Cyber-Physical-Social Systems and Resilient Infrastructures – A Perspective from NSF

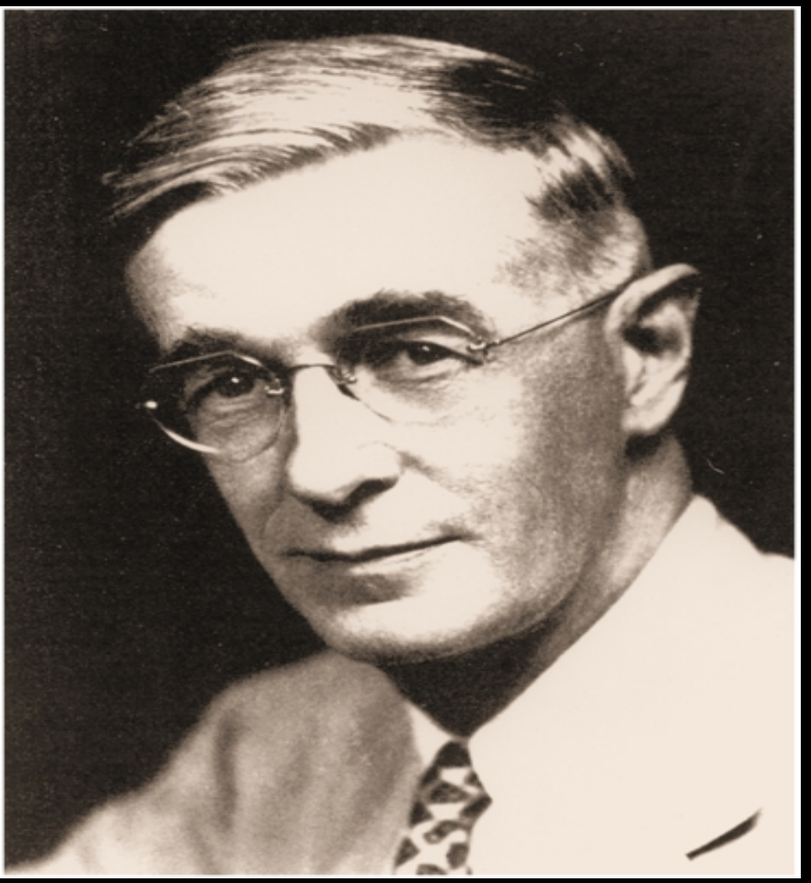
Pramod P. Khargonekar

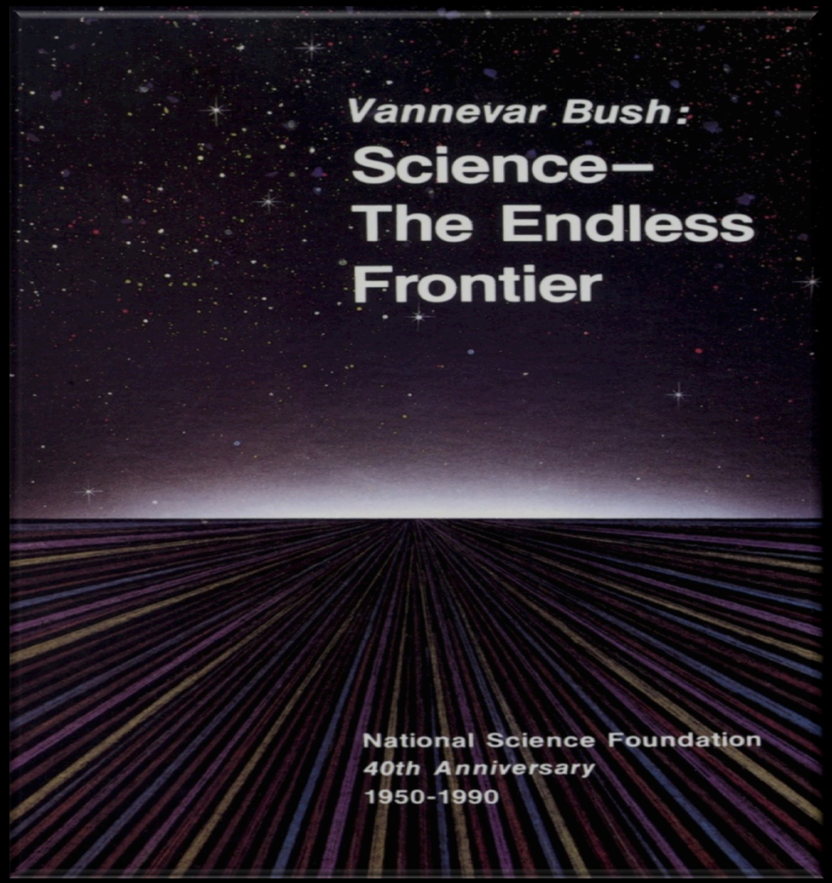
National Science Foundation
Assistant Director *for*
Engineering Directorate

HMNII Workshop
October 5, 2015
KAUST, Saudi Arabia

Outline

- NSF Overview
- Context
- Key Programs and Project Highlights
- Conclusions





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.

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

Image courtesy MIT Museum

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National Science Foundation
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TEL: 703.292.5111 | FIRS: 800.877.8339 | TDD: 800.281.8749

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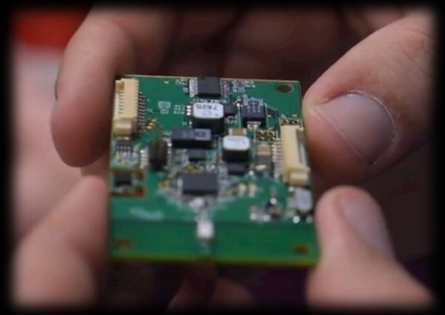
NSF ENG

Investing in engineering research and education and fostering innovations to benefit society



Directorate for Engineering

Fundamental

EFRI

CBET
- Chemical & Biochemical Systems
- Bioengineering and Engineering Healthcare
- Environmental Engineering and Sustainability
- Transport, Thermal, & Fluid Phenomena

CMMI
- Advanced Manufacturing
- Mechanics and Engineering Materials
- Resilient and Sustainable Infrastructure
- Operations Design and Dynamical Systems

ECCS
- Electronics, Photonics, and Magnetic Devices
- Communications, Circuits, and Sensing Systems
- Energy, Power, Control and Networks

EEC
- Engineering Research Centers
- Engineering Education
- Engineering Workforce

Translational

IIP
- Academic Partnerships
- Small Business Partnerships

ENG R&RA Budget ($M)

	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%

Context

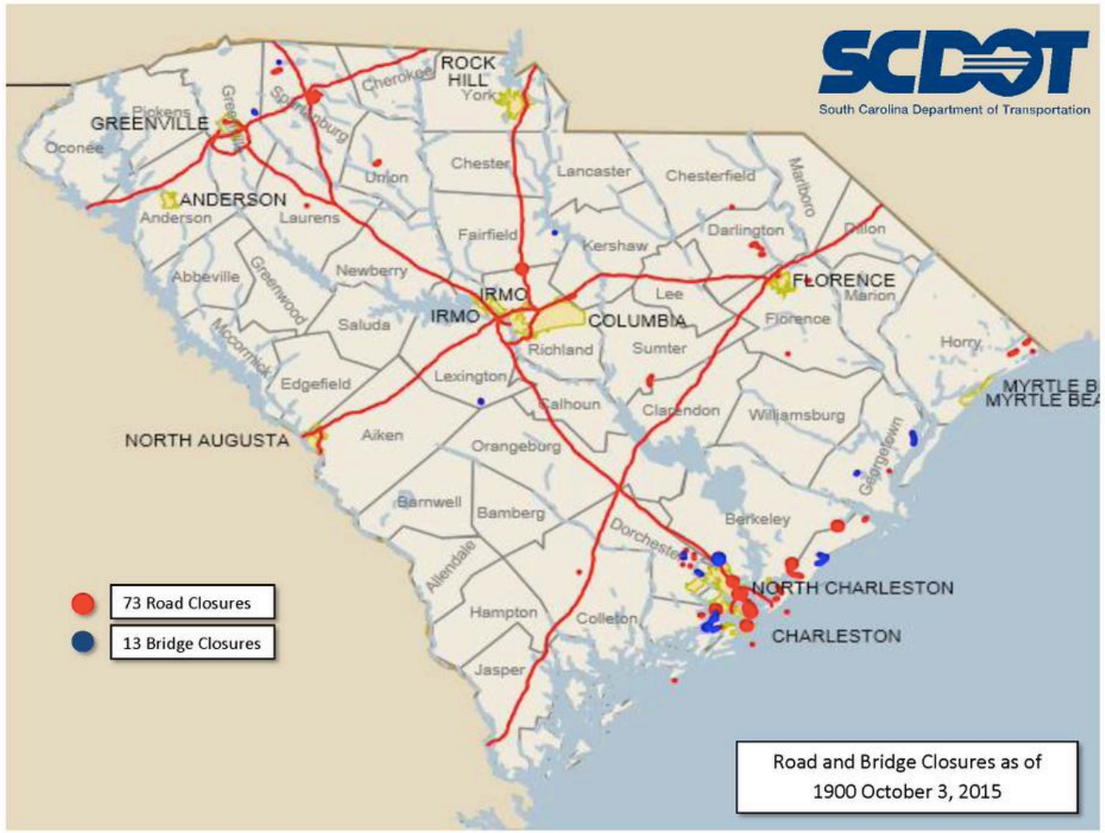
Critical Infrastructures are a mainstay of the national economy, security and societal functioning

Critical Infrastructure Sectors

Source: DHS

Critical Infrastructure and Extreme Events

- In the U.S. and much of the world, these infrastructures are
  - Aging
  - Operating at capacity limits
  - Often vulnerable due to their locations, e.g. in floodplains, along fault lines, proximate to urban areas vulnerable to malicious attack
- Each hurricane or storm sends us a stark reminder of the vulnerability of these infrastructures to extreme events
- Also vulnerable to man-made events



Paradigm Shift:
Infrastructure as a (Cyber-Enabled) *Service*

The Service Economy

Last updated: January 24, 2013 6:27 pm

Xerox says shift to services is paying off

By Anjli Raval in New York

Medtronic's Ishrak outlines health services expansion plans

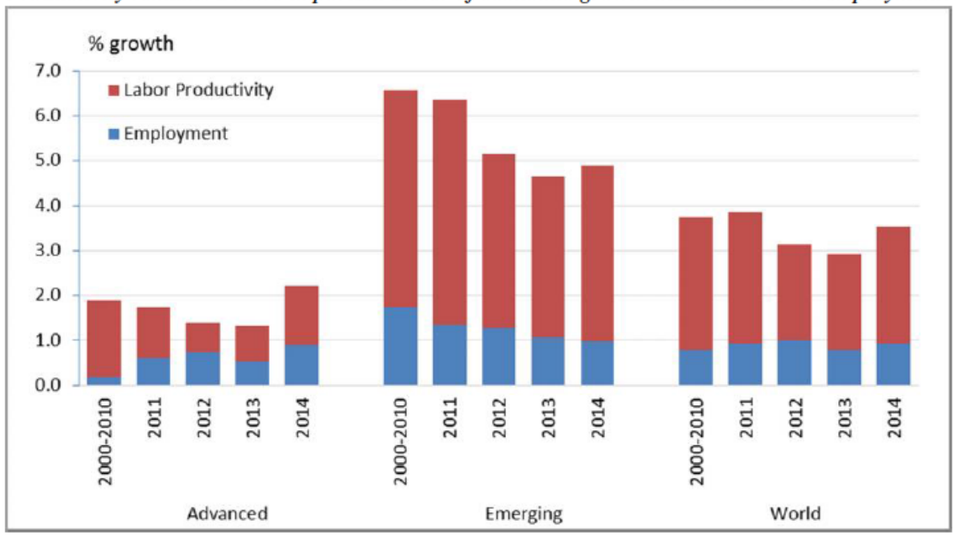
August 21, 2013 | By Mark Hollmer

- The U.S. service sector is responsible for:
  - Employing approximately 80% of workers
  - Creating approximately 80% of GDP
- Manufacturing (product) industries are increasingly incorporating value-added service components
- We need high-quality, low-cost, and highly personalized solutions in education, healthcare, manufacturing, transportation, and agriculture.

Productivity and Economic Growth

Chart 3: Percentage Contribution of Employment and Labor Productivity to Global Growth

Productivity remains a more important driver of economic growth than increases in employment.



Source: The Conference Board *Total Economy Database*™, January 2014

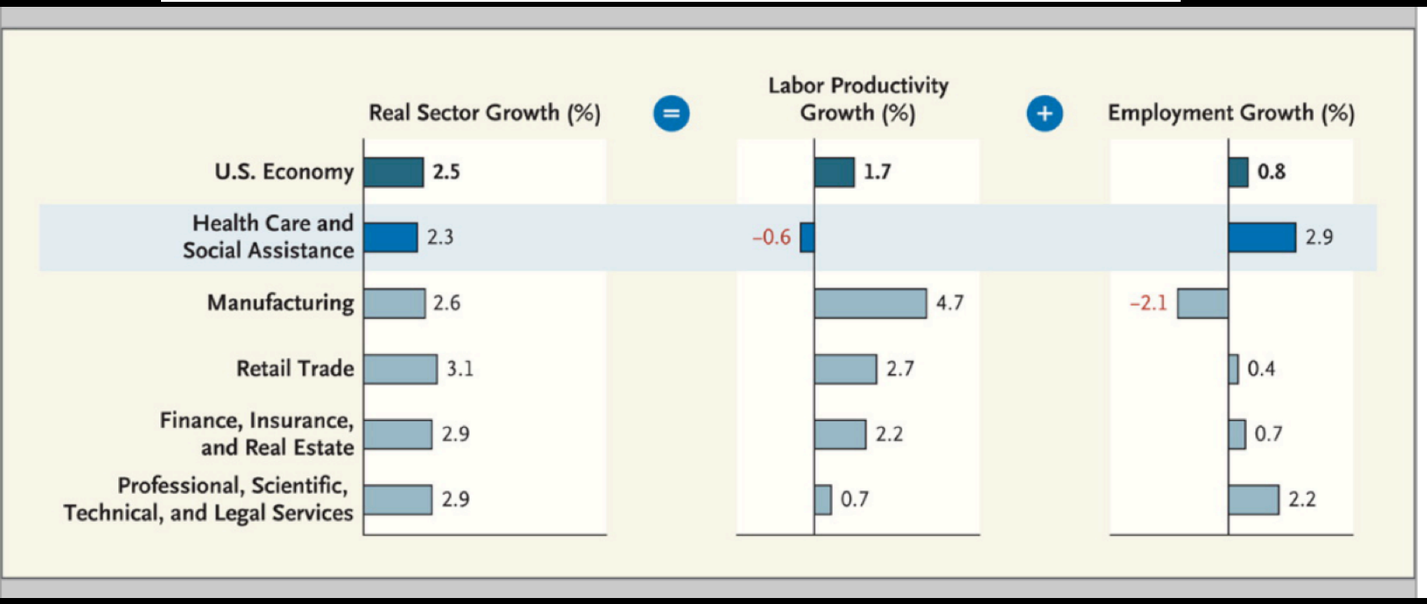
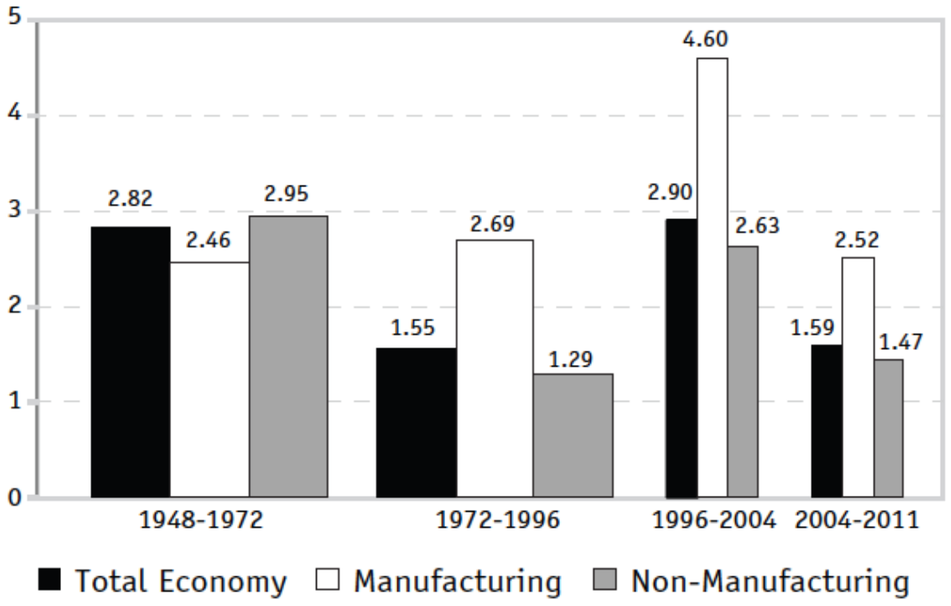


Chart 1

Output per Hour in the United States, Total Economy and Selected Sectors, 1948-2011

(average annual rate of change, per cent)



Source: BLS and BEA

Real Sector Growth (Compound Annual Growth Rate), Broken into Labor Productivity Growth and Employment Growth in Various Sectors of the U.S. Economy, 1990–2010.

Source: Gordon, International Productivity Monitor, Spring 2013

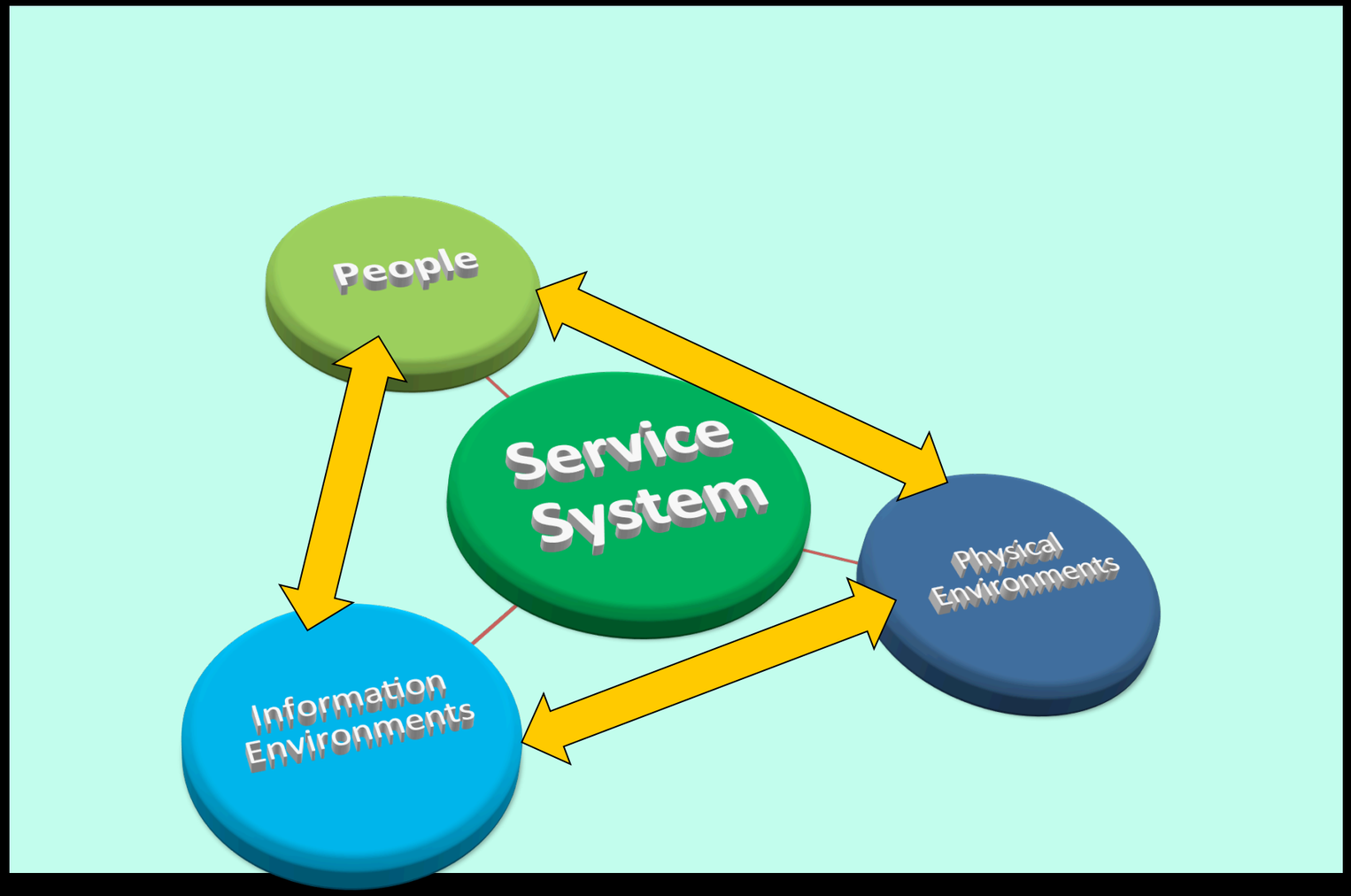
Source: Kocher and Sahni, N Engl J Med, October 2011

"Manufacturing is performing a magnificent ballet on a shrinking stage."

-Robert Gordon

Service System – A Working Definition

A cyber-physical-social system



A system for human interactions with physical and informational environments mediated by advanced technologies to add value

The Second Machine Age

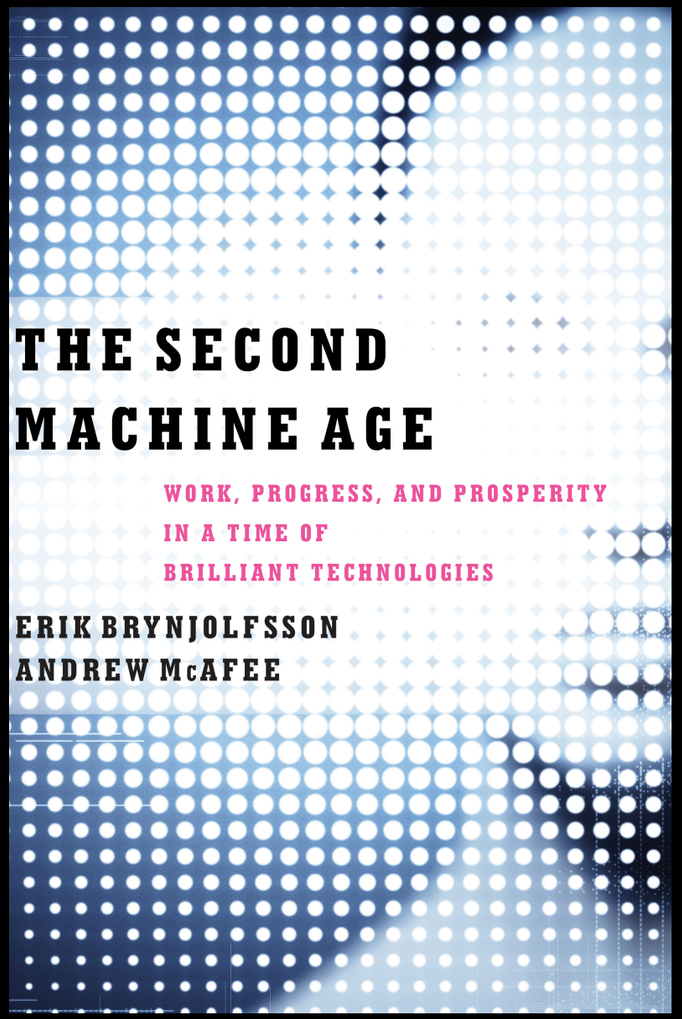


Image courtesy Erik Brynjolfsson and Andrew McAfee

"In short, we're at an inflection point—a point where the curve starts to bend a lot—because of computers. We are entering a second machine age."

Advanced Manufacturing – A National Priority

"But in most of the firms in which we carried out our research the traditional line between "manufacturing" and "services" has become so blurred that it no longer serves to distinguish separable and distinct activities or end products."

- MIT PIE Report

"The Internet of Things has already set in motion the idea of a fourth industrial revolution—a new wave of technological changes that will decentralize production control and trigger a paradigm shift in manufacturing."

-Markus Löffler, McKinsey

Retail Revolution under Way

Article | *McKinsey Quarterly*

When Toyota met e-commerce: Lean at Amazon

Amazon's former head of global operations explains why the company was a natural place to apply lean principles, how they've worked in practice, and where the future could lead.

February 2014 | by Marc Onetto

"Given the business evolution of Amazon from a bookstore to the store for everything, we had to reinvent automation, following the lean principle of "autonomation": keep the humans for high-value, complex work and use machines to support those tasks."

Programs and Project Highlights

FY14: Resilient Interdependent Infrastructure Systems (RIPS)

- To enhance understanding and design of interdependent critical infrastructure systems and processes resilient in the face of disruptions and failures from any cause
- ENG, CISE, and SBE funded 10 projects for $17M in FY 2014

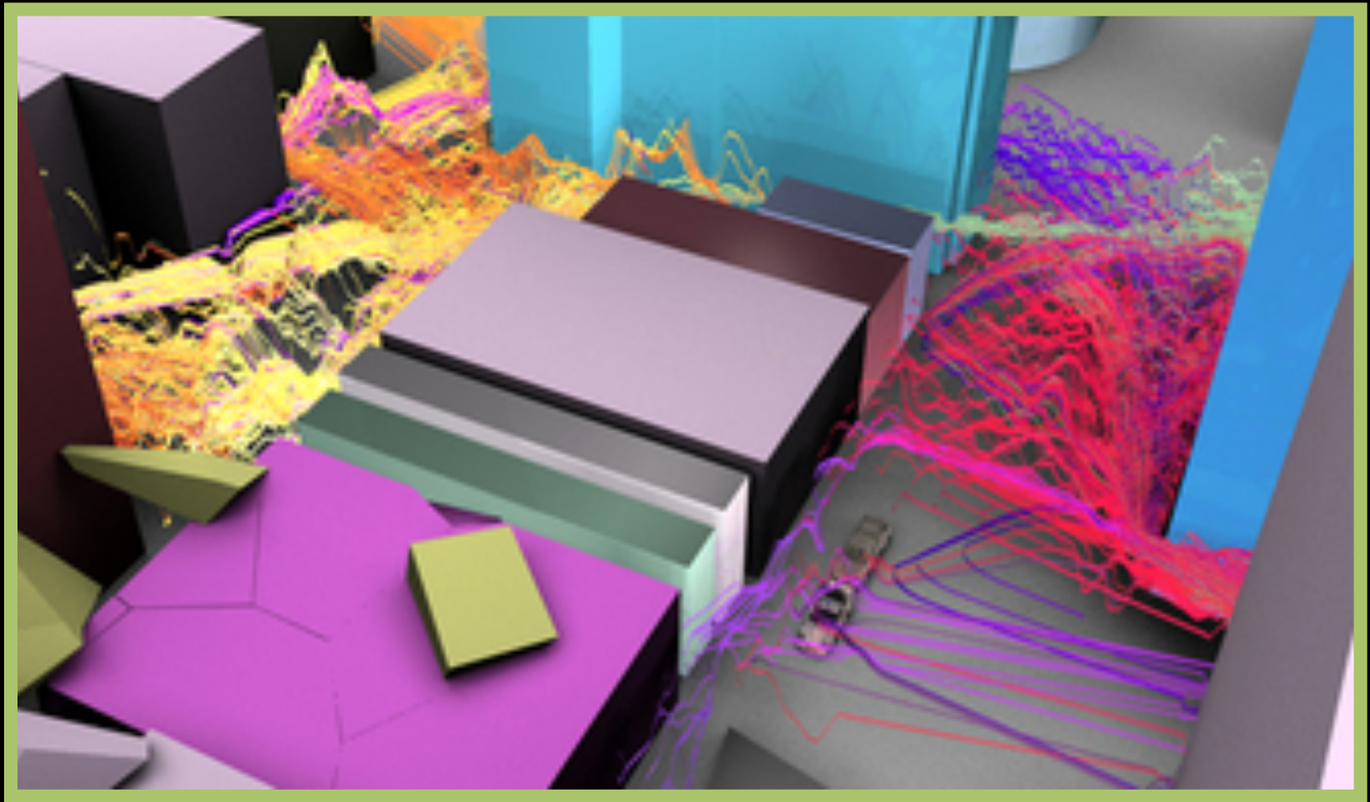
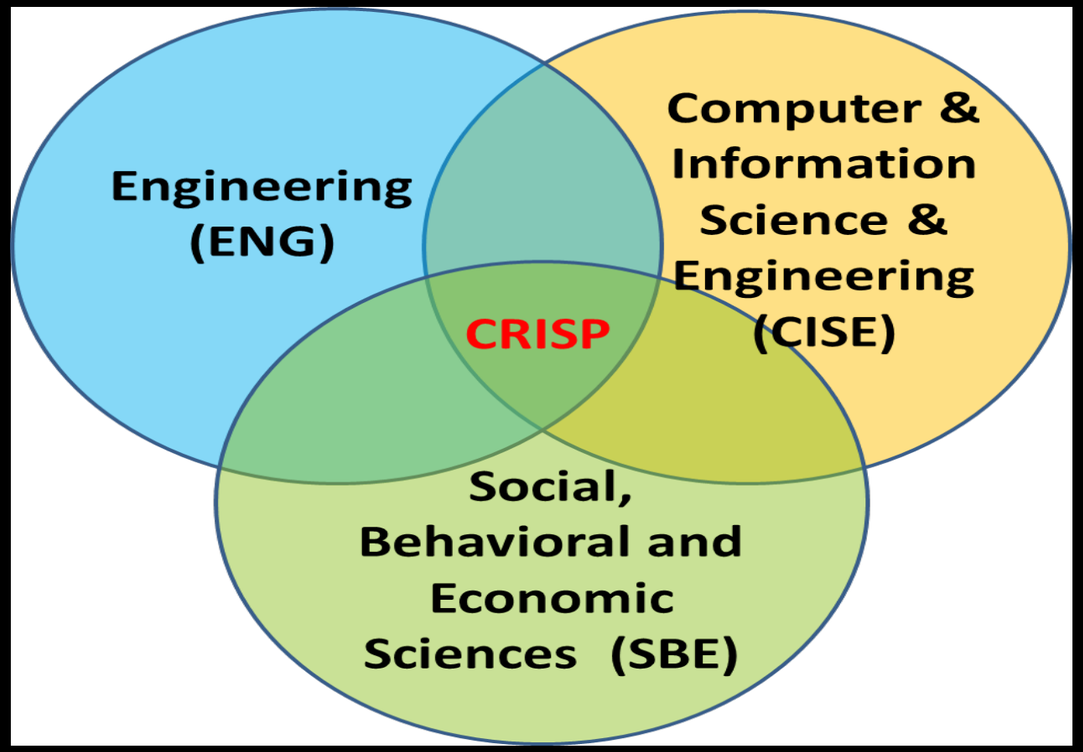


Image credit: Paul M. Torrens, Geography and UMIACS, University of Maryland, College Park

http://www.nsf.gov/news/news_summ.jsp?cntn_id=132852&org=NSF&from=news

FY15 CRISP: Critical Resilient Interdependent Infrastructure Systems & Processes

- FY15 funding for CRISP: $20 million
  - *Type 1 Awards*: 3-year projects, $500k max
  - *Type 2 Awards*: 3-4 year projects, $1M-$2.5M



Emphasis on Multi-disciplinarity

- Engineering
- Computing
- Social and behavioral sciences

Interdependent Critical Infrastructure Systems (ICIs)

- Infrastructures are viewed as:
  - as networks of systems and processes
  - that function collaboratively and synergistically
  - that produce & distribute continuous flow of essential goods & services
  - as interdependent and connected

Interdependencies

- Dependencies
  - Direct, indirect, disjunctive (depends on >1 node) and conjunctive (depends on one of two nodes) dependencies
- Interdependencies
  - Physical (e.g. through materials flows)
  - Cyber
  - Geographic
  - Logical (e.g. substitutability, shared resources)

  →Existence of feedback loop distinguishes from dependencies
- Failures can propagate from one system to the next due to these interconnectivities

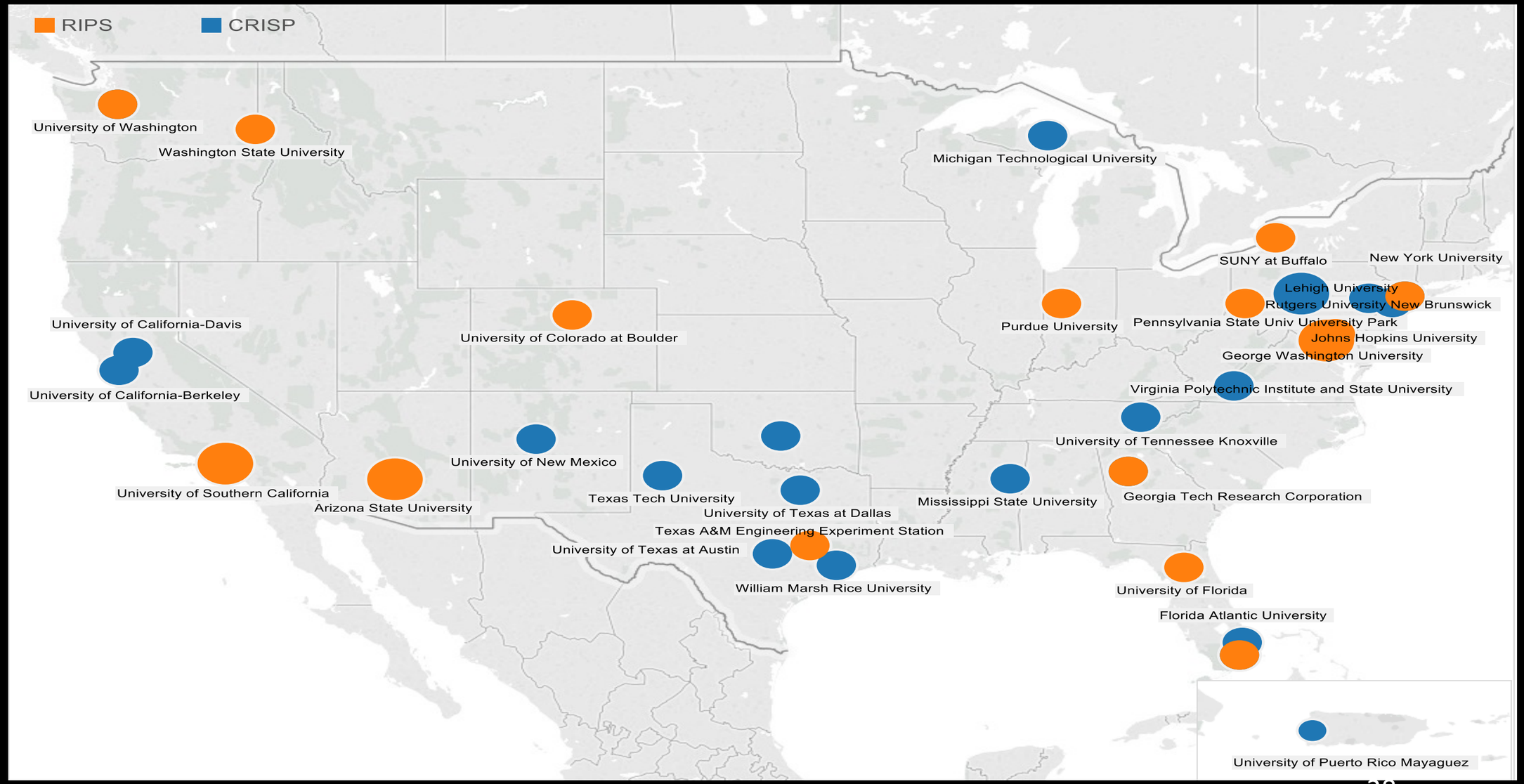
Resilience – the Concept

- Resilience as a term has taken on many meanings
- Common to most resilience definitions are two components (DHS):
  1) Ability to withstand disruption event with little loss in function
  2) Rapidly and efficiently restore functionality if loss incurred
- Many measures have been proposed:
  - Some focus on <u>time to recovery</u>
  - Others focus on <u>loss</u>: post-event performance over time, or after some elapsed time

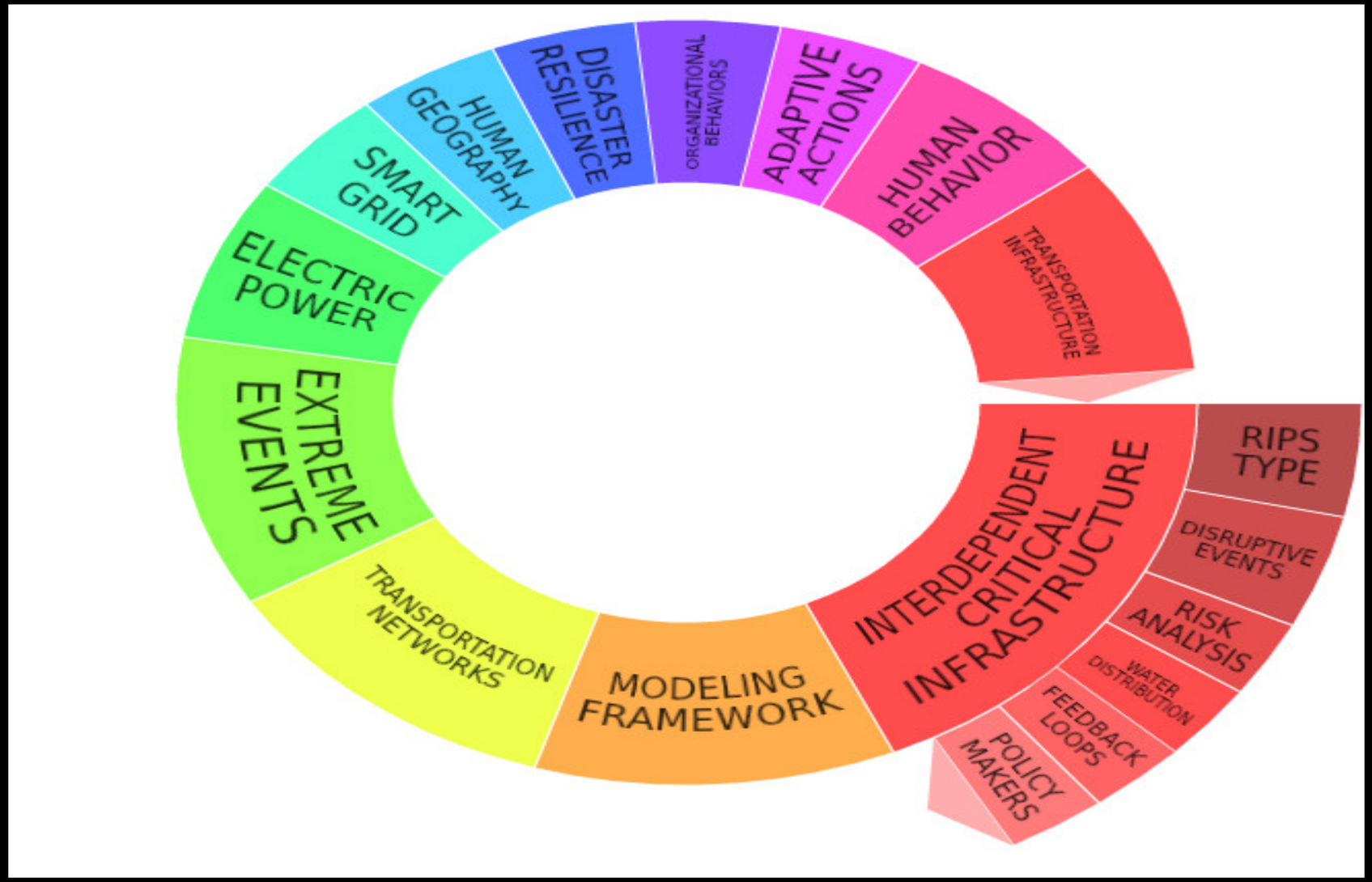
CRISP Program Goals

1. Create new approaches/solutions for design/operation of infrastructures as processes/services
2. Enhance understanding/design of ICIs and processes under disruptions from any cause
   - natural, technological, organizational or malicious
   - various timescales and intensities
3. Create knowledge for innovation in ICIs to safely, securely, and effectively expand range of goods and services they enable
4. Improve ICI's effectiveness, efficiency, dependability

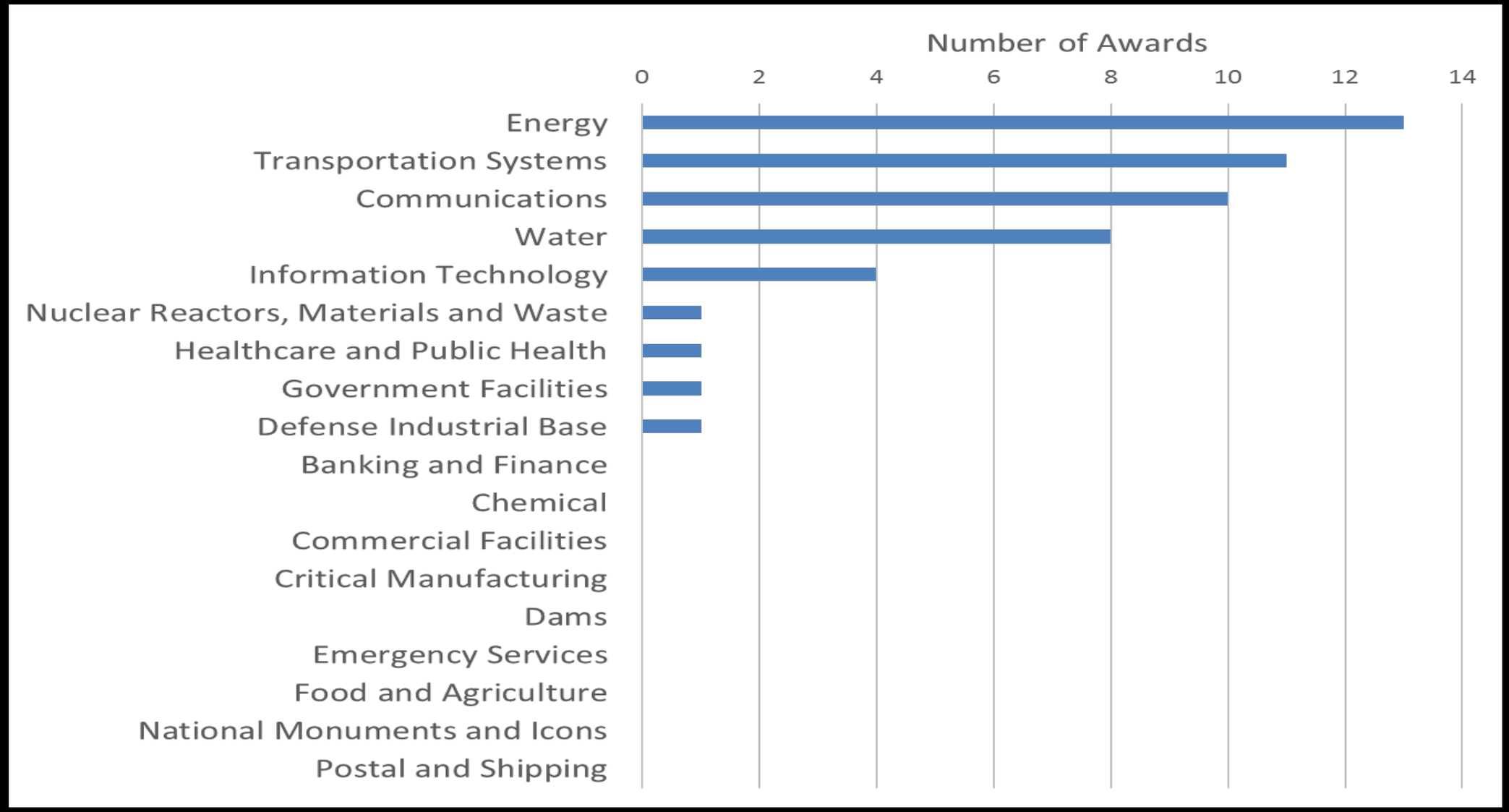
2014 RIPS and 2015 CRISP Awards



RIPS and CRISP Awards Topics



Targeted Infrastructures in the Awards



CRISP Proposed Research Topics

- Water-Energy-Food Nexus
- Urban/Rural Infrastructure Resilience
- Autonomous Transportation Systems
- Smart Grid
- Alternative Energy
- Crowd-sourcing
- Community Resilience
- Climate Change
- Attack Scenarios

Methodological Approaches in the Awards

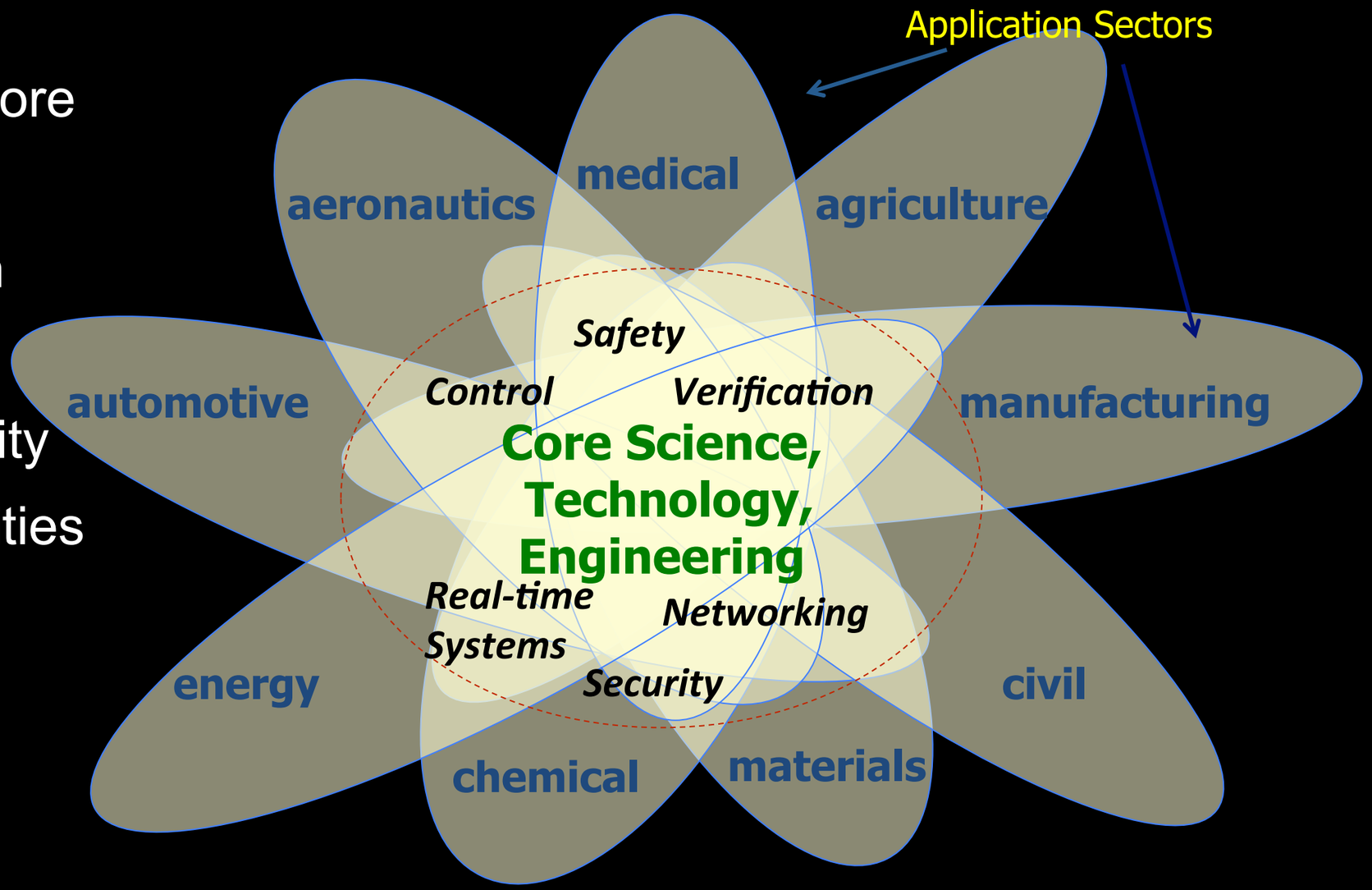
1) **Mathematical Modeling and Optimization**: graph theory; network models; stochastic and nonlinear optimization and modeling; Markov modeling; Bayesian networks; queueing theory; algorithms and heuristics; control theory; game theory; artificial intelligence
2) **Simulation**: agent-based approaches – both for discovery and validation

Methodological Approaches in the Awards

3) **Statistical**: statistical inference (correlation, regression, clustering, natural language processing); expert opinion; attitudinal studies; community surveys; time-geography theory; machine learning; network formation for social networks; behavioral studies of humans;…
4) **Reliability and systems modeling**
5) **Systems of systems and explanatory sciences**

Cyber-Physical Systems Program

- Abstract from sectors to more general principles
- Apply these to problems in new sectors
- Build a new CPS community
- Encourage other communities to join



CPS In Context

IoT

Low-cost sensors, MEMs, low power, 5G, …

National Priorities

Energy, health care, advanced manufacturing, …

CPS

Industrial Interests

commercialization, monetization, standards, consortia, …

S&T Advances

machine learning, big data, control, sociotechnical systems, advanced materials…

IoT Core Technologies

- Security and Privacy
- Energy Management
- Real-time computing
- Sensors and Actuators
- Wireless Networking
- Signal Processing
- Sensing and Control
- Mobile Computing
- Big Data

Imagine a (cyber-physical-social) future …

Credit: Nicolle Rager Fuller, NSF

Cyber-Physical and Social - Bridging the Gap

1548501: Neville Hogan and Dagmar Sternad; MIT & NEU

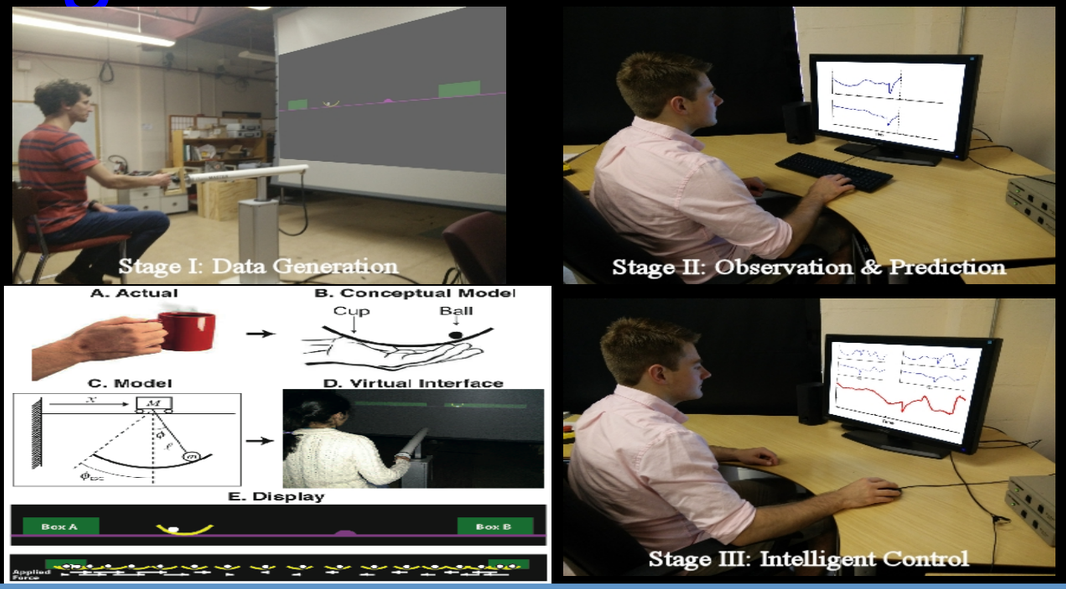
EAGER: Challenging the Cognitive-Control Divide

MAIN OBJECTIVES/IDEAS:

Human observation, prediction and control of complex systems is based on *dynamic primitives* of motor behavior

INTERDISCIPLINARITY:

A model of cognition for complex system control requires experimental psychology and applied control theory



WHAT DOES SUCCESS LOOK LIKE:

Subjects predict structure in data better and faster when it is composed of dynamic primitives of motor behavior

WHAT NEXT:

Develop controller design methods to mimic human-based dynamic primitives in complex system behavior

TRANSFORMATIVE OUTCOME:

Identification of best 'basis functions' for quantitative engineering models of human observation, prediction and control of complex systems

A common theoretical framework for cognition and control based on motor system dynamic primitives

1549723: David Woods and Anuradha Annaswamy

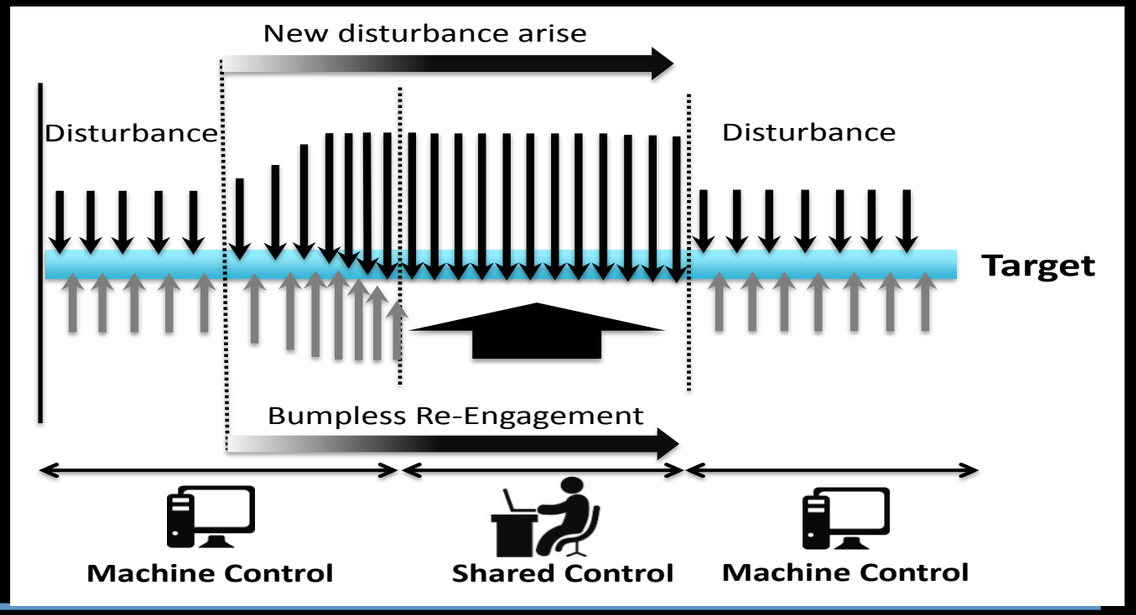
EAGER: Bumpless Re-Engagement in Shared Control

MAIN OBJECTIVES/IDEAS:

Introduce a new form of adaptive control that reduces risk of decompensation when anomalies cascade via more effective human-automation coordination.

INTERDISCIPLINARITY:

- Apply cognitive engineering/science to anomaly response for autonomous critical digital services.
- Extend the boundaries of automated services by utilizing adaptive control theory.



WHAT DOES SUCCESS LOOK LIKE:

Triggering timely and smooth human re-engagement in shared control to reduce risk of decompensation when anomalies cascade.

WHAT NEXT:

Generalize the results to safety-critical systems, cyber-security, energy, and transportation systems with highly autonomous

TRANSFORMATIVE OUTCOME:

- Extend models of human perception, cognition and action for supervision of highly autonomous processes during anomaly response.
- Combine above with adaptive control theory in a new architecture for dynamic shared control in human-automation systems that measurably reduces the risk of decompensation.

1548417: Mary Cummings and Kris Hauser; Duke

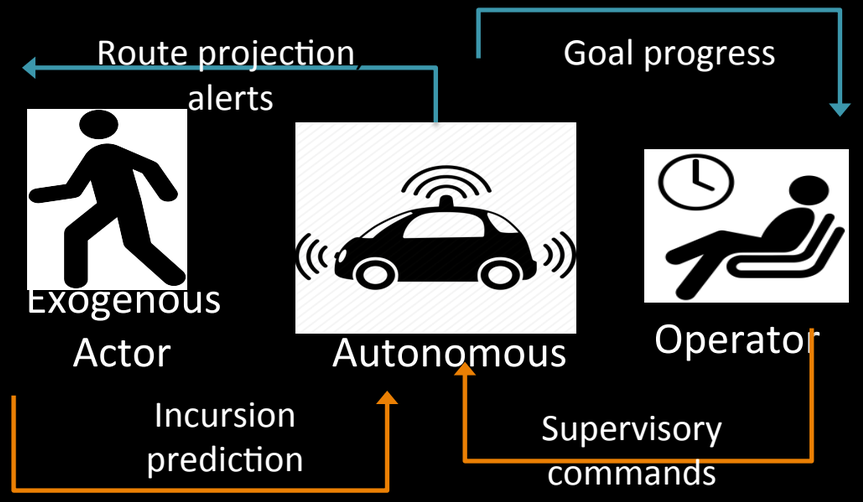
EAGER: Modeling Intent Communication Pathways for Human-Autonomous System Collaboration

OBJECTIVE:

Explore reciprocal relationships in the communication of intent between humans and autonomous systems

INTERDISCIPLINARITY:

Combines research in computer vision, robot motion planning, human-computer interaction, cognitive psychology and kinesiology



WHAT DOES SUCCESS LOOK LIKE:

A set of methods to communicate system intent among the system and stakeholders, validated by models

Extend the models to other domains such as manufacturing that could benefit from increasing autonomy to identify generalizable interaction

TRANSFORMATIVE OUTCOME:

Using models of human and automation performance, identify new design guidelines for safe autonomous systems that have awareness of the intent of humans in and around the system, with reciprocal relationships for those same humans

1548234: Erin MacDonald and John Duchi; Stanford

EAGER: Using Learning Algorithms to Morph Product Behavior for Specific Task Contexts and Cognitive Styles of Users

MAIN OBJECTIVE:

Create a design method that uses morphing algorithms to generate customized product behavior in response to the user's cognitive style and task at-hand.

INTERDISCIPLINARITY:

Combining research on:

- Cognitive Style (Psychology and Marketing)
- Morphing, Inverse Optimal Control (Machine Learning)
- Design Methods, Sensor Data (Engineering Design)

	Tasks	Calculations
Calibration Prior to in vivo morphing ~200 test subjects	1. Measure cognitive styles & task preferences to establish segments.	1. Assign users to a cognitive-style segment.
	2. Observe users w/ **sensors**, collect data on each segment.	2. **Calibrate** model to infer user's segment from sensor
Operation In vivo faucet General population	1. Observe a user w/sensors. Use model to **infer user's latent cognitive style** segment.	1. Calculate user's cognitive style probabilities for each latent segment.
Exploration / **Exploitation**	2. Observe user's manual **feedback** (temperature, flow, timing). **Update** model for each segment and design behavior.	1. Index value for each segment X design combination after the nth use.
	3. **Design** to best product **behavior** using latent segment probabilities and indices.	3. (Near-) optimal assignment of a morph to the nth use to balance exploration and exploitation.

WHAT DOES SUCCESS LOOK LIKE:

Faucet (product) flow and temperature (behavior) set precisely as a person would have adjusted it themselves (cognitive style and task) in a simulation study.

WHAT NEXT:

Apply model in real-world experiments, reducing water use for daily tasks.

TRANSFORMATIVE OUTCOME:

Moving from "smart" products, that are in reality not very smart, to "telepathic" products that can seemingly read one's mind. These telepathic products will be capable of predicting, testing, and potentially changing a user/ product interaction, with help from a model that links product behavior and user's cognitive style.

1547864: Maurizio Porfiri and Oded Nov; NYU

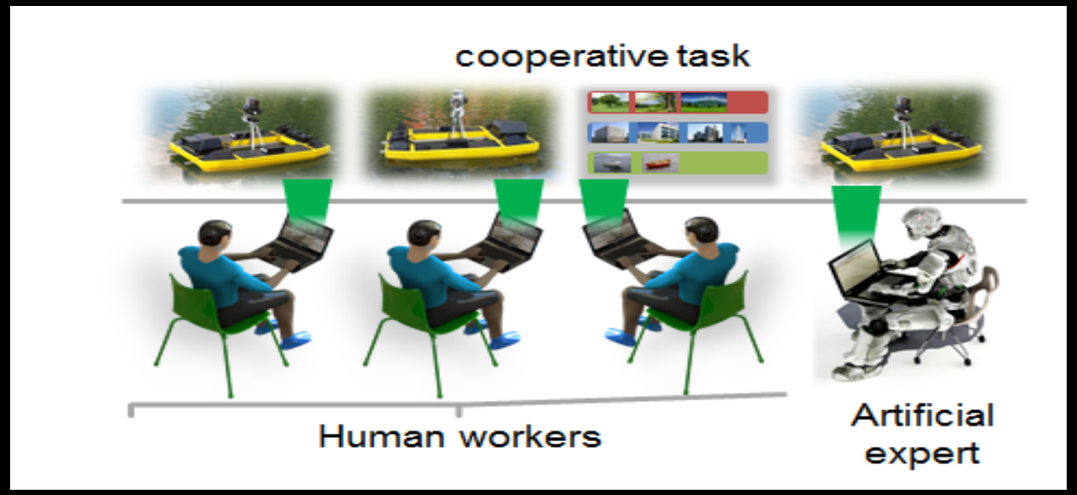
EAGER: Dynamics of collaboration between humans and engineered systems: system design for collective expertise

MAIN OBJECTIVES/IDEAS:

Humans learn and develop new skills (evolve), which can determine the performance of collaborative human-engineered systems.

INTERDISCIPLINARITY:

This effort will leverage social computing and dynamical systems theory to advance collaboration between humans and engineered systems.



WHAT DOES SUCCESS LOOK LIKE:

A validated network-based model of human collaboration for exploring interactions between humans and engineered systems

WHAT NEXT:

These results will lay the foundation for informing the design of next-generation human-engineered systems, towards enhanced performance through engineered

TRANSFORMATIVE OUTCOME:

A framework for understanding, predicting, and ultimately, controlling the evolution of the collaboration between humans and engineered systems.

1548521: Babak Heydari and Susan Mohammed; Stevens Institute of Technology

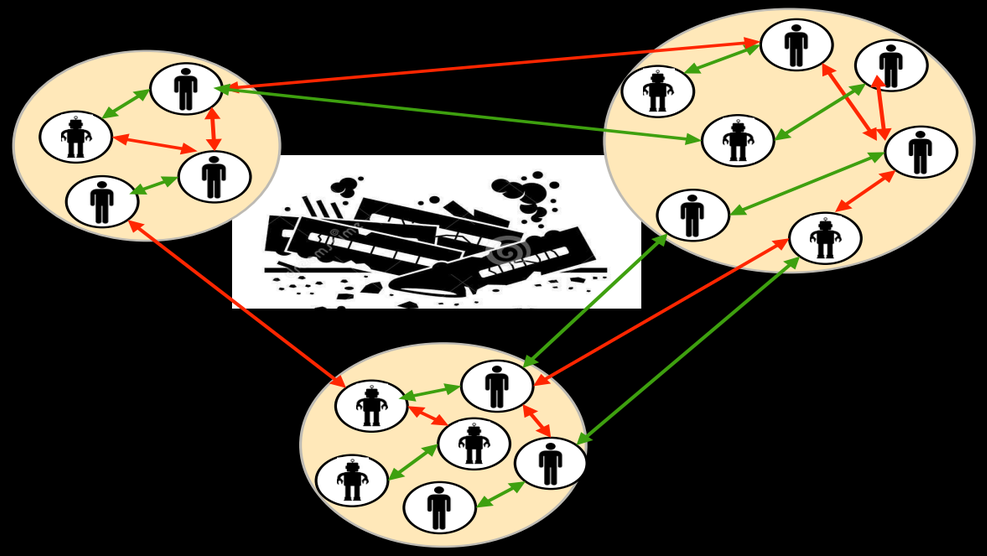
EAGER: Hybrid Socio-Technical Teams: A Theoretical Framework for Modeling and Design of Hybrid Networks of Human and Autonomous Agents

MAIN OBJECTIVES/IDEAS:

Fundamental research for understanding dynamics, behavior, and coordination mechanisms of human-agent networks.

INTERDISCIPLINARITY:

Combine multi-agent computational methods such as complex network analysis and game theory with social psychology of team behavior



WHAT DOES SUCCESS LOOK LIKE:

Parametric, context-dependent, analytical and computational models to understand how team-level coordination and cooperative behavior are affected by composition of team members, communication network structure, distribution of humans and machines on networks nodes, and the environment.

WHAT NEXT:

A long term research plan on:

1) Architecture of human-agent structure
2) Methods for analysing collective behaviour of human-agent systems

TRANSFORMATIVE OUTCOME:

This project will result in improved understanding of the behavior of human-agent networks, and hence more efficient design of future intelligent systems for disaster response, energy and transportation, all of which will in the future rely on efficient, dynamic coordination between a group of people and a network of autonomous agents.

1548502: Maja Mataric, Shinyi Wu and Liz Zelinski, Univ. of Southern California

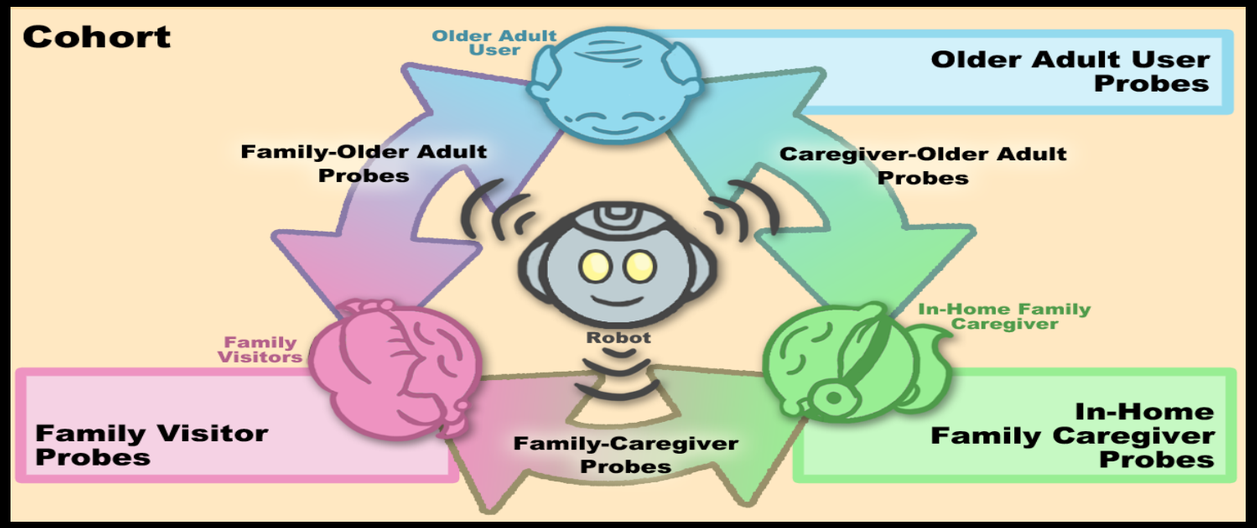
EAGER: Studying the Dynamics of In Home Adoption of Socially Assistive Robot Companions for the Elderly

MAIN OBJECTIVES/IDEAS:

Robot that actively observes and facilitates family dynamics in the context of in-home elder care

INTERDISCIPLINARITY:

Algorithm and engineered system development informed by user experience, gerontology, social psychology



WHAT DOES SUCCESS LOOK LIKE:

Evaluation study users refuse to return the robot. Robot is able to maintain engaging interaction resulting in positive outcomes in objective and subjective measures.

TRANSFORMATIVE OUTCOME:

Develop engineered system and data driven quantitative models of human-machine interaction in the home that inform the design of next generation in-home robots that facilitate positive interactions among family members under otherwise stressful eldercare circumstances.

1548394: Parikh, Flach, and Wischgoll (Wright State) and Gue (University of Louisville)

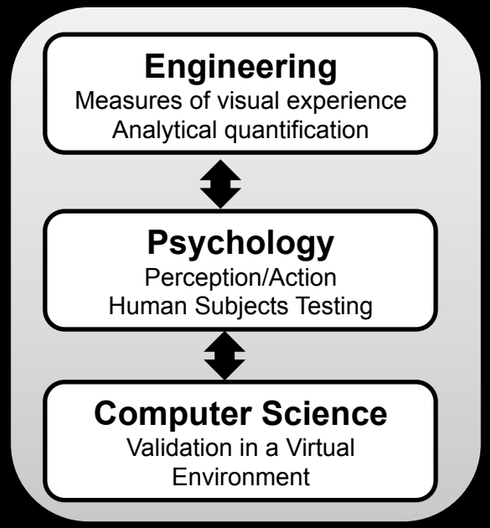
EAGER: A New Science of Visual Experience

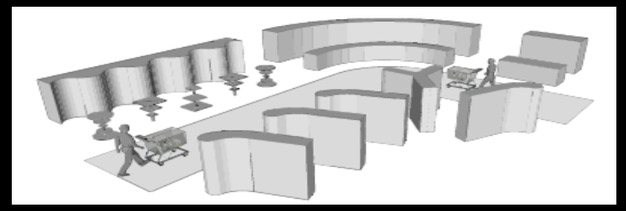
MAIN OBJECTIVES/IDEAS:

Develop an analytical language to model visual experience in 3D environments

INTERDISCIPLINARITY:

Engineering: Analytical modelling
Psychology: Perception/action phenomenon
Computer Science: Virtual environment for validation with human subjects





WHAT DOES SUCCESS LOOK LIKE:

Analytical quantification of measures of visual experience across one or more specific 3D environments, validated via human subjects testing in a virtual environment

WHAT NEXT:

Generalize our analytical framework to design a generic 3D environment, with consideration for bidirectional human-machine interaction

TRANSFORMATIVE OUTCOME:

Project will serve as the foundation towards developing a *universal set* of analytical models that emerge from analysis of a variety of context-specific human-environment interactions that form the basis for visual experience when designing 3D environments

1548616: Neera Jain & Tahira Reid; Purdue

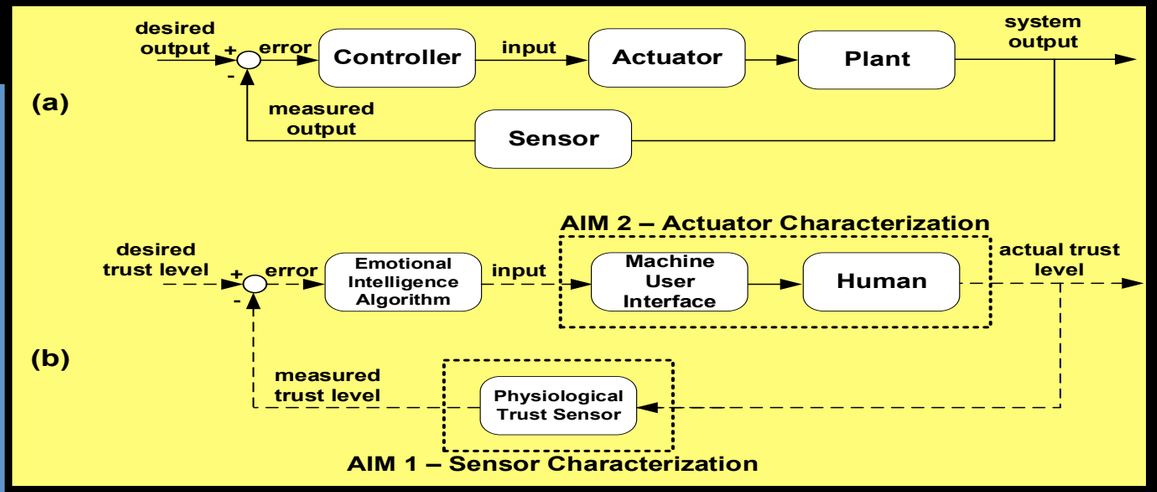
EAGER: A Mathematical Framework for Increasing Trust in Human-Machine Interactions

MAIN OBJECTIVES/IDEAS:

To study the use of psychophysiological tools and eye tracking to measure human trust and derive dynamic mathematical models that capture how humans respond emotionally to machine user interfaces (UIs).

INTERDISCIPLINARITY:

Close collaboration between dynamic modelling, and application of psychological analyses of human judgement.



(a) A standard feedback control system; (b) Research aims shown in the context of a closed-loop emotional intelligence system.

WHAT DOES SUCCESS LOOK LIKE:

- An empirically verified approach for measuring trust, particularly in human-machine contexts
- Mathematical models that can be used to develop closed-loop feedback between humans and machines

WHAT NEXT:

- Design a class of emotional intelligence algorithms that enable machines to build cooperative and trusting relationships with humans and these to real world applications and formulate new hypotheses for future studies

TRANSFORMATIVE OUTCOME:

Dynamic models of trust in terms of psychophysiological measurements and UI design features.

This will improve human-machine interactions through redesigning machine UIs to include an emotional intelligence system that enables the machine to respond to the human in real-time.

1548409: Naira Hovakimyan, Camille Goudeseune and Ranxiao Wang; UIUC

EAGER: Human-Centered Robotic System Design

MAIN OBJECTIVES/IDEAS:

Design flying and ground robots based on how humans perceive them, in order to maximize humans' comfort level.

INTERDISCIPLINARITY:

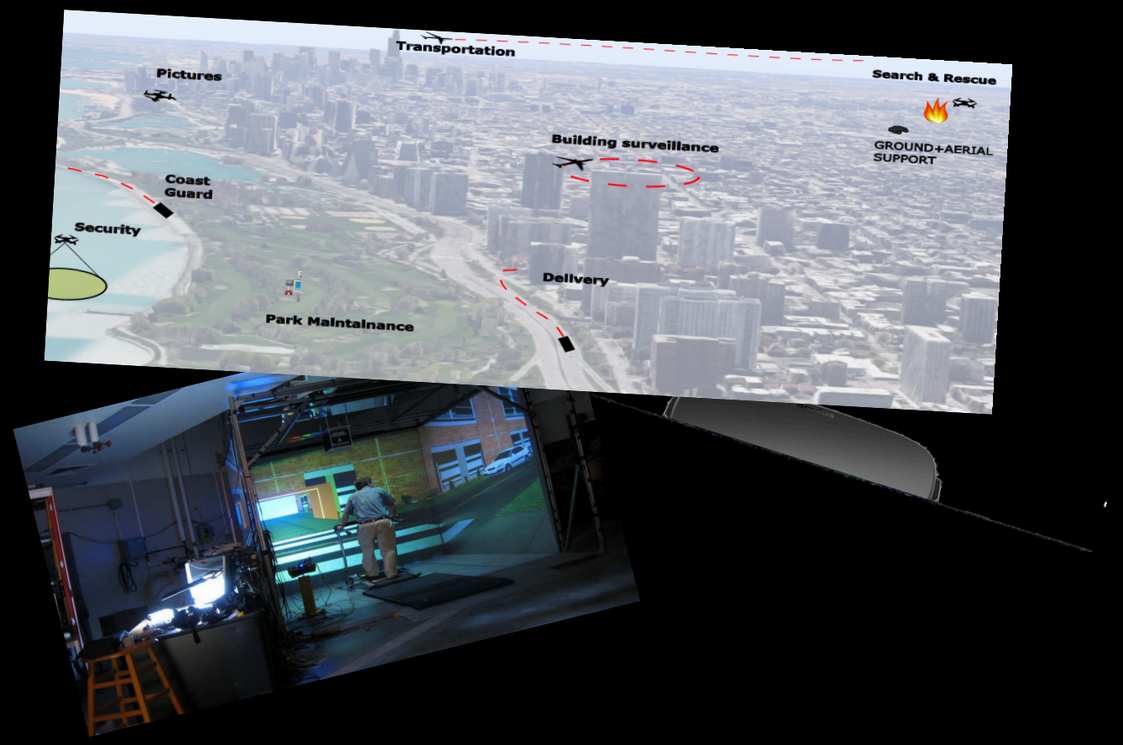
Computer science, cognitive psychology, robot design and control will be brought together with the goal of creating a virtual reality environment, which enables the study of **human perception of robots**.

WHAT DOES SUCCESS LOOK LIKE:

A virtual reality environment, in which humans, pilotless planes, driverless cars, and robots co-exist, and populate the same airspace, roads

WHAT NEXT:

When successful, the team will proceed by designing, building, and controlling real robots.



TRANSFORMATIVE OUTCOME:

Design of 'Non-Intrusive, Collaborative, Empathetic, Robust (NICER)' robots.

1548517: Burcin Becerik-Gerber and Jonathan Gratch; University of Southern CA

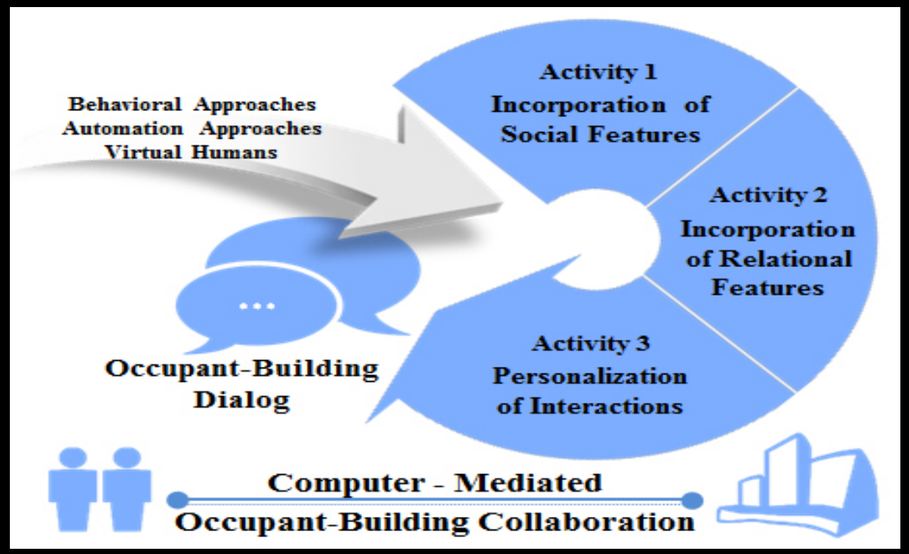
EAGER: Developing a Mathematical Framework to Enable Bi-Directional Interactions of Humans with Smart Engineered Systems Using Relational Elements

MAIN OBJECTIVES/IDEAS:

Facilitate behavior change by incorporating relational elements into human-automation interaction

INTERDISCIPLINARITY:

Marries research on mathematical modelling, behavioral sciences, and human-computer interaction



WHAT DOES SUCCESS LOOK LIKE:

A mathematical framework that enables two-way interactions between people and buildings. The research will contribute to the goal of enabling cyber-physical systems to interact and collaborate with humans

WHAT NEXT:

Developing fully automated virtual agents working from computational models to facilitate behavior change

TRANSFORMATIVE OUTCOMES:

New knowledge of how theories of human interpersonal trust and influence can inform the design of automation

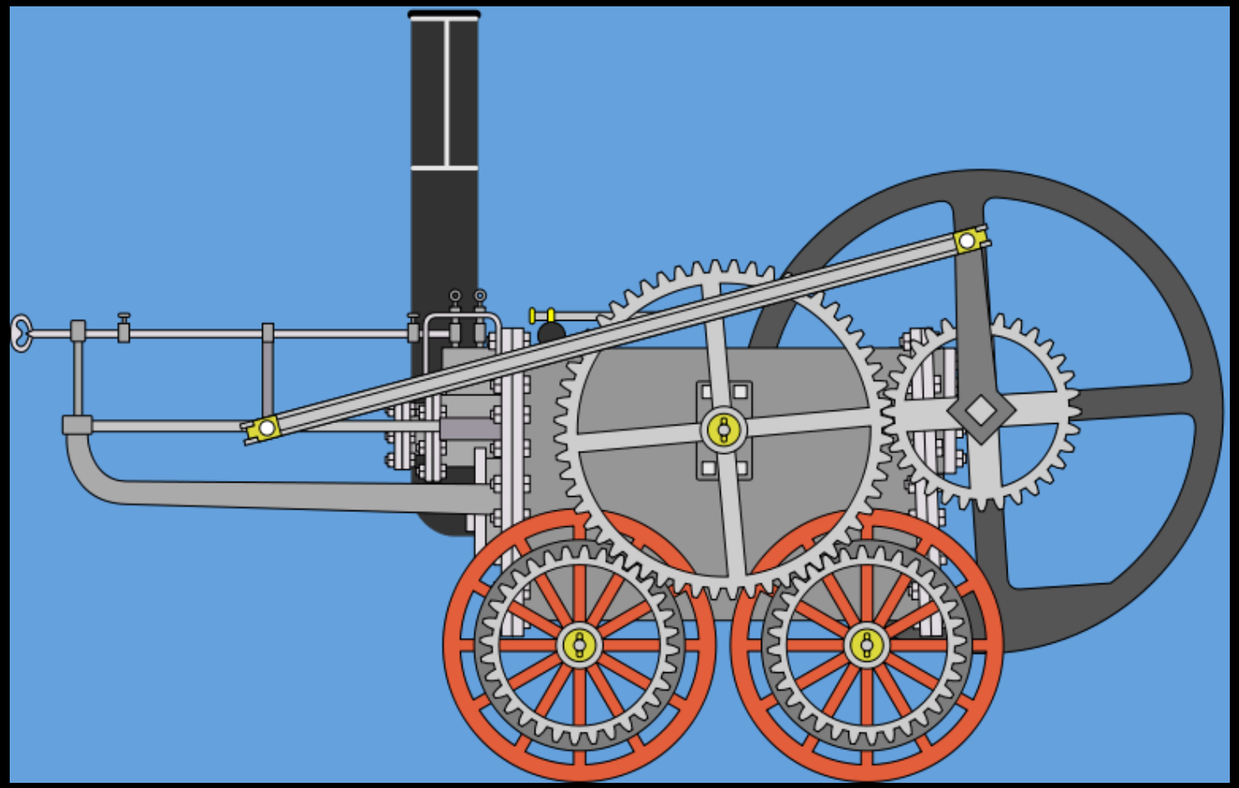
Increased fundamental understanding of human-machine teamwork, including elucidating theories of why and how people build connections with automated systems

Advanced understanding of how automation exhibiting relational features can facilitate behavior change in the population served by those systems

A Thought Experiment

- Imagine designing a railway engine at the dawn of the 19th century
- No systematic mechanical engineering at that time
- Are we in an analogous situation in various service systems?
- What might we learn from the experience in the development of different engineering fields?

Locomotive made by Richard Trevithick and Andrew Vivian (1801)



Credit: By Urizzato at en.wikipedia [Public domain], from Wikimedia Commons

Models

- Models are fundamental building blocks in all engineering fields
- Leverage scientific knowledge in physics, chemistry, biology, and the power of mathematics
- What might constitute “models” as we think about engineering for service systems?
- What would be the role of social and behavioral sciences in this regard?

Analysis and Design Tools

- What analysis and design tools might be developed to systematize the process of engineering service systems?
- How do we leverage advances in cyber-physical systems and machine learning?
- What are cyber security implications and needs in this context?
- How do we put people in the center in framing design questions?
- What can we learn from early experiences in infrastructure? and retail?

Example: Learning and Education

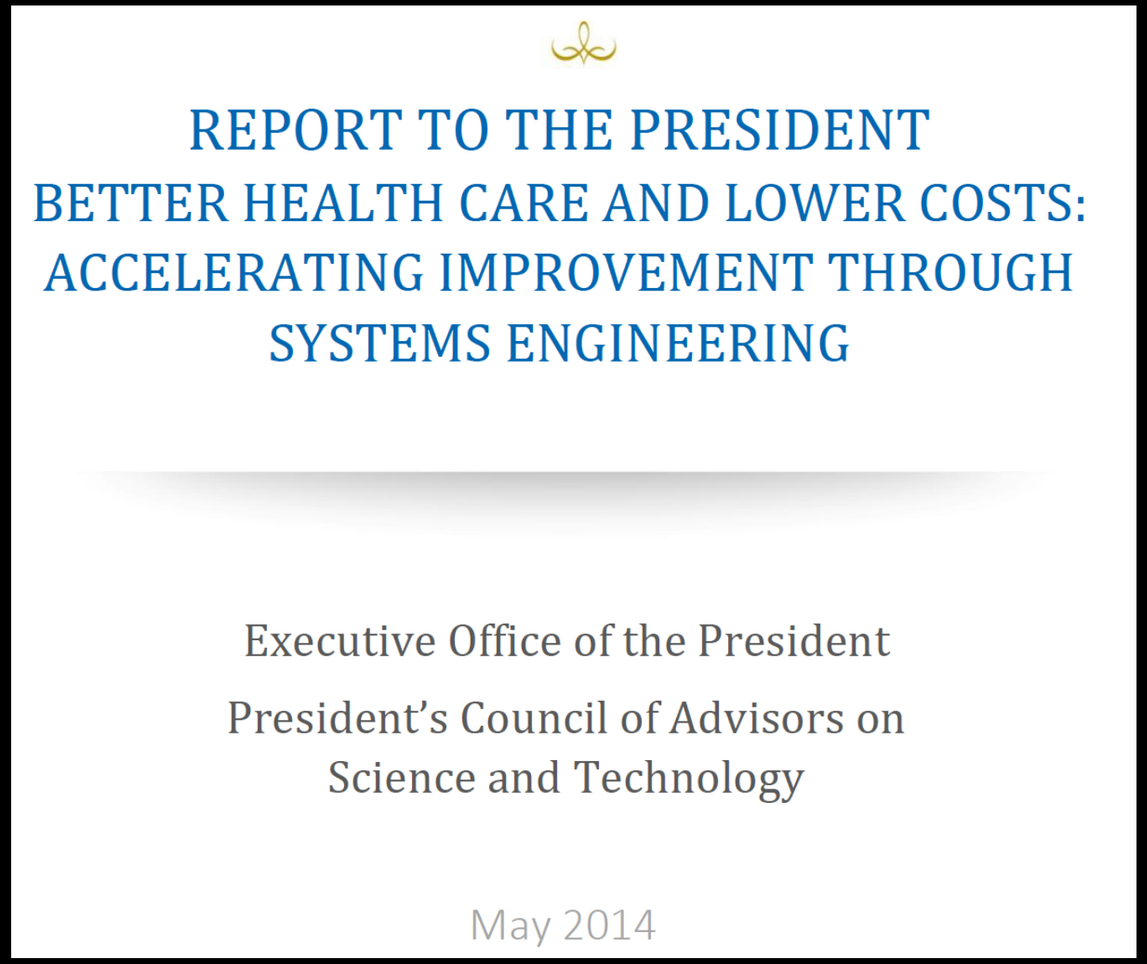
- Productivity of a teacher has not improved significantly in decades
- Major challenges in K-16 education
- Growing body of knowledge in learning science and education
- Modern information technology tools provide an unprecedented opportunity to transform education into just-in-time, personalized education
- Idea of a learning engineer

Plenary session presenters discussed advances in the fundamental science of learning—the underlying research base as to how individuals learn—and called for the development of a new applied discipline—termed learning engineering—which was intended to translate these fundamental insights into new learning environments and tools.

Advancing Technology-Enhanced Education: A Workshop Report, IDA STPI, December 2013

Example: Health Care

- Aging is one of the mega trends for the next many decades
- Cost, quality, access, and efficacy of health care are major societal issues of our time
- PCAST report on Systems Engineering for health care
- Health care engineers



REPORT TO THE PRESIDENT
BETTER HEALTH CARE AND LOWER COSTS: ACCELERATING IMPROVEMENT THROUGH SYSTEMS ENGINEERING

Executive Office of the President

President's Council of Advisors on Science and Technology

May 2014

Concluding Remarks

- Exploration at the boundaries of cyber-physical engineering and behavioral/social sciences
- Potential for significant new knowledge creation
- Great potential to positively impact large parts of society

Thank you!

Questions? *Comments?*

pkhargon@nsf.gov