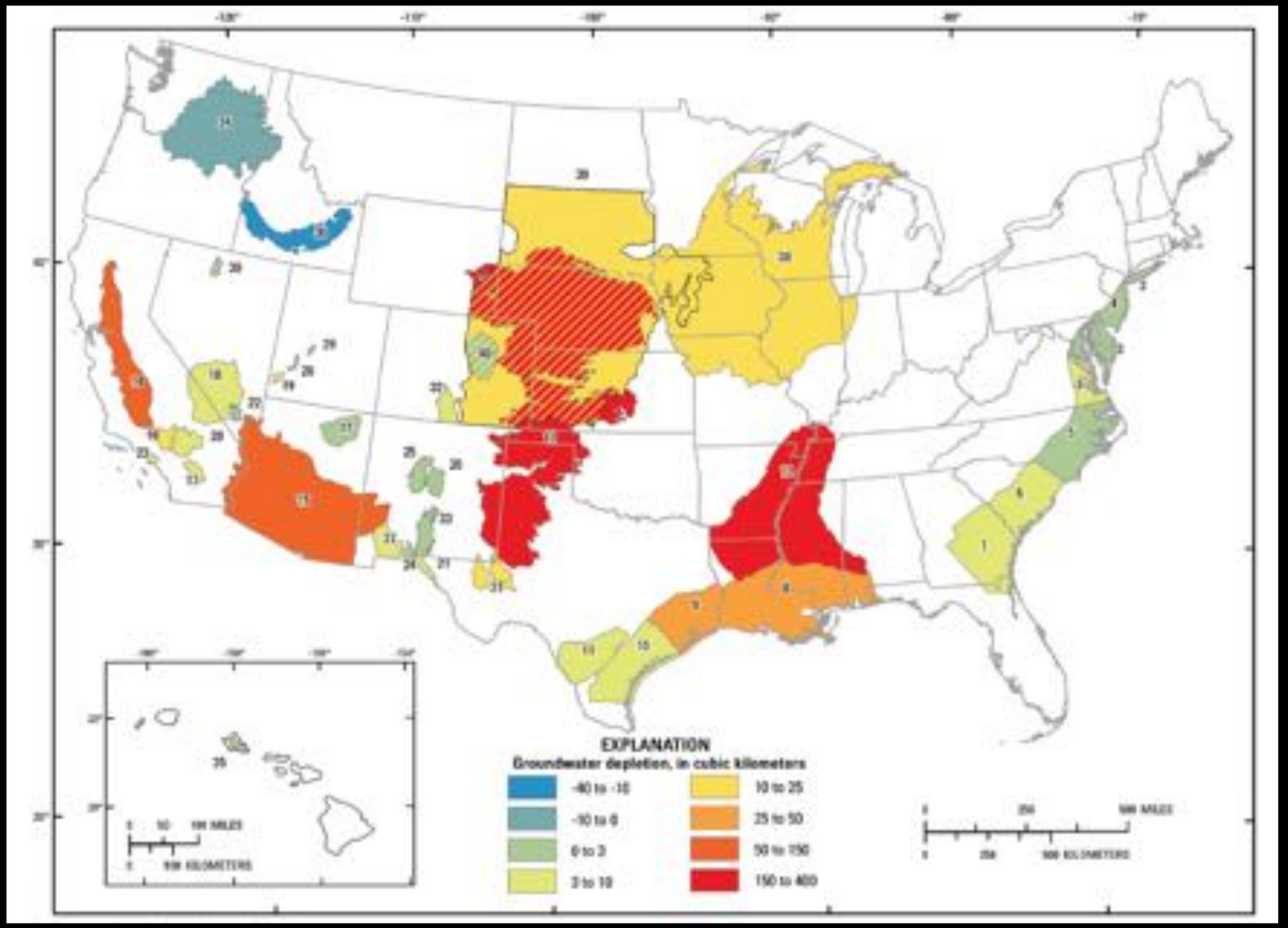
Source: LLNL 2015. Data is based on DOE/EIA-0035(2015-03), March, 2014. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Source: LBNL



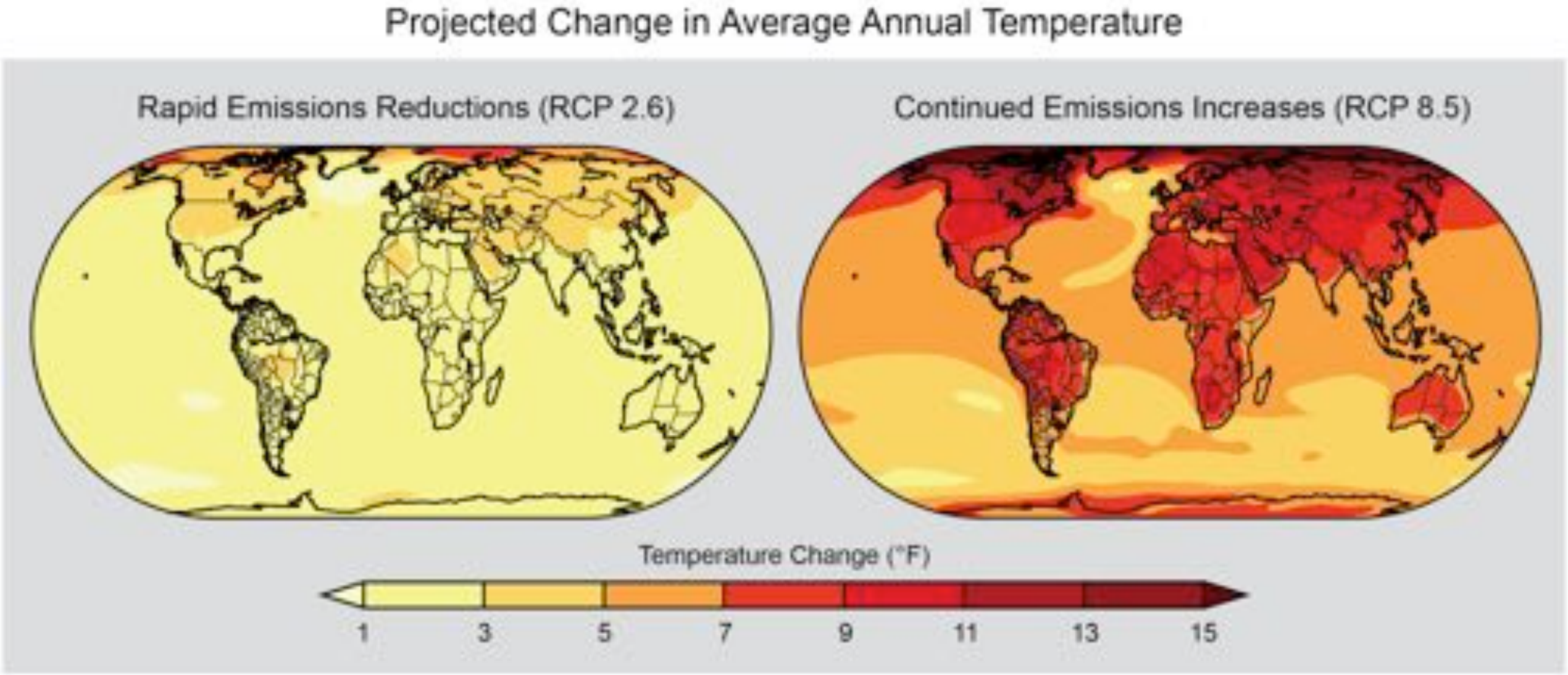
Source: World Resources Institute

Groundwater Depletion 1900-2008



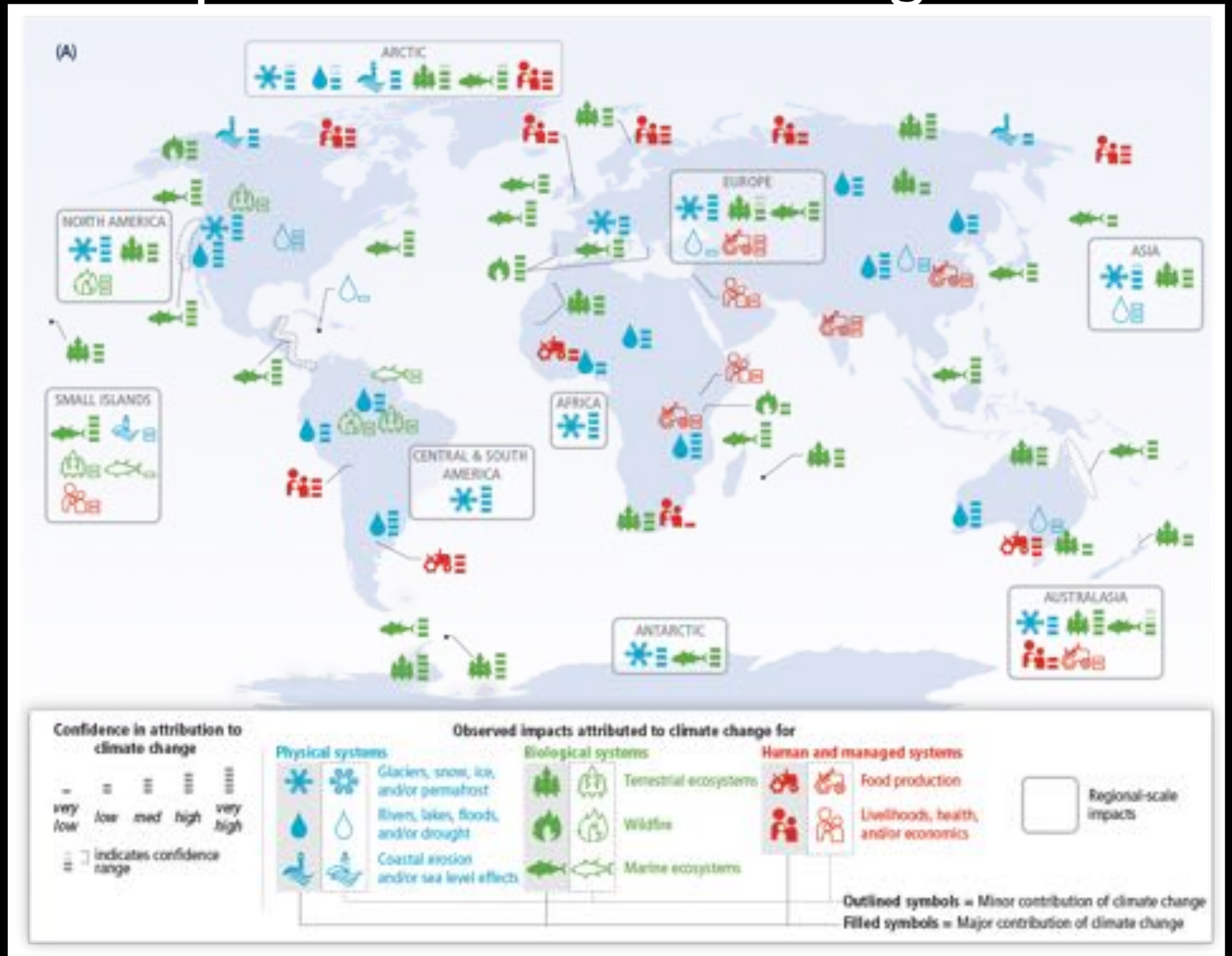
Source: USDOI and USGS, Scientific Investigations Report 2013–5079

Climate Change



Source: Walsh, J., D. Wuebbles, K. Hayhoe, J. Kossin, K. Kunkel, G. Stephens, P. Thorne, R. Vose, M. Wehner, J. Willis, D. Anderson, S. Doney, R. Feely, P. Hennon, V. Kharin, T. Knutson, F. Landerer, T. Lenton, J. Kennedy, and R. Somerville, 2014: Ch. 2: Our Changing Climate. Climate Change Impacts in the United States: The Third National Climate Assessment, J. M. Melillo, Terese (T.C.) Richmond, and G. W. Yohe, Eds., U.S. Global Change Research Program, 19-67. doi:10.7930/J0KW5CXT. Available at http://nca2014.globalchange.gov/report/our-changing-climate/future-climate-change

Potential Impacts of Climate Change



Source: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Figure SPM.2A

Smalley's List of Top 10 Problems

- Energy
- Water
- Food
- Environment
- Poverty
- Terrorism and War
- Disease
- Education
- Democracy
- Population

Richard Smalley
Our Energy Future, 2003

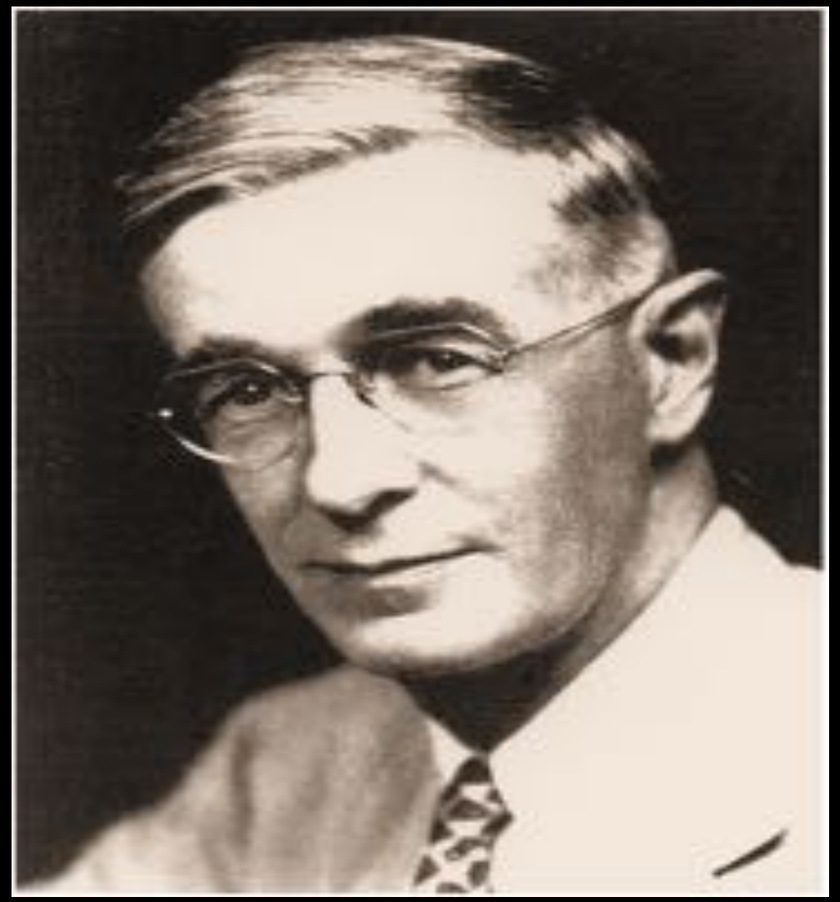
Image courtesy Oak Ridge National Laboratory

McKinsey on Disruptive Technologies

- Mobile Internet
- Automation of knowledge work
- The Internet of Things
- Cloud technology
- Advanced robotics
- Autonomous and near-autonomous vehicles
- Next-generation genomics
- Energy storage
- 3D printing
- Advanced materials
- Advanced oil and gas exploration and recovery
- Renewable energy

Source: McKinsey Global Institute, 2013

What is NSF Engineering Directorate Enabling?



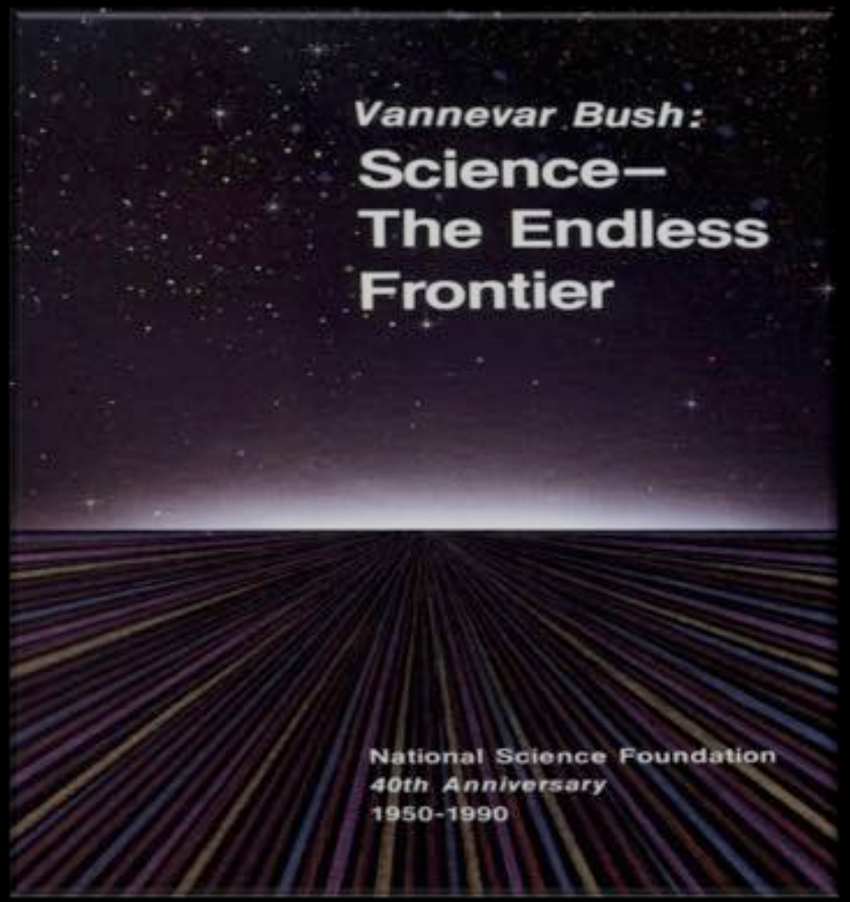


Image courtesy MIT Museum

"to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…"
NSF Act, 1950

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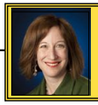

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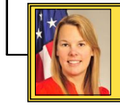

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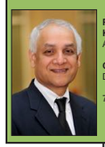

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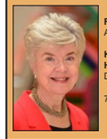

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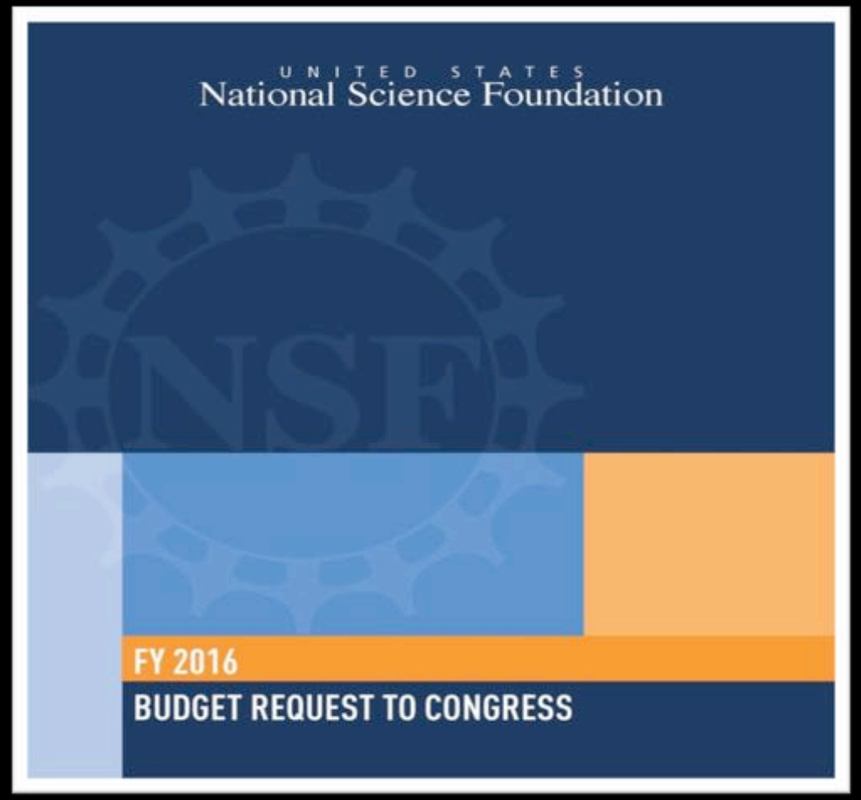
November 2015

FY 2016 Budget Request



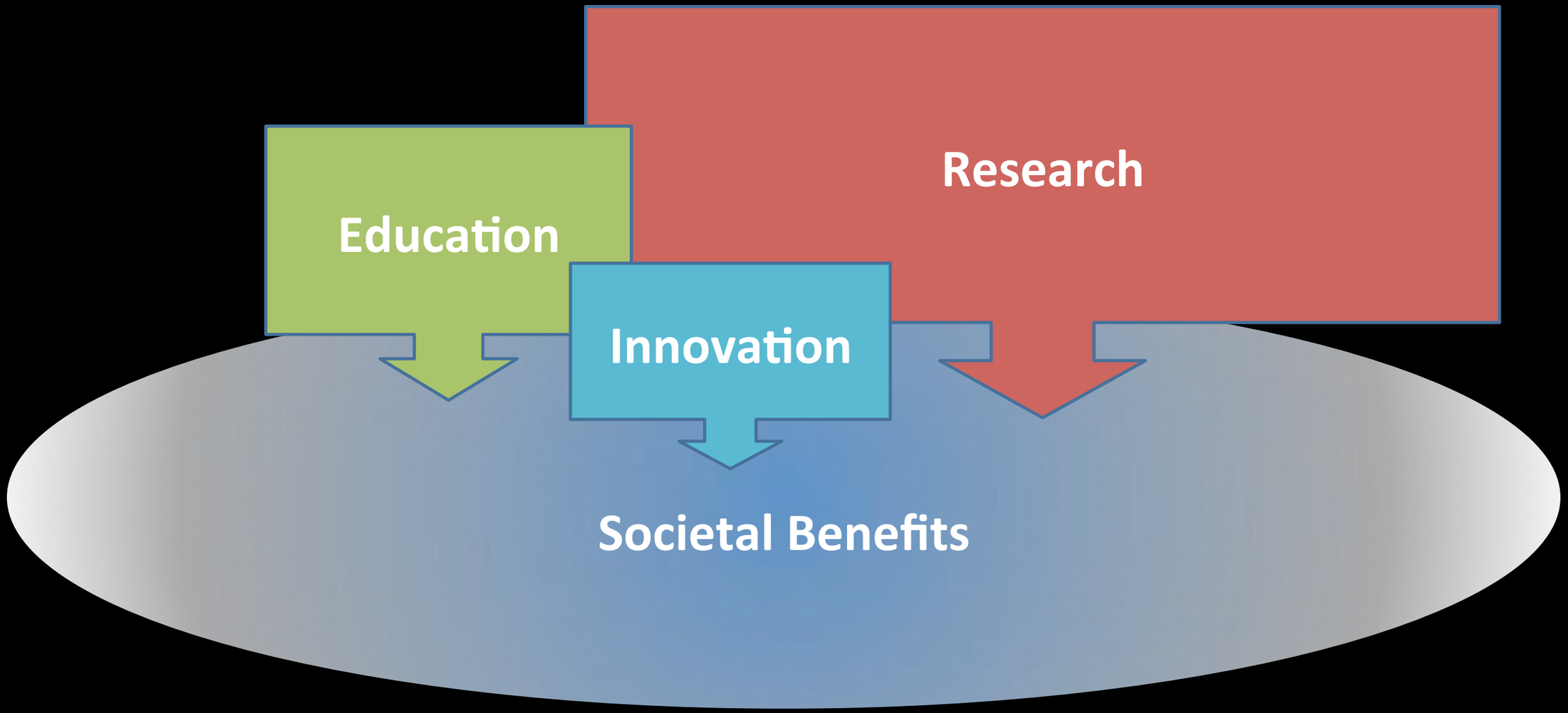
NSF

- FY 2016 Budget Request: $7723.55 Million
- Increase over FY 2015 Est: $379.34 Million, +5.2%

ENG

	FY 2014 Actual*	FY 2015 Current Plan	FY 2016 Request	Change over FY 2015 Current Plan	
				Amount	Percent
CBET	$167.76	$177.82	$192.26	$14.44	8.1%
CMMI	195.23	209.52	222.73	13.21	6.3%
ECCS	100.37	110.43	119.24	8.81	8.0%
EEC	119.50	117.49	110.39	-7.10	-6.0%
IIP	205.99	226.98	248.11	21.13	9.3%
SBIR/STTR	*159.99*	*177.11*	*194.36*	*17.25*	*9.7%*
EFMA	44.27	50.07	56.49	6.42	12.8%
ENG TOTAL	$833.12	$892.31	$949.22	$56.91	6.4%

NSF ENG: Investing in engineering research and education to foster innovations for benefit to society



Major Trends and Forces

- Ubiquitous computing and communications
  - Computational modeling, data, simulation, optimization pervasive in all fields of engineering
  - Networks and computation deeply integrated into engineered systems
  - Machine intelligence
- Systems science and engineering
  - Multi-scale analysis, design, and optimization
  - Integration of physical and cyber components
  - Range: nano- to micro- to macro-scale
  - Scale and complexity: large numbers of components
  - Safety, robustness, resilience, …

Major Trends and Forces

- Nanoscale science and technologies
  - Improving understanding and new tools at the atomic and molecular scales
  - Progressing from passive components to active systems and design
- Biological/Medical
  - Interaction of engineered systems and biology at all scales – DNA to cells to organs to organisms to eco-systems
  - Engineering for neuroscience and brain
  - Synthetic biology
  - Plants, food, and agriculture
  - Advanced biomanufacturing
  - Biologically inspired engineering

Major Trends and Forces

- Behavioral/economic/cognitive sciences
  - Human behavior and game theory in engineered systems and technology
  - Prominent role in infrastructure systems such as telecommunications, electricity, transportation, gas, water, food, health
  - Social, economic, regulatory, policy issues
- Design*, creativity, aesthetics, …*

ENG Initiatives and Priorities Address National Interests

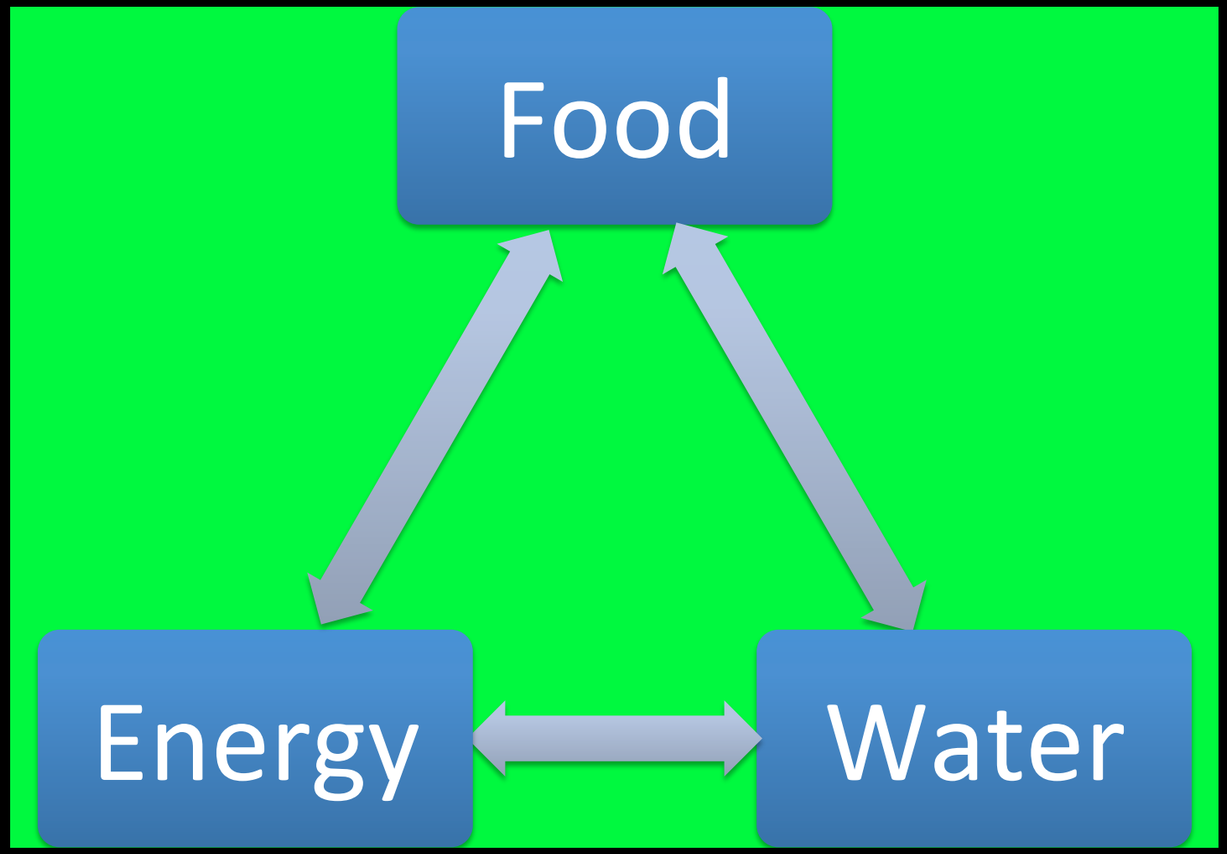
- **Innovations at the Nexus of Food, Energy, and Water Systems**
- **Risk and Resilience**
- Urban Science
- Clean Energy Technology*
- Cyber-Enabled Materials, Manufacturing, and Smart Systems
  - Advanced Manufacturing*
- National Nanotechnology Initiative*
- Communications and Cyberinfrastructure
- Optics and Photonics

* National Initiatives

- **Understanding the Brain**
- Education and Broadening Participation
  - **Inclusion across the Nation of Communities of Learners that have been Underrepresented for Diversity in Engineering and Science (INCLUDES)**
- Innovation Corps
- Emerging Frontiers in Research and Innovation
- Integrative Research Centers

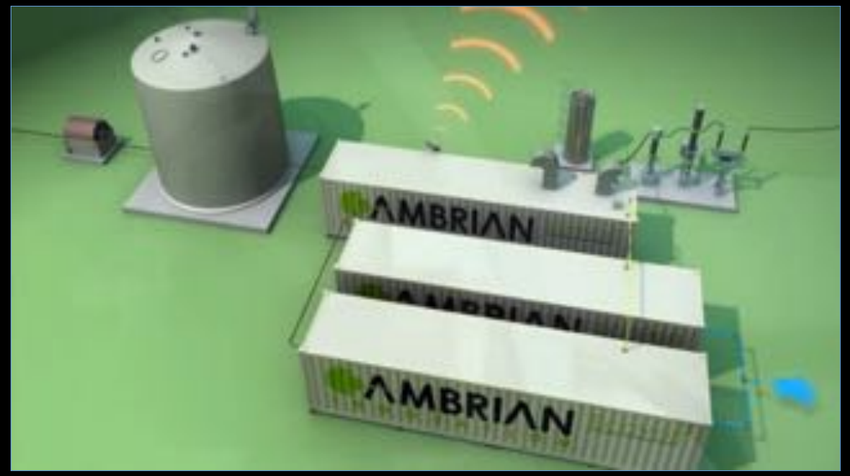
Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS)

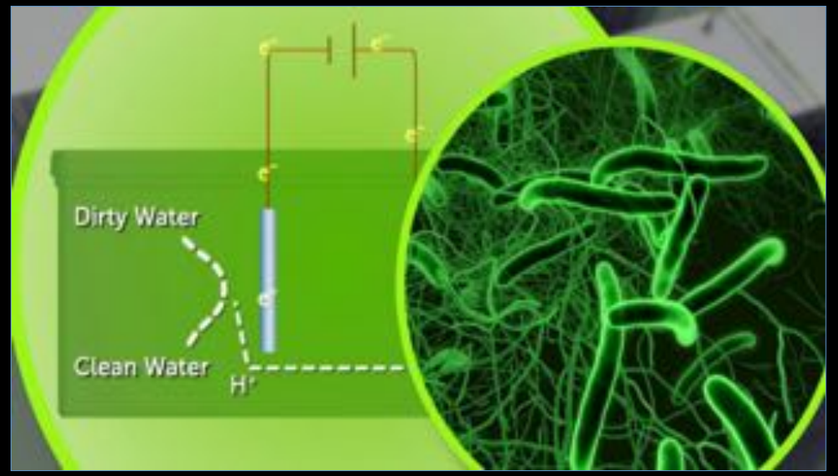
- Goal: To understand, model, design, and manage the interconnected food-energy-water (FEW) system
  - quantitative and computational modeling
  - real-time, cyber-enabled interfaces
  - basic research for innovative system and technological solutions
  - scientific workforce capable of studying and managing the FEW system



Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS)

- Builds on prior NSF programs under Science, Engineering and Education for Sustainability (SEES) initiative
- FY 2015: SEES Food-Energy-Water workshops and research supplements
- FY 2016: Proposed Launch of INFEWS





Images courtesy Cambrian Innovation

NSF ENG Clean Energy Investments: 2012-2014

Renewable Energy Production

Alternative Fuels
Biofuels (bio & chemical routes)
Solar Fuels (CO_2, water splitting)

Electricity
Solar Photovoltaics
Wind
Water (hydrokinetic/tidal/wave)
Solar Thermal
Geothermal

$139,236,192 (64%)

Storage & Grid

Energy Storage
Batteries & capacitors
Fuel Cells
Thermal Storage

Other Topics
Grid (micro, smart)
Energy Efficiency
Carbon Capture

$71,653,915 (34%)

Cyber-Physical Systems (CPS)

- Roots in Cybernetics: idea goes back to Norbert Wiener
- Computation, communications, networking elements being increasingly infused into the physical world
- Computer science disciplines converging with disciplines that govern physical (and biological) worlds at multiple temporal and spatial scales
- Enable Internet-of-Things

Transportation	▪ **Faster and safer aircraft** ▪ **Improved use of airspace** ▪ **Safer, more efficient cars**
Energy and Industrial Automation	▪ **Homes and offices that are more energy efficient and cheaper to operate** ▪ **Distributed micro-generation for the grid**
Healthcare and Biomedical Systems	▪ **Increased use of effective in-home care** ▪ **More capable devices for diagnosis** ▪ **New internal and external prosthetics**
Critical Infrastructure	▪ **More reliable power grid** ▪ **Highways that allow denser traffic with increased safety**

Critical Infrastructures are a mainstay of the national economy, security and societal functioning

U.S. 2014 Billion-Dollar Weather and Climate Disasters

This map denotes the approximate location for each of the eight billion-dollar weather and climate disasters that impacted the United States during 2014.

Critical Resilient Infrastructures Systems and Processes (CRISP)

- Create new approaches/solutions for design/operation of infrastructures as processes/services
- Enhance understanding/design of ICIs and processes under disruptions from any cause
- Create knowledge for innovation in ICIs to safely, securely, and effectively expand range of goods and services they enable

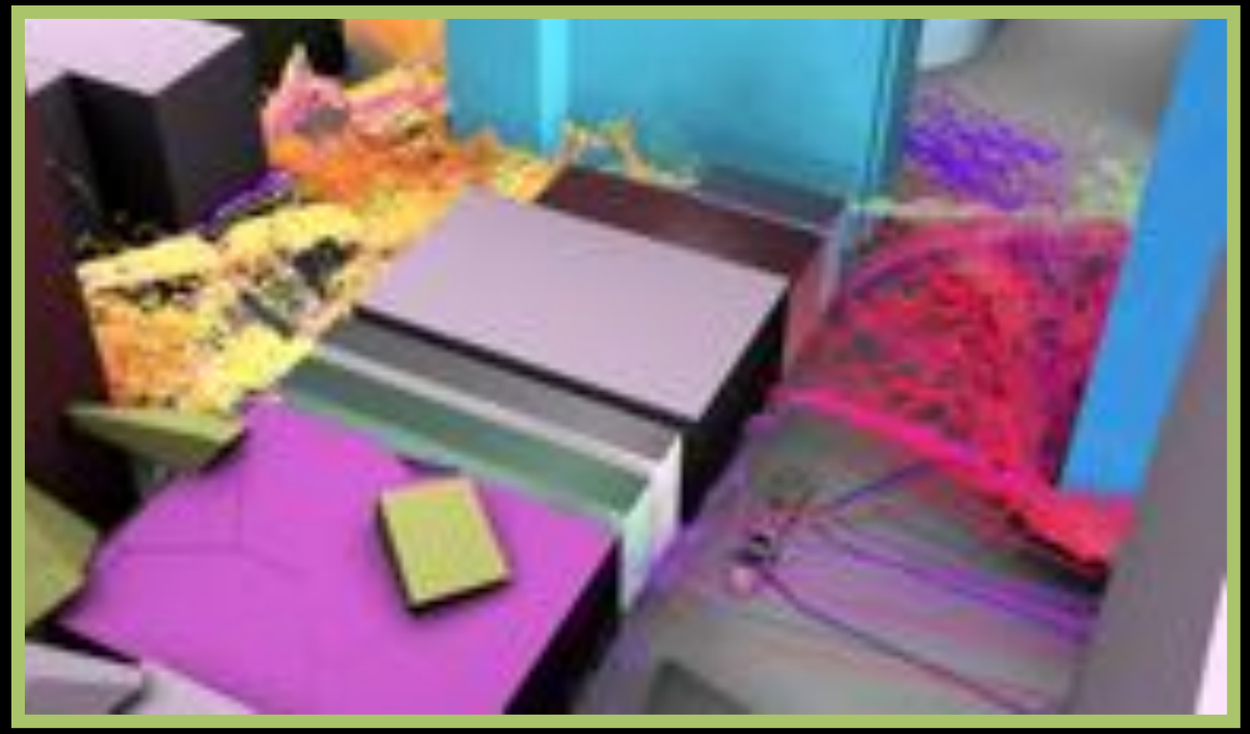


Image credit: Paul M. Torrens, Geography and UMIACS, University of Maryland, College Park

Smart and Connected Communities

- To intelligently and effectively design, adapt and manage the smart and connected communities of the future

- To enable more livable, workable, sustainable, and connected communities
  - Builds on Cyber-Physical Systems (CPS), CRISP and Smart Service Systems (under PFI:BIC) programs

- Dear Colleague Letter: Supporting Research Advances in Smart and Connected Communities (NSF 15-120)
  - Collaboration between ENG, CISE, EHR, GEO, and SBE

Enhance Access to Wireless Spectrum (EARS)

- Spectrum - a finite resource
- Mobile computing and internet-of-things efficient use of wireless spectrum
- EARS: improve the efficiency of use of radio spectrum and access
- Interdisciplinary research, recognizing the interplay among technology, public policy, economics, and social sciences in modern spectrum management
- Funding amounts: FY12 - $11.4M, FY13 - $23.5M, FY14 - $24.5M, FY15 ~ $15M
- In the last 36 months, NSF's EARS has become the center of national attention for spectrum R&D

http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503480

Large-scale Integration of Renewables into the Power Grid

- Create new foundational knowledge
  - Dear Colleague Letter: Research on Theory and Analytical Tools for Power Networks with High Levels of Renewable Generation
- Provided $4M for 14 projects
  - System dynamics, stability and control methods
  - Electricity generation and demand scheduling
  - Market design
  - System protection

Solar panels at Arizona State University, home of the NSF ERC for Quantum Energy and Sustainable Solar Technologies (QESST). *Image credit: NSF*

Natural Hazards Engineering Research Infrastructure (NHERI)

FY 2015 – FY 2025 Investment

Boundary layer wind tunnel. Image Credit: John Jernigan, University of Florida.

- $40M initial investment in multi-hazards research facilities, cyberinfrastructure and tools to address the national need for resilience
  - FY 2015: One cyberinfrastructure and seven experimental facilities awarded
  - FY 2016: Competition for coordination office, simulation center, and rapid-response research capability

President Obama at Carnegie Mellon University
June 24, 2011

“Today, I’m calling for all of us to come together- private sector industry, universities, and the government- to spark a renaissance in American manufacturing and help our manufacturers develop the cutting-edge tools they need to compete with anyone in the world,”

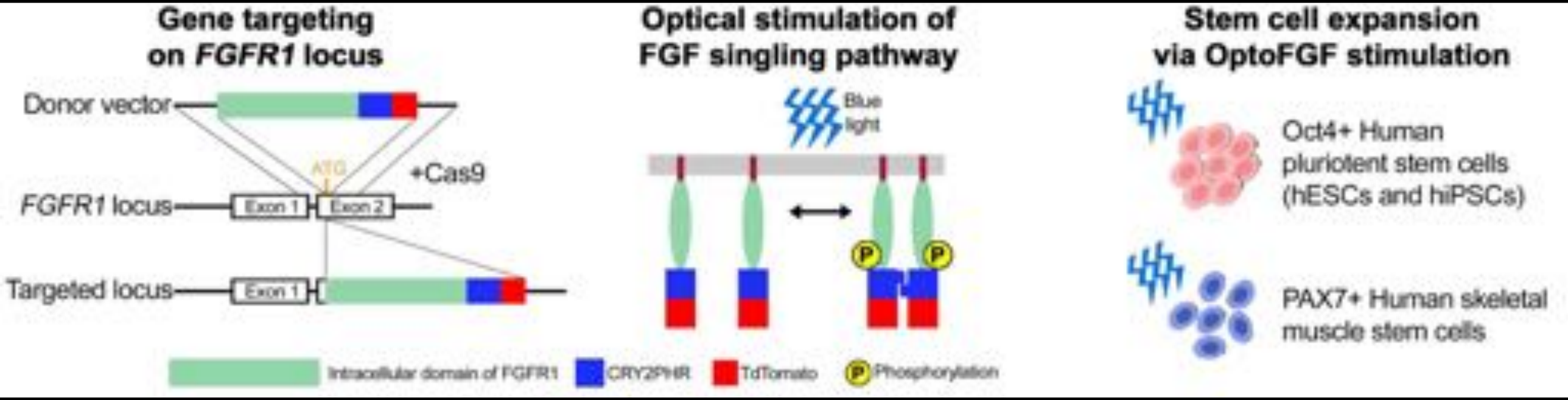
Advanced Manufacturing

Cellular Biomanufacturing

- FY 2015: $3.7M for 13 high-risk, high-impact research projects on the manufacturing of cells and cell-based products for future healthcare.
- Fundamental research on:
  - Novel cell expansion, differentiation, characterization, monitoring, isolation/separation methodologies
  - Reproducible, robust cellular biomanufacturing processes

Controlling stem cell behavior via novel photo activation of FGF signaling pathway using blue light

Lee, Johns Hopkins



Advanced Manufacturing

Cybermanufacturing

- Context: Factory of the future, Internet of things, supply chains, …
- FY 2015: $6.5M for 30 research projects to explore manufacturing research in the internet age
- Collaboration between ENG and CISE
- Key themes: production-as-a-service, manufacturing apps and operating systems, interoperability, manufacturing exchanges, security, predictive analytics

Design of an Agile and Smart Manufacturing Exchange

Chakrabbarty, Maggs and Zavlanos, Duke University

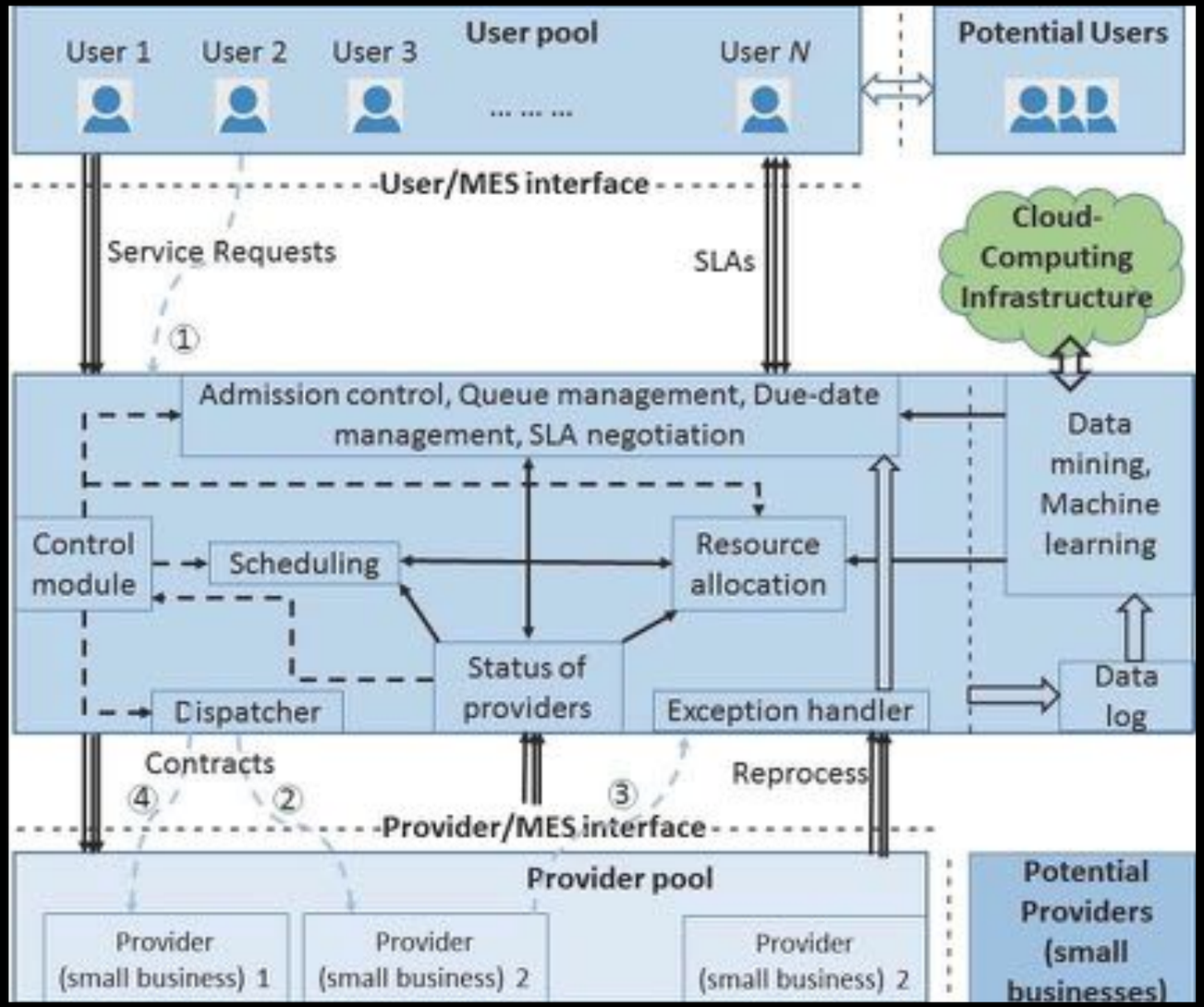
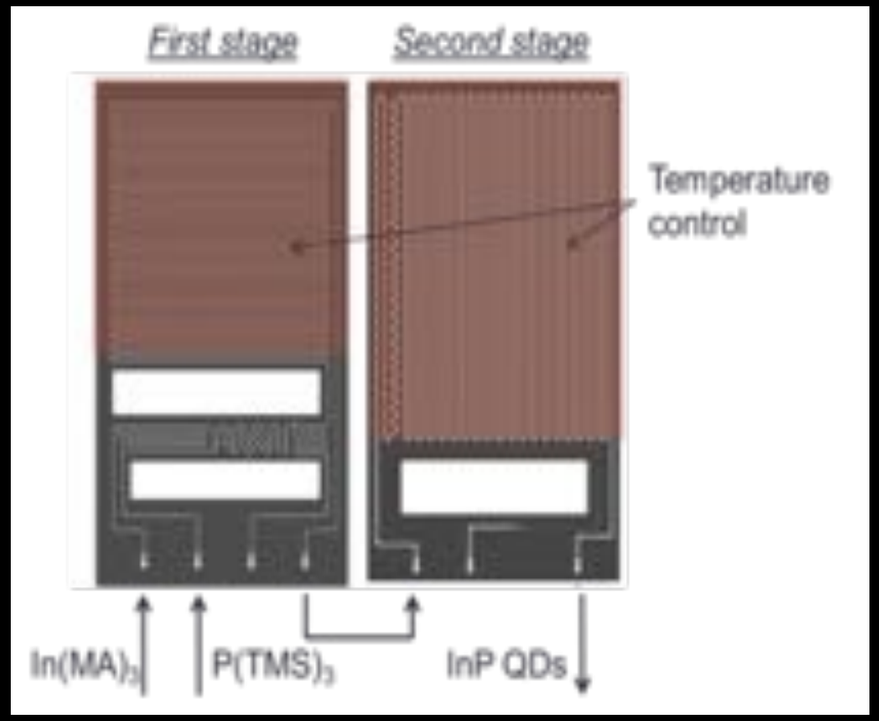


Image credit: Chakrabbarty, Maggs and Zavlanos, Duke University

Advanced Manufacturing

Scalable Nanomanufacturing

- Overcome critical scientific and engineering barriers that prevent the production of useful nanomaterials, nanostructures, devices and systems
- Address scale-up, large-area, continuous, parallel, and roll-to-roll
- Encourage industrial collaboration
- Address nanomanufacturing value chain
- FY 2015: $9.8M for 7 projects



Microreactor for quantum dots.
Image credit: Jensen, MIT

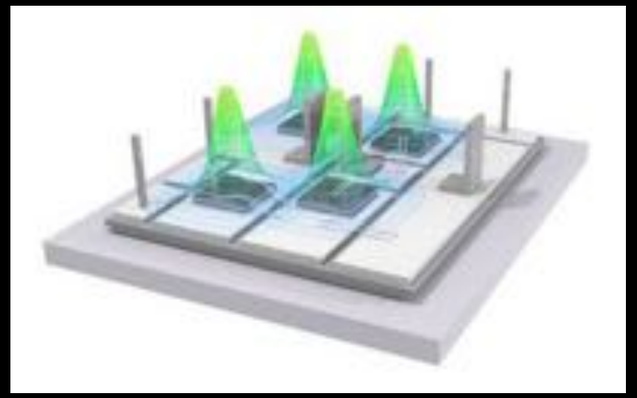
Convergence: Engineering Biology

- An emerging research paradigm: The convergence of engineering, physical sciences and life sciences
- Intellectual merit: deep integration of knowledge, ideas, tools, techniques for greater understanding and innovative designs
- Broader impacts:
  - Medicine, pharmaceuticals
  - Manufacturing (bio-products, chemical intermediates)
  - Environment
  - Agriculture
- Research needs:
  - Understand the physical, chemical and biological principles that govern life
  - Improve tools, techniques and methodologies for prediction and design
  - Enable scaling-up, usability, interoperation, safety, security, and ethics
  - Develop a future workforce with interdisciplinary education and training
  - Address challenges in advanced manufacturing to ensure future US competitiveness
- Build on NSF investments in metabolic engineering and synthetic biology

Engineering Research Centers (ERCs)

- Launched 3 new ERCs in FY15

Compact mobile power



ERC for Power Optimization for Electro-Thermal Systems (POETS), led by the University of Illinois at Urbana-Champaign

Nature-inspired soil engineering

ERC for Bio-mediated and Bio-inspired Geotechnics (CBBG), led by Arizona State University

Off-grid drinking water

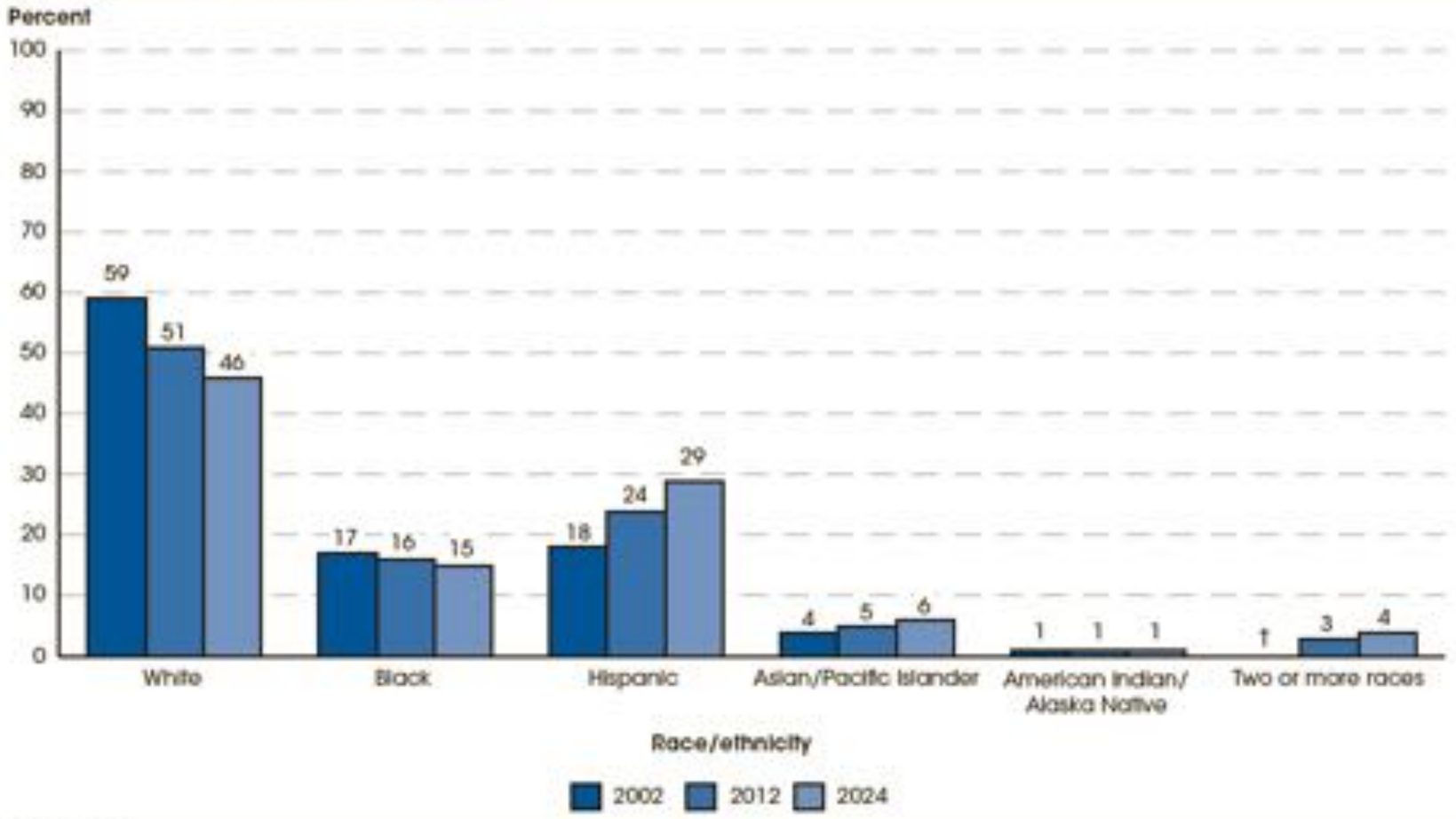
Nanosystems ERC for Nanotechnology Enabled Water Treatment Systems (NEWT), led by Rice University

- New ERC Competition launched in August 2015, new awards in 2017

Who will be the Engineers in the 21st Century?

Student Demographics

Figure 1. Percentage distribution of students enrolled in public elementary and secondary schools, by race/ethnicity: Fall 2002, fall 2012, and fall 2024



† Not applicable.
NOTE: Race categories exclude persons of Hispanic ethnicity. Prior to 2008, separate data on students of Two or more races were not collected. Detail may not sum to totals because of rounding. Data for 2024 are projected.
SOURCE: U.S. Department of Education, National Center for Education Statistics, Common Core of Data (CCD), "State Nonfiscal Survey of Public Elementary and Secondary Education," 2002–03 and 2012–13; and National Elementary and Secondary Enrollment Projection Model, 1972 through 2024. See *Digest of Education Statistics 2014*, table 203.50.

Source: Department of Education

Engineering Degrees

Bachelor's Degrees by Gender, 2013

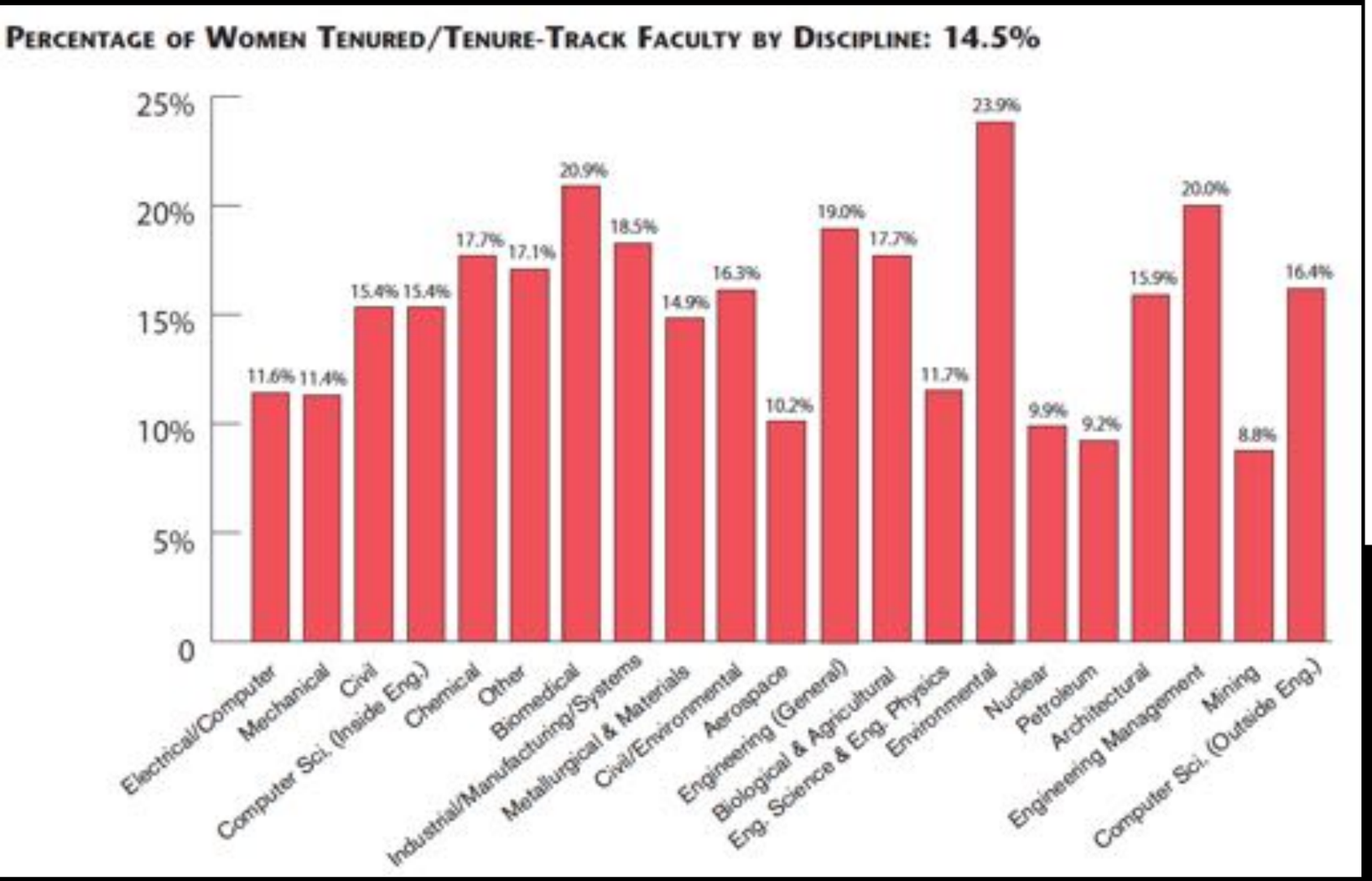
	2004	2005	2006	2007	2008	2009	2010	2011	2012
Female	20.3%	19.5%	19.3%	18.1%	18.0%	17.8%	18.1%	18.4%	18.9%
Male	79.7%	80.5%	80.7%	81.9%	82.0%	82.2%	81.9%	81.6%	81.1%

Bachelor's Degrees by Ethnicity, 2013*

	2004	2005	2006	2007	2008	2009	2010	2011	2012
Black or African American	5.1%	5.3%	5.0%	4.9%	4.7%	4.6%	4.5%	4.2%	4.2%
Hispanic	5.6%	5.8%	6.0%	6.2%	6.5%	6.6%	7.0%	8.5%	9.0%
Other	8.0%	8.6%	8.5%	8.3%	8.9%	11.0%	1.2%	1.6%	2.0%
Asian American	14.2%	14.1%	13.8%	13.3%	13.0%	12.4%	12.2%	12.2%	12.2%
White	67.1%	66.2%	66.7%	67.3%	66.9%	65.4%	69.8%	66.6%	66.2%
Unknown							5.3%	6.9%	6.5%

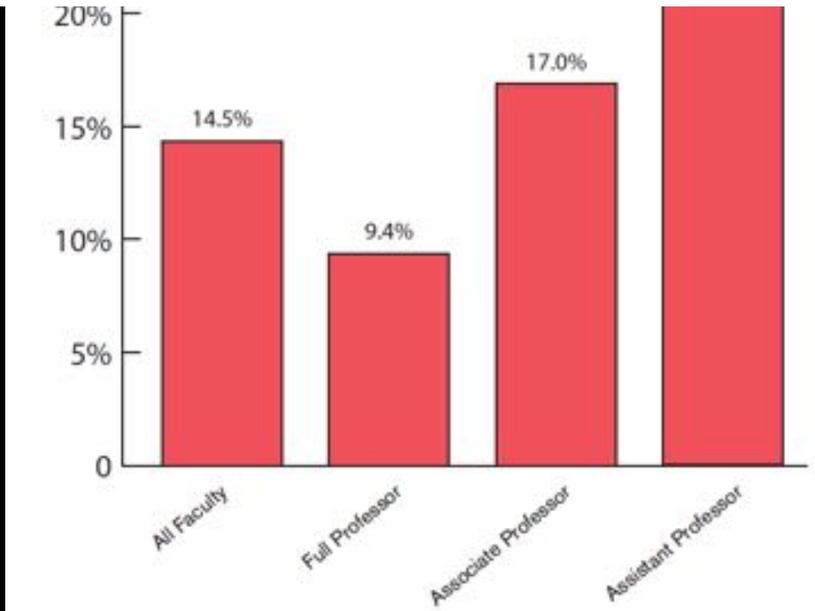
Source: ASEE, By the Numbers,11-47

Faculty Diversity



	Women	African-American	Asian	Hispanic
2004	10.4%	2.3%	20.2%	3.2%
2005	10.6%	2.4%	20.9%	3.2%
2006	11.3%	2.4%	22.0%	3.3%
2007	11.8%	2.5%	22.6%	3.4%
2008	12.3%	2.5%	22.7%	3.5%
2009	12.7%	2.5%	23.3%	3.5%
2010	13.2%	2.5%	23.9%	3.6%
2011	13.8%	2.5%	24.1%	3.7%
2012	14.0%	2.7%	24.6%	3.9%
2013	14.5%	2.6%	25.2%	3.6%

*Note: Includes faculty data from University of Puerto Rico, Mayaguez, Polytechnic University of Puerto Rico and Turabo University



Source: ASEE, By the Numbers,11-47

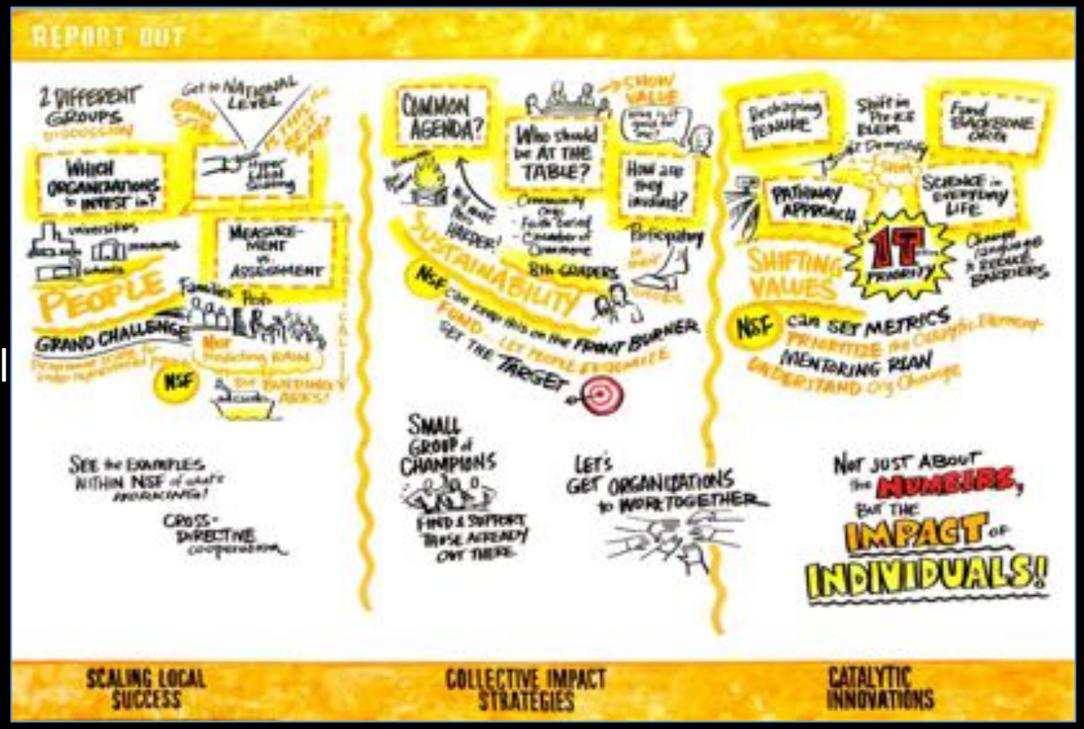
Observations

- Engineering continues to have major issues with attracting women and URMs
- More progress wrt women at the doctoral level and junior faculty ranks

Can engineering as a field and profession have a great future if we do not address broadening participation issues?

NSF INCLUDES: Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science

- Aims to achieve scale for inclusion in STEM
- Collective impacts and collaborative networks
- Director's Workshop, June 3, 2015
  - Learn from and build on existing successes
  - Wide ranging partnerships involving "more than the usual suspects"
  - Shared measurements and systematic networked coordination, collaboration and leveraging
  - National agenda with sensitivity to local differences
  - Connect research and practice of "science of broadening participation"



REvolutionizing engineering and computer science Departments (RED)

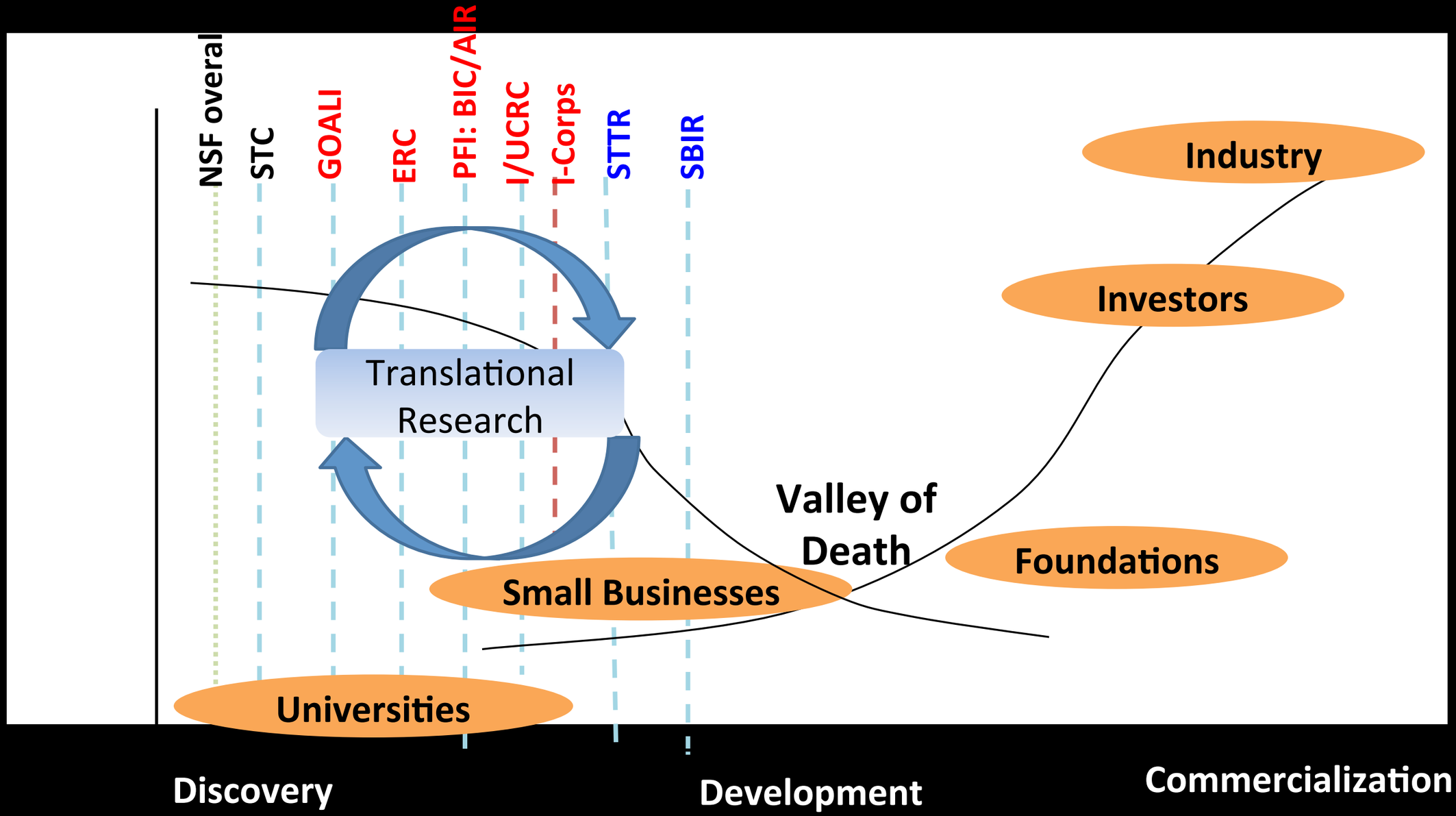
Concept of professional formation of engineers

Strategically create and support an innovative and inclusive engineering profession for the 21st century

- Support student success in attaining professional formation
- Broaden participation through cultures of inclusion
- Disseminate successful change processes nationally

A student works on circuit board project at the University of San Diego, chosen as one of six engineering departments chosen for a RED award. *Credit: University of San Diego*

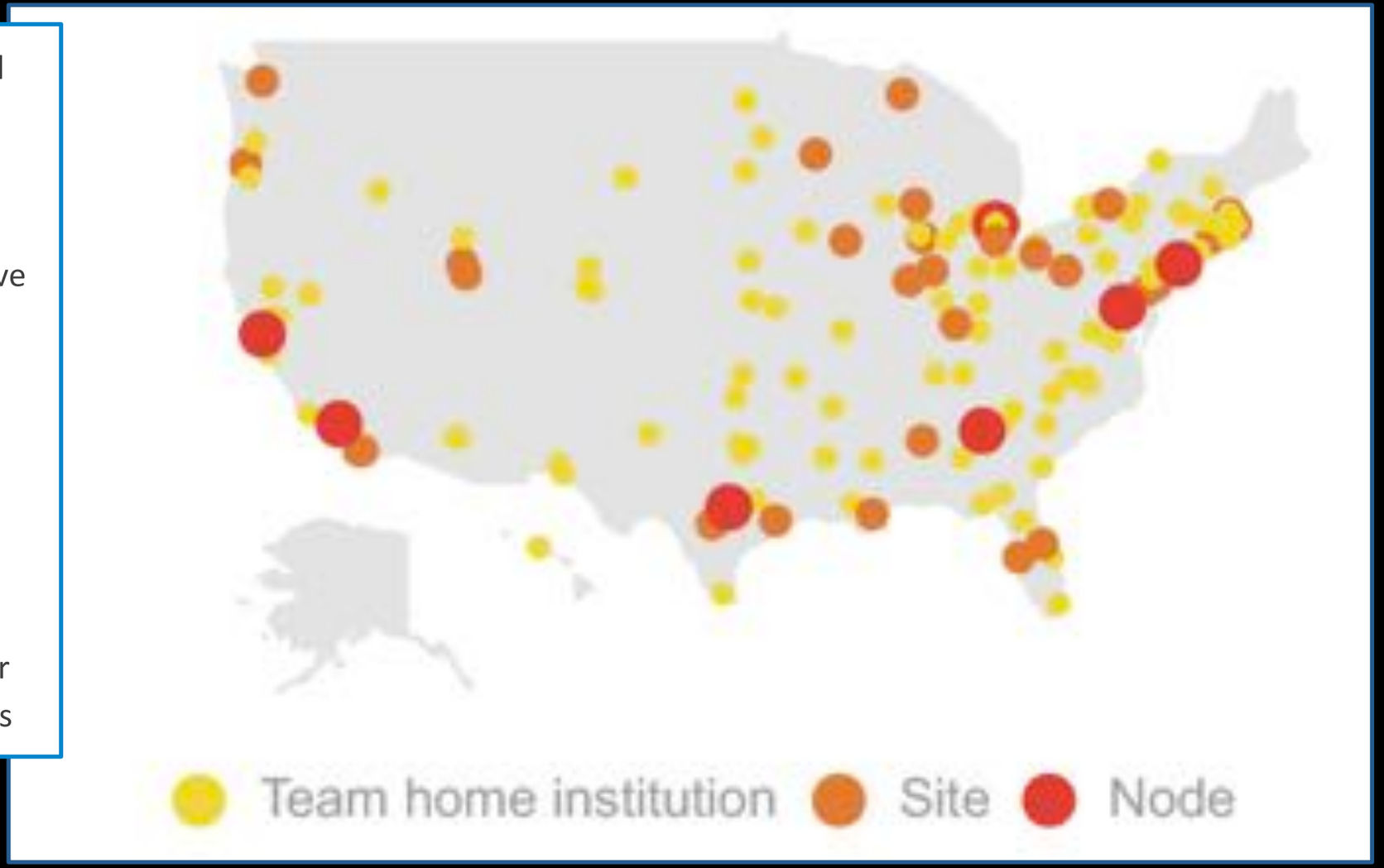
Research to Commercialization: NSF Programs



7 Nodes provide entrepreneurial learning environments and curriculum development

36 Sites leverage existing entrepreneurial activities

- More than **500 teams** and **1,600 people** have completed I-Corps™ training
- **261 I-Corps™ startups** have raised more than **$49 million in funding** from outside sources
- **176 teams** to date have reported new collaborations between their universities and industry, investors, and/or state or local governments



Technology and Employment

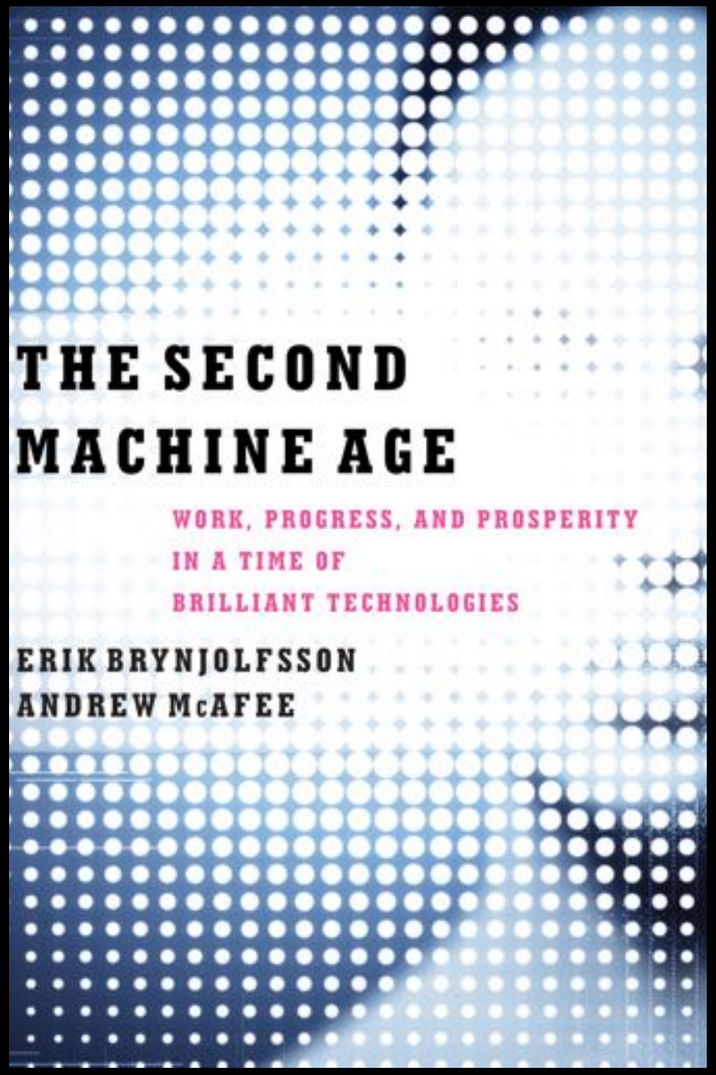


Image courtesy Erik Brynjolfsson and Andrew McAfee

THE FUTURE OF EMPLOYMENT: HOW SUSCEPTIBLE ARE JOBS TO COMPUTERISATION?,

Osborne and Frey, 2013, Oxford University

In this paper, we address the question: how susceptible are jobs to computerisation? … First, drawing upon recent advances in Machine Learning (ML) and Mobile Robotics (MR), we develop a novel methodology to categorise occupations according to their susceptibility to computerisation. Second, we … estimate the probability of computerisation for 702 detailed occupations, … impacts … on US labour market outcomes.

QUESTIONS?

IDEAS, THOUGHTS!

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