Opportunities in Engineering Research, Education and Innovation: A Perspective from NSF

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National Science Foundation

Carnegie Mellon University
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Outline

• Context, Drivers, and Trends
• NSF Engineering Budgets and Priorities
• Education Challenges
• Innovations Promise
• Broader Impacts and Grand Challenges
• Conclusions
“to promote the progress of science; to advance the national health, prosperity, and welfare; to secure the national defense…” NSF Act, 1950

Science offers a largely unexplored hinterland for the pioneer who has the tools for his task. The rewards of such exploration both for the Nation and the individual are great. Scientific progress is one essential key to our security as a nation, to our better health, to more jobs, to a higher standard of living, and to our cultural progress.
Investing in engineering research and education and fostering innovations to benefit society
Larger Context

• Employment and Wages:
  – Productivity, economic growth, competitiveness with a sustainability imperative

• Societal Problems:
  – Food, health, energy, water, security, education, infrastructure, …

• Globalization:
  – Flows of components, products, services, knowledge, and people

• People
  – Stubborn long-standing issues in STEM talent, diversity, and education
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 learning, robotics, AI

• Systems science and engineering
  – Multi-scale analysis, design, and optimization
  – Cyber-physical-social systems
  – Spatial range: nano- to micro- to macro-scale
  – 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, design, and manufacturing
  – Energy and sustainability applications

• Biological/biomedical frontier
  – 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/social sciences
  – Human behavior and game theory in engineered systems and technology design
  – Prominent role in infrastructure systems such as electric grid, transportation, water, gas
  – Economic, regulatory, policy issues

• Design, creativity, aesthetics, …
Directorate for Engineering

**Fundamental**
- CBET
  - Chemical, Biochemical, and Biotechnology Systems
  - Biomedical Engineering and Engineering Healthcare
  - Environmental Engineering and Sustainability
  - Transport and Thermal Fluids Phenomena
- CMMI
  - Advanced Manufacturing
  - Mechanics and Engineering Materials
  - Resilient and Sustainable Infrastructure
  - Systems Engineering and Design
- ECCS
  - Electronics, Photonics, and Magnetic Devices
  - Communications, Circuits, and Sensing Systems
  - Energy, Power, and Adaptive Systems

**Translational**
- EEC
  - Engineering Research Centers
  - Engineering Education
  - Engineering Workforce
- IIP
  - Academic Partnerships
  - Small Business Partnerships
ENG Budget ($M)

FY14 - $833M
FY15 - $892M
FY16(request) - $949M
ENG Research Awards to New and Prior NSF Researchers

<table>
<thead>
<tr>
<th></th>
<th>ENG Awards - prior</th>
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<th>ENG Funding Rate - new</th>
<th>ENG Funding Rate - all</th>
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<tr>
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<td>FY 2014 Est.</td>
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ENG Initiatives and Priorities Address National Interests

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

• 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
• Innovation Corps
“Advanced manufacturing is a family of activities that
(a) depend on the use and coordination of information, 
automation, computation, software, sensing, and networking, and/or
(b) make use of cutting edge materials and emerging capabilities enabled by the physical and biological 
sciences, for example nanotechnology, chemistry, and biology.
It involves both new ways to manufacture existing products, and 
the manufacture of new products emerging from new advanced 
technologies.”

President’s Council of Advisors on Science and Technology
Report to the President on Ensuring American Leadership in Advanced Manufacturing
Advanced Manufacturing – Key National Priority

• Strategic directions
  – Advanced biomanufacturing
  – Cybermanufacturing
  – Scalable nanomanufacturing

• PCAST Recommendation from AMP 2.0: mechanism for academic-industry input on future manufacturing technologies
  – Joint solicitation by NSF and NIST in 2015
  – Award to University of Michigan at Ann Arbor: MForesight – Alliance for Manufacturing Foresight

• I/UCRC in manufacturing
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
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
- Collaboration between ENG and MPS
Cyber-Physical Systems

- Cyber-physical systems (CPS) are engineered systems that are built from, and depend upon, the seamless integration of computational algorithms and physical components.
- NSF aims to develop the core system science needed to engineer complex cyber-physical systems upon which people can depend with high confidence.
National Robotics Initiative

- **Realization of co-robots**: robotic systems that serve as co-workers, co-inhabitants, co-explorers, and co-defenders

- **Collaboration among ENG, CISE, EHR, SBE, NASA, NIH, USDA in FY 2014, plus DOD and DARPA in FY 2015**
Understanding the Brain (UtB)

- Enable scientific understanding of the full complexity of the brain in action and in context
- ENG: Innovative neurotechnologies and tools, approaches, theories and models
  - Aligns with President’s BRAIN Initiative
- Integrative Strategies for Understanding Neural and Cognitive Systems (NCS)
  - Collaboration between ENG, CISE, SBE, and EHR
  - NSF provided $13M in FY 2015 for 14 projects
    - Neuroengineering and brain-inspired concepts and designs
    - Individuality and variation

Understanding how brain cells form may tell us how the structure of neural networks relates to their function. Shown here are young cells (red) two weeks into their transformation into neurons. Credit: Arun Mahadevan, Qutub Lab, Department of Bioengineering, Rice University
Engineering Biology

• Context
  – NSF investments in metabolic engineering and synthetic biology
  – NAS Report on Industrialization of Biology

• Engineering Biology: The ability to predict the behavior of and design complex biological systems

• 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
Critical Resilient Interdependent Infrastructure Systems and Processes (CRISP)

- Improve the resilience, interoperation, performance, and readiness of critical infrastructure
  - Advances knowledge of risk assessment and predictability
  - Supports the creation of novel tools, technologies, and engineered systems solutions for increased resilience
  - Enhances the understanding and design of interdependent critical infrastructure systems and processes

- Jointly supported by ENG, CISE, and SBE

Section of downtown Salt Lake City, Utah, following a simulated earthquake. Potential safe movement paths around debris are shown as multi-color ribbons. Credit: Paul M. Torrens, Geography and UMIACS, University of Maryland, College Park
Targeted Infrastructures in CRISP Awards

- Energy: 14 awards
- Transportation Systems: 12 awards
- Communications: 10 awards
- Water: 8 awards
- Information Technology: 6 awards
- Nuclear Reactors, Materials and Waste: 4 awards
- Healthcare and Public Health: 2 awards
- Government Facilities: 2 awards
- Defense Industrial Base: 2 awards
- Banking and Finance: 2 awards
- Chemical: 2 awards
- Commercial Facilities: 2 awards
- Critical Manufacturing: 2 awards
- Dams: 2 awards
- Emergency Services: 2 awards
- Food and Agriculture: 2 awards
- National Monuments and Icons: 2 awards
- Postal and Shipping: 2 awards
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
Large-scale Integration of Renewables into the Power Grid

• Create new foundational knowledge

• Provided $4M for 14 EAGER projects
  – System dynamics, stability and control methods
  – Electricity generation and demand scheduling
  – Market design
  – System protection
Cyber-Physical and Social - Bridging the Gap
Innovations at the Nexus of Food, Energy, and Water Systems (INFEWS)

• By 2050, world population projected at 9 billion and US population 400 million
• Greater demand for energy, water, and food
• Increased variability in precipitation and temperatures
• 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)

- FY 2015: SEES Food-Energy-Water workshops and research supplements
  - 17 workshops and 40 supplemental awards

- FY 2016: Proposed Launch of INFEWS
  - DCL on Nitrogen, Phosphorus, and Water (ENG and MPS)
  - INFEWS as an emphasis area for NSF Research Traineeship (NRT)
Graphene Oxide Membranes for Ionic and Molecular Sieving
Baoxia Mi, University of California, Berkeley

• Sieving membranes that enable fast solute separation from aqueous solutions are essential for water purification and desalination, sensing, and energy production.

A. Transport of ions and molecules in the GO membrane

B. Desalination or hydrofracking

Water, fuel, or chemical purification

Biomedical filtration

C. Vacuum filtration

Layer-by-layer assembly

Covalently bonded

Electrostatically bonded

Electrostatically or covalently bonded

Image courtesy Baoxia Mi, University of California, Berkeley
EFRI: Advancing Communications Quantum Information Research in Engineering (ACQUIRE)

• **Key Goal:** Address key engineering research challenges to enable secure, scalable quantum communication networks
  
  – Room temperature single photon sources, detectors, memories, repeaters and other low-energy photonic components
  – Scalable on-chip integration of quantum photonics with silicon electronics
  – Leveraging novel engineered materials, quantum structures, and devices
  – Potential impact on ultra secure communication network and other capabilities impossible to achieve with classical technology
EFRI: New Light & Acoustic Wave Propagation (NewLAW)

- **Key Goal:** Breaking symmetries and challenging fundamental laws governing wave motion and field transport
  - Disruptive approach to design of electronic, photonic and acoustic devices, and enabler of totally new functionalities
  - Acoustic technologies, such as soundproofing and sonar stealth systems, energy absorbing materials, and imaging
  - Integrated nanophotonic elements based on topological insulators, full-duplex wireless communications
Engineering Research Centers (ERCs)

• FY 2015: Launched 3 new ERCs
  
  - Compact mobile power
  - Nature-inspired soil engineering
  - Off-grid drinking water

  ERC for Power Optimization for Electro-Thermal Systems (POETS), led by the University of Illinois at Urbana-Champaign
  ERC for Bio-mediated and Bio-inspired Geotechnics (CBBG), led by Arizona State University
  Nanosystems ERC for Nanotechnology Enabled Water Treatment Systems (NEWT), led by Rice University

• New ERC Competition launched in August 2015, new awards in 2017
The Future of Center-Based, Multidisciplinary Engineering Research

• New award to NAS to study the future of center-scale research in engineering

• Key Questions:
  – What models might most effectively enable breakthrough engineering research and discoveries that require center-scale investment considering the convergence of physical science, engineering and life science?
  – What educational models of center-based engineering research programs are best suited to creating a more diverse, internationally aware, and flexible engineering talent pool that is capable of addressing complex, real-world problems?
  – What academic-industry partnership models might most effectively promote advances in use-inspired basic and translational research, accelerate technology commercialization, and strengthen the broader innovation ecosystem?
  – What metrics can be used to define successes and risks of such center programs?
Engineering Education and Workforce
Engineering Degrees

Bachelor’s Degrees by Gender, 2014

Male 80.1%
Female 19.9%

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<th>Year</th>
<th>Female</th>
<th>Male</th>
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<tbody>
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<td>19.5%</td>
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<td>19.3%</td>
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<td>18.1%</td>
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<tr>
<td>2008</td>
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<tr>
<td>2009</td>
<td>18.0%</td>
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<tr>
<td>2010</td>
<td>18.4%</td>
<td>81.6%</td>
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<tr>
<td>2011</td>
<td>18.9%</td>
<td>81.1%</td>
</tr>
<tr>
<td>2012</td>
<td>19.1%</td>
<td>80.9%</td>
</tr>
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</table>

Bachelor’s Degrees by Ethnicity, 2014*

White 65.9%
Asian-American 13.1%
Hispanic 10.1%
Black or Afr.-American 3.5%
Unknown 4.5%
Other 2.9%

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<tr>
<th>Ethnicity</th>
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<tbody>
<tr>
<td>Black or African American</td>
<td>5.3%</td>
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<td>4.9%</td>
<td>4.7%</td>
<td>4.6%</td>
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<tr>
<td>Hispanic</td>
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<td>6.6%</td>
<td>7.0%</td>
<td>8.5%</td>
<td>9.0%</td>
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<tr>
<td>Other</td>
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<td>8.5%</td>
<td>8.3%</td>
<td>8.9%</td>
<td>11.0%</td>
<td>1.2%</td>
<td>1.6%</td>
<td>2.0%</td>
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<td>Asian American</td>
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<td>12.2%</td>
<td>12.2%</td>
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<tr>
<td>White</td>
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Source: ASEE, By the Numbers, 11-47
Faculty Diversity

Percentage of Women Tenured/Tenure-Track Faculty by Discipline: 15.2%

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<tr>
<th>Discipline</th>
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<th>African-American</th>
<th>Asian</th>
<th>Hispanic</th>
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<td>10.6%</td>
<td>2.4%</td>
<td>20.9%</td>
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<td>11.3%</td>
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<td>2007</td>
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<td>2011</td>
<td>13.8%</td>
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<td>2013</td>
<td>14.5%</td>
<td>2.6%</td>
<td>25.2%</td>
<td>3.6%</td>
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<tr>
<td>2014</td>
<td>15.2%</td>
<td>2.5%</td>
<td>25.6%</td>
<td>3.9%</td>
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*Note: Includes faculty data from the University of Puerto Rico, Mayaguez and the Polytechnic University of Puerto Rico.

Percentage of Women Tenured/Tenure-Track Faculty by Level:

- All Faculty: 15.2%
- Full Professor: 10.2%
- Associate Professor: 18.0%
- Assistant Professor: 22.8%
Observations

• Engineering continues to have major issues with attracting women and URMs
  – It is trailing certain other fields of science
  – There are significant differences among engineering disciplines
• More progress wrt women at the doctoral level and junior faculty ranks
• Mechanical Engineering has become the largest major in engineering
  – ME lags engineering overall in diversity in % terms
  – Note: there has been an increase in raw numbers
  – ME shares this trait with EE, Comp Eng, Civil Eng, …

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

“Demography is destiny”
Auguste Comte
Questions to Ponder

• Models: What are the most successful models for change?
• Transferability: How can success at one institution be used to achieve success at another?
• Scaling: How can we scale successes to “move the needle” at the national scale?
• Culture: What is the role of culture – societal, academic, engineering, institutional – in rate of change?
• How can we make faster progress?
Where will the leadership for new visions and change in engineering education come from?

What we might we achieve together?
Engineering Education
Professional Formation of Engineers

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

• IUSE/REvolutionizing engineering and computer science Departments (RED)
  – Collaboration between ENG, CISE, and EHR
• Research in the Formation of Engineers
  – Evolution from Research in Engineering Education
• Research Initiation in Engineering Formation (RIEF)

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

• FY 2015
  – Stakeholders convened
  – Research synthesized

• FY 2016 Request: $15M
  – Launch Pilots
  – Ideas Labs and workshops
Engineering CAREER Awards for FY 2015

- $73M investment in the next generation of engineering early-career faculty
- 146 5-year grants at $500K each
  - 81 institutions in 36 states, including 16 EPSCoR states
  - 29% women and 9% under-represented minorities, according to available demographic data
  - 51% to new PIs
Research to Commercialization: NSF Programs

- Investors
- Industry
- Foundations
- Small Businesses
- Universities
- Valley of Death
Innovation Corps (I-Corps™)

- Immersive experiential entrepreneurial education
- Transformative experience for graduate students and faculty
- Continue to build the I-Corps network
- Next phase: Scaling via partnerships with other federal agencies, universities, state government and non-profit organizations

What has been done so far:
- ~500 I-Corps™ Teams
- ~45% started companies
- 37 I-Corps™ Sites
- 7 I-Corps™ Nodes
NSF Merit Review Criteria – Broader Impacts

• **Intellectual Merit**: The Intellectual Merit criterion encompasses the potential to advance knowledge;

• **Broader Impacts**: The Broader Impacts criterion encompasses the potential to benefit society and contribute to the achievement of specific, desired societal outcomes.

Broader Impacts – Institutional Approach

• “Just as institutions play an important role in facilitating research-related activities of their investigators, … such a role can extend to activities directed toward the broader impacts of the project as well.”

• What would be novel and/or creative about implementing broader impacts activities at an institutional level?

• How can engineering colleges and departments respond to this opportunity?
Possible Mechanisms

• Facilitation on campuses for BI formulations
• Leveraging complementary activities
• Alignment and coherence among BI activities and goals
• Together, these mechanisms have the potential to achieve results at scale
Role of Grand Challenges

• Grand challenges can be very useful in catalyzing major breakthroughs and advances
  – NAE Grand Challenges in Engineering

• Key characteristics:
  – Big impact
  – Ambitious yet achievable
  – Compelling vision
  – Right level of specificity

• How can the engineering research community use the grand challenge vehicle for big research achievements?
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? … drawing upon recent advances in Machine Learning (ML) and Mobile Robotics (MR), … a novel methodology to categorise occupations … susceptibility to computerisation. Second, … estimate the probability of computerisation for 702 detailed occupations, … impacts … on US labour market outcomes.

47% of US jobs are at risk
QUESTIONS?

IDEAS, SUGGESTIONS!

pkhargon@nsf.gov