Does Scale Really Matter?:

Ultra-Large-Scale Systems Seven Years after the Study

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Software Engineering Institute
May 24, 2013

Software Engineering Institute | Carnegie Mellon

Software Engineering Institute (SEI)

- Department of Defense R&D Laboratory
- Created in 1984
- Part of Carnegie Mellon University
- Headquartered in Pittsburgh, Pennsylvania; Offices in Washington, Los Angeles, and Frankfurt
- **Mission:** To advance the technologies and practices needed to acquire, develop, operate, and sustain software systems that are innovative, affordable, trustworthy, and enduring.

My Comfort Zone

Ultra-Large-Scale (ULS) Systems

My Talk

ULS System Study Reprise

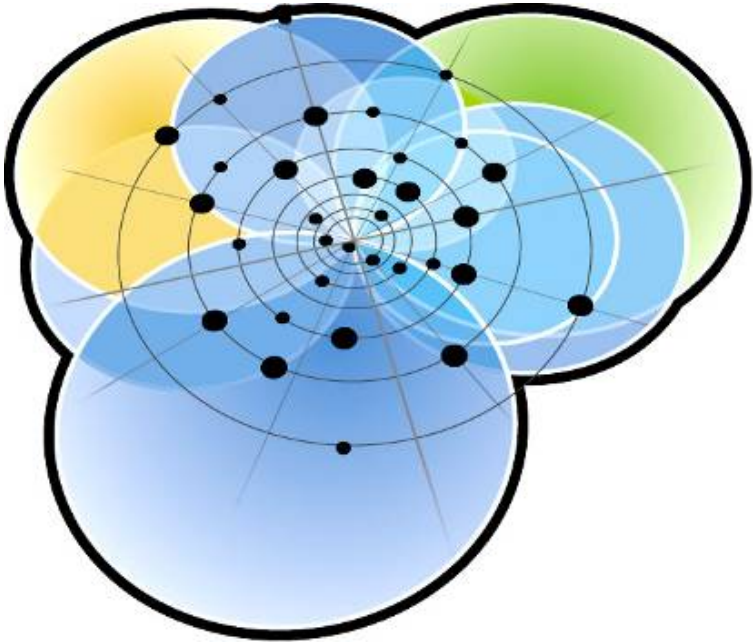
Current Climate

Experiences with Systems at Scale

ULS Systems-Related Research

Reflection

Interaction

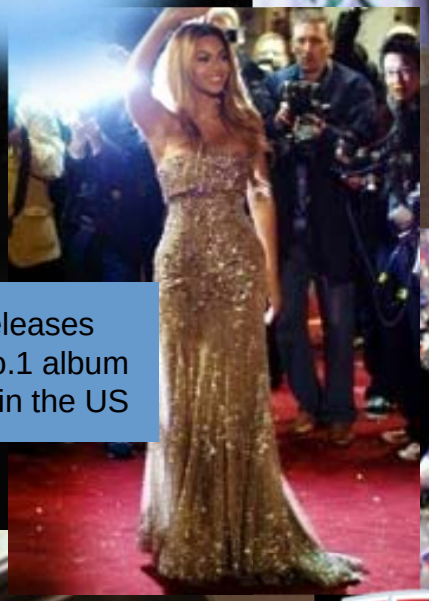


Beginning of the ULS System Journey

Seven Years Ago

Windows Vista released

Saddam Hussein sentenced to death and executed



Beyonce Knowles releases second consecutive No.1 album and fourth No.1 single in the US

NASA's Mars Reconnaissance Orbiter enters Mars orbit

BlackBerry users numbered 4,900,000 in March, 2006

Pittsburgh Steelers win Super Bowl XL

Societal Problems

Climate change and the environment

Powering our civilization

Disease, epidemics, and health care

Livable megacities

Safety and security

Transportation

Society's Dependence on Software

Trend Toward Increasing Scale-1

- enormous web service and computing infrastructure
- supply chain systems
- software-based engineering systems

Trend Toward Increasing Scale - 2

Healthcare Infrastructure

Military Systems

Homeland Security

Networked Automobiles

Saving the Environment

Increasing Scale In Military Systems

Increasingly Complex Systems

- ultra-large, network-centric, real-time, cyber-physical-social systems
  - thousands of platforms, sensors, decision nodes, weapons, and warfighters
  - connected through heterogeneous wired and wireless networks

- *Transient and enduring resource constraints and failures*
- *Continuous adaptation*
- *Sustainable - legally, technically, politically*

Ultra-Large-Scale (ULS) Systems Study

Asst Sec Army
Claude Bolton

August 16, 2005

"…*How can future systems, which are likely to be a billion lines of code, be built reliably if we can't even get today's systems right?*"

Gather leading experts to study these ULS systems of the future.

Intended outcomes:

- ULS System Research Agenda
- program proposal
- collaborative research network

About the Effort

Funded by the Army (ASA ALT)

Created and led by the SEI

Staffing: 9 member SEI team
13 member expert panel

Duration: one year (04/05 -- 05/06)

Expert Panel

Gregory Abowd
Georgia Institute of Technology

Peter Neumann
SRI International Computer Science Laboratory

Douglas Schmidt
Vanderbilt University

Carliss Baldwin
Harvard Business School

Mary Shaw
Carnegie Mellon University

Bob Balzer
Teknowledge Corporation

Dan Siewiorek
Carnegie Mellon University

Richard P. Gabriel
Sun Microsystems

Kevin Sullivan
University of Virginia

Gregor Kiczales
University of British Columbia

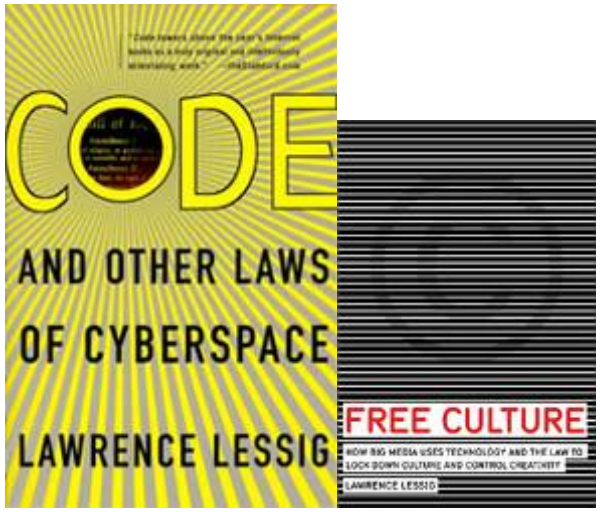
Ali Mili
New Jersey Institute of Technology

John Lehoczky
Carnegie Mellon University

Jack Whalen
PARC

The Journey

Inspiration: Open Source and Cooperative Communities



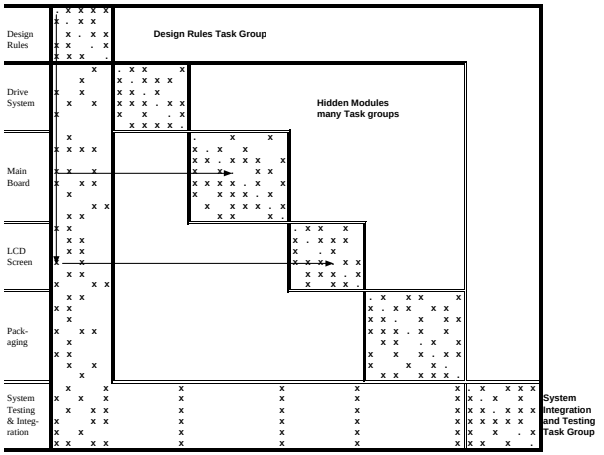
ebay

Google

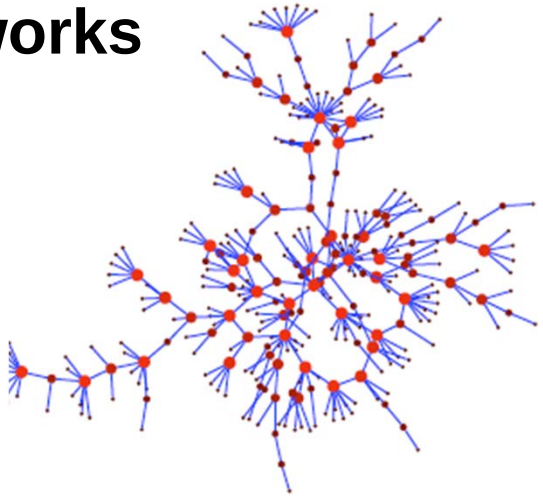
More Inspiration

Game Theory

Economics

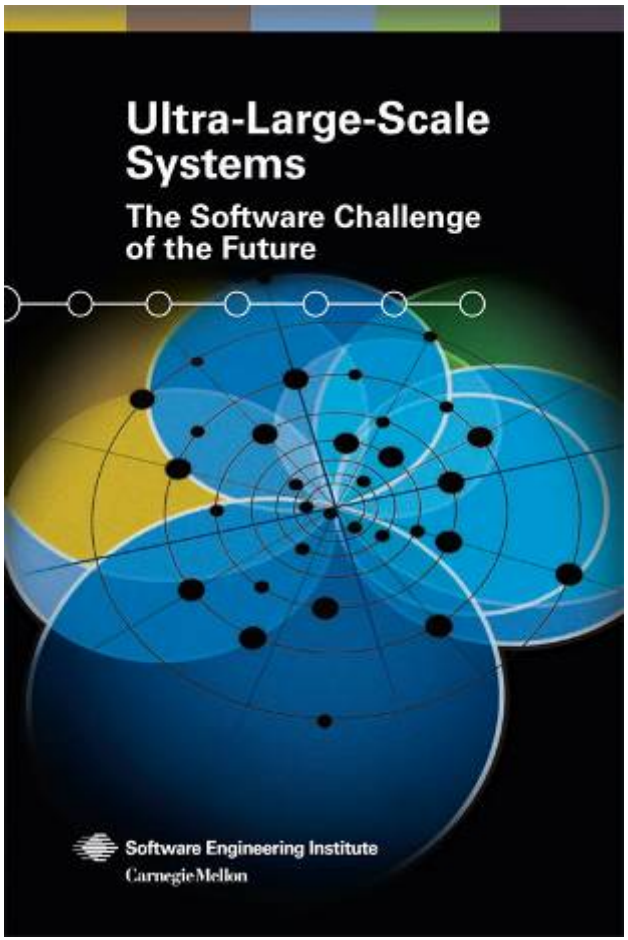


Networks



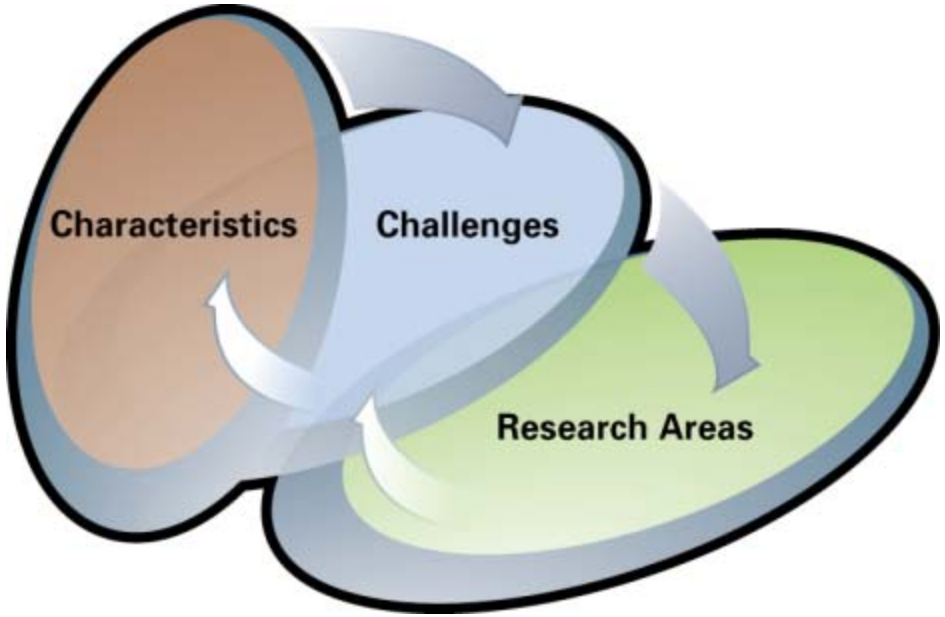
Statistical Mechanics

ULS Systems Research Study Report



http://www.sei.cmu.edu/uls/

ULS Systems Research Agenda

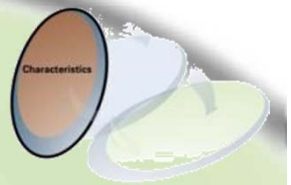


Describes

- the characteristics of ULS systems
- the associated challenges
- promising research areas and topics

Is based on a new perspective needed to address the problems associated with ultra-large-scale systems.

What Is an Ultra-Large-Scale (ULS) System?



A ULS System has unprecedented scale in some of these dimensions:

- lines of code
- amount of data stored, accessed, manipulated, and refined
- number of connections and interdependencies
- number of hardware elements
- number of computational elements
- number of system purposes and user perception of these purposes
- number of routine processes, interactions, and “emergent behaviors”
- number of (overlapping) policy domains and enforceable mechanisms
- number of people involved in some way
- …..

ULS systems are interdependent webs of software-reliant systems, people, policies, cultures, and economics.

Consequences of Scale

Characteristics of ULS systems arise because of their scale.

- Decentralization
- Inherently conflicting, unknowable, and diverse requirements
- Continuous evolution and deployment
- Heterogeneous, inconsistent, and changing elements
- Erosion of the people/system boundary
- Normal failures
- New paradigms for acquisition and policy

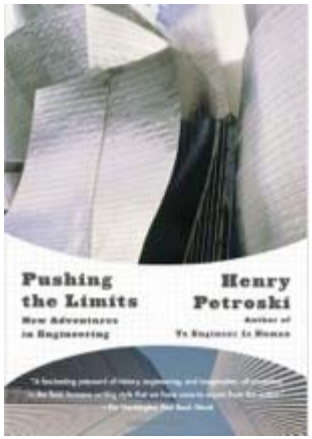
Approaches to Software Development

The Engineering Perspective

The Agile Perspective

A New Perspective is Required

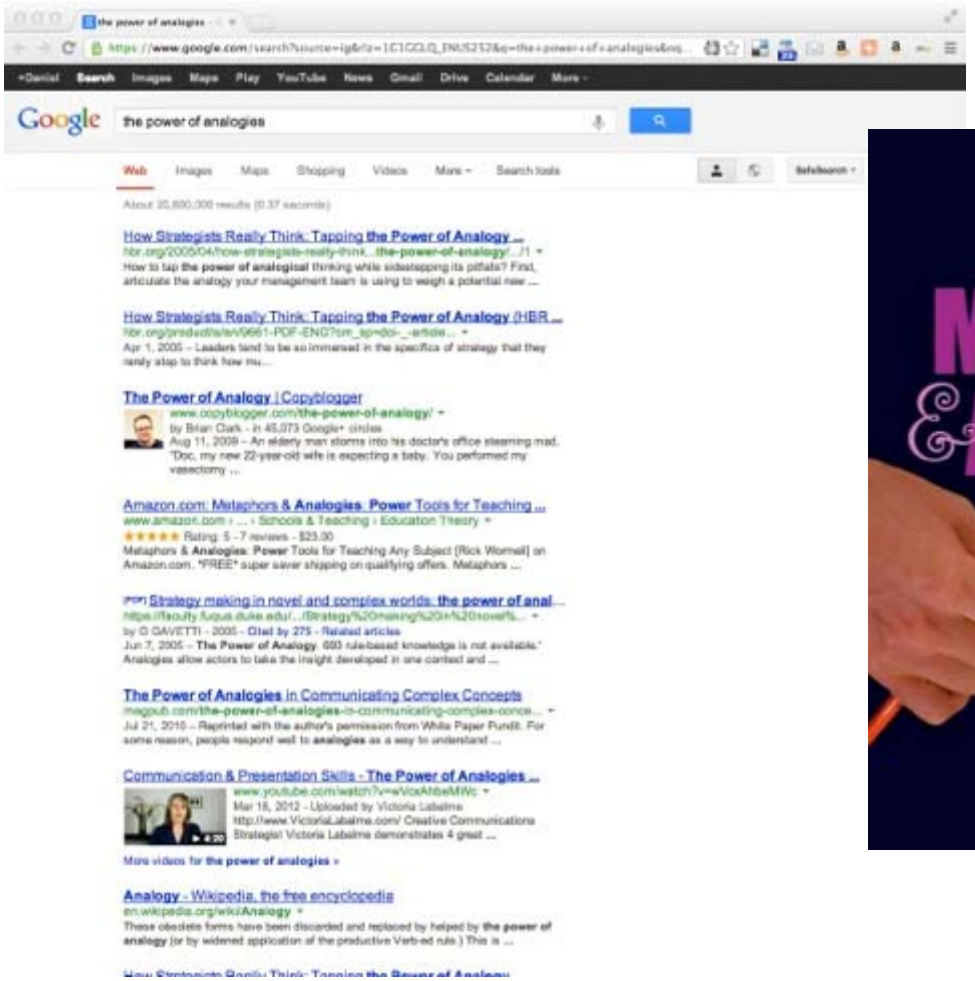
"The older is not always a reliable model for the newer, the smaller for the larger, or the simpler for the more complex…Making something greater than any existing thing necessarily involves going beyond experience."

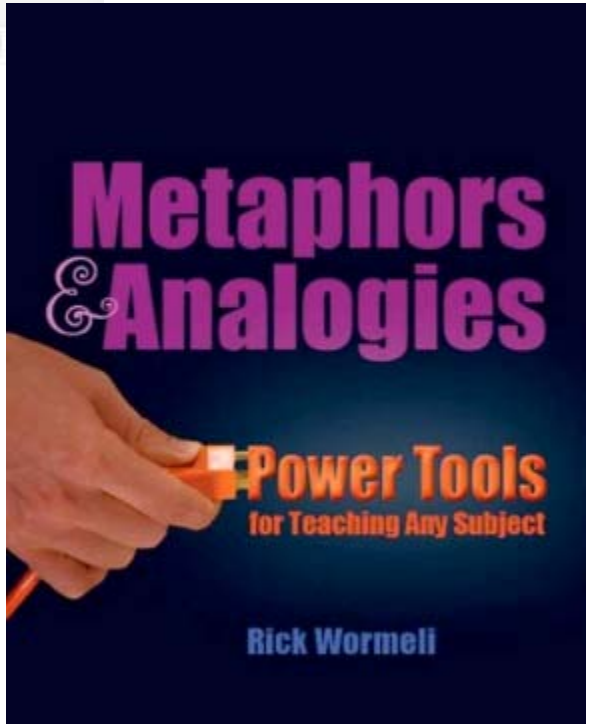


Henry Petroski

Pushing the Limits: New Adventures in Engineering

Analogies are Useful

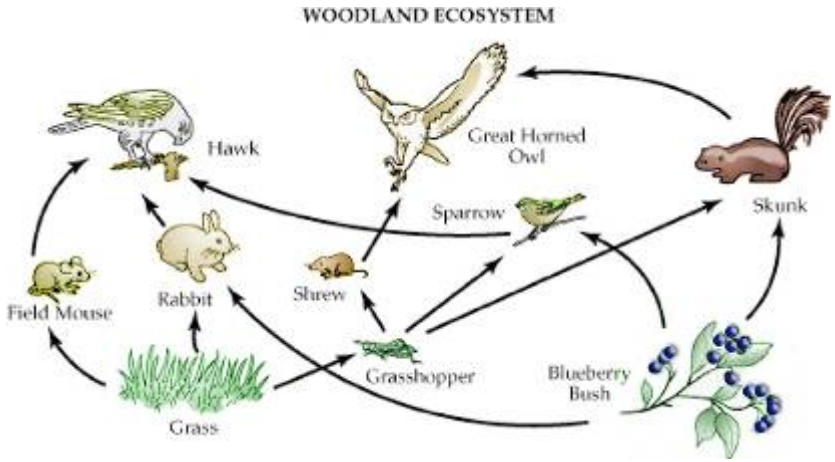




Think Cities not Buildings

"Cities are places of massive information flows, networks, and conduits, and myriad transitory information exchanges."
Howard Rheinegold: *Smart Mobs*

Think Ecosystem



Diverse users with complex networked dependencies and intrinsic adaptive behavior

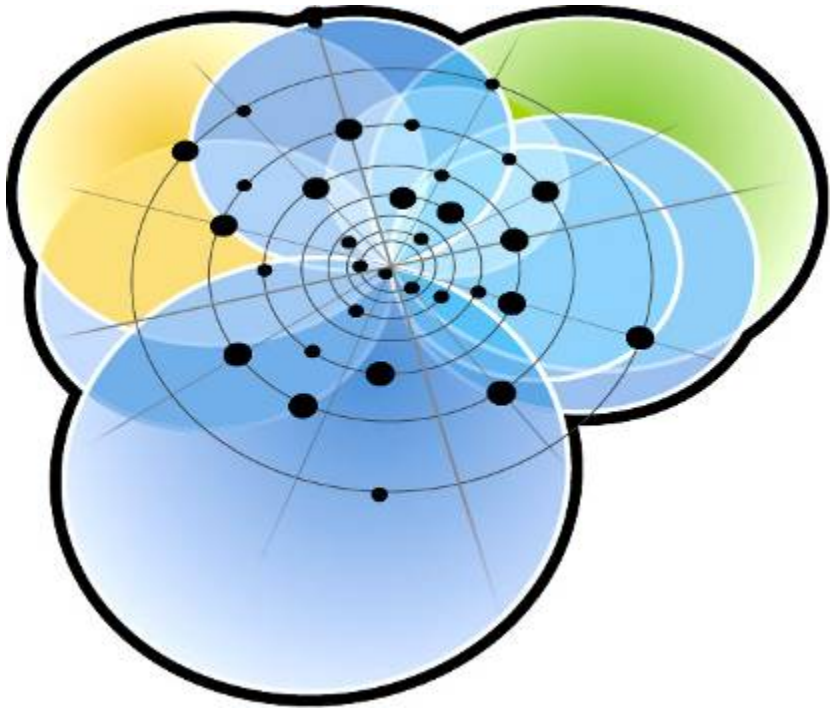
Has:

- Robustness mechanisms: achieving stability in the presence of disruption
- Measures of health: diversity, population trends, other key indicators

Think Socio-Technical Ecosystems

Socio-technical ecosystems include people, organizations, and technologies at all levels with significant and often competing interdependencies.

- dynamic communities
- interaction between and among all entities – roles, responsibilities, and information flows
- competition for resources
- rules, incentives, and adaptation



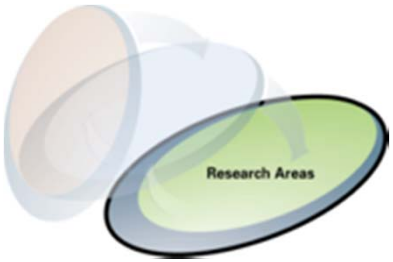
Challenges

ULS systems will present challenges in three broad areas:

- Design and evolution
- Orchestration and control
- Monitoring and assessment

"There are challenges associated with ULS systems that today's perspectives are very unlikely to be able to address."

Research Portfolio



6.1 Human Interaction

6.2 Computational Emergence

6.3 Design

6.4 Computational Engineering

6.5 Adaptive System Infrastructure

6.6 Adaptable and Predictable System Quality

6.7 Policy, Acquisition, and Management

What We Learned

There is an unstoppable trend toward increasing scale in many systems important to our society.

Scale changes everything.

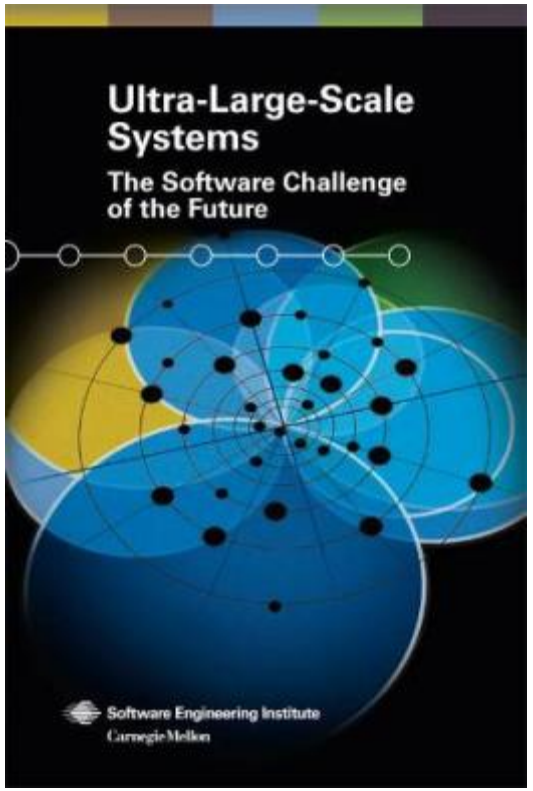
These changes undermine the assumptions we routinely make in traditional software engineering approaches.

Manifestations of scale and its attendant complexity arise in many disciplines, and can be understood as a phenomenon in its own right.

New, interdisciplinary perspective and new research in building ultra-large-scale systems is long overdue.

Our Assertion

"Fundamental gaps in our current understanding of software and its development at the scale of ULS systems present profound impediments to the achievement of mission objectives. These gaps are strategic, not tactical. They are unlikely to be addressed by incremental research in established categories. We require a broad new conception of both the nature of such systems and new ideas for how to develop them."



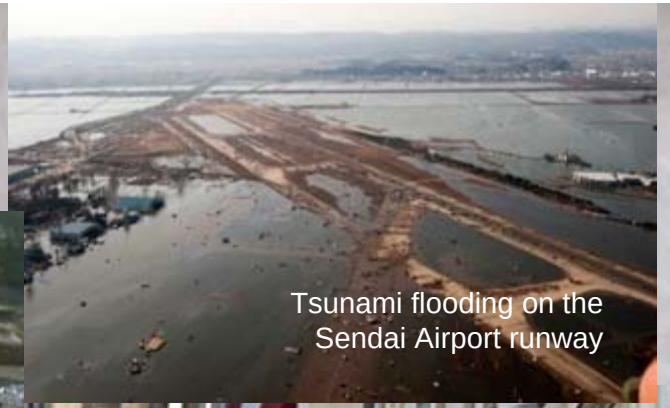
Early Post-Study Observations

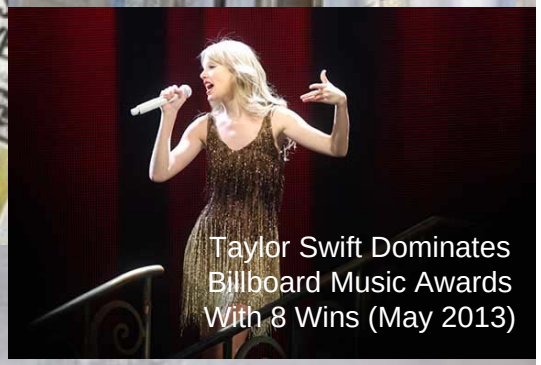
- We never suggested that all systems of the future will be ULS systems. Clearly, they won't be.
- What you call it (system of systems, ULS system, complex net-centric system) is really unimportant.
- It is important that ULS system characteristics are recognized.
- Systems engineering does not have all the answers.
- Not having a research area on network security was a lightening rod.
- The research identified in the ULS system study has a positive impact on systems that are not ULS.

Seven Years Later

Since Then


Demonstrators in Cairo's Tahrir Square on February 8, 2011


Tsunami flooding on the Sendai Airport runway


Taylor Swift Dominates Billboard Music Awards With 8 Wins (May 2013)

Societal Problems

Climate change and the environment

Powering our civilization

Disease, epidemics, and health care

Livable megacities

Safety and security

Transportation

Software is Ubiquitous and Often Transparent

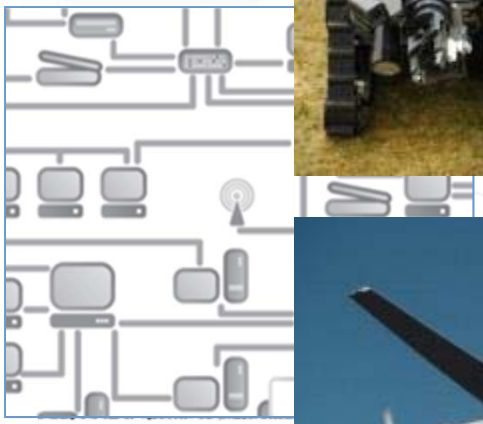
Software-Reliant Systems: What HAS Changed?

Increased connectivity

Challenges

- scale and complexity
- decentralization and distribution
- “big data”
- increased operational tempo
- mismatched ecosystem tempos
- vulnerability
- collective action
- disruptive and emerging technologies

More Fuel for Scale



Our Milieu

The "Crowd"

GitHub

match.com

reddit

DARPA BAA 11-64: Social Media in Strategic Communication (SMISC)

Research to investigate innovative approaches that enable revolutionary advances in science, devices, or systems for strategies to:

1. Detect, classify, measure and track the (a) formation, development and spread of ideas and concepts (memes), and (b) purposeful or deceptive messaging and misinformation.

2. Recognize persuasion campaign structures and influence operations across social media sites and communities.

3. Identify participants and intent, and measure effects of persuasion campaigns.

4. Counter messaging of detected adversary influence operations.

Some ULS Systems Buzz

~21,266 downloads and hardcopy

75+ citations in refereed publications

Presentations

Workshops

Blog, journal, and twitter references

Initiatives and degree programs

LSCITS
Large Scale Complex IT Systems

Queen's University

Health IT as an Ultra Large-Scale System

Dr. Doug Fridsma

Chief Science Office and Director
Office of Science and Technology
Office of National Coordinator
US Health and Human Services

Health IT Buzz

February 21, 2013

http://www.healthit.gov/buzz-blog/electronic-health-and-medical-records/healthcare-building-interoperable-health-system-tough/

More Buzz

Ultralarge Systems:
Redefining Software Engineering?

Greg Goth

March/April 2008 IEEE Software

although the ULSS report focused on challenges faced by the United States Department of Defense in engineering software intensive systems, "its description of how the fundamental principles of software design will change in a global economy … is finding wide appeal."

Managing Scale and Agility:
Transformational Architecture for the Smart Grid

Wayne Longcore

SATURN 2010

"We are creating the first true instantiation of a high-functioning Ultra-Large-Scale System—the Smart Grid."

Notes on ultra-large-scale systems

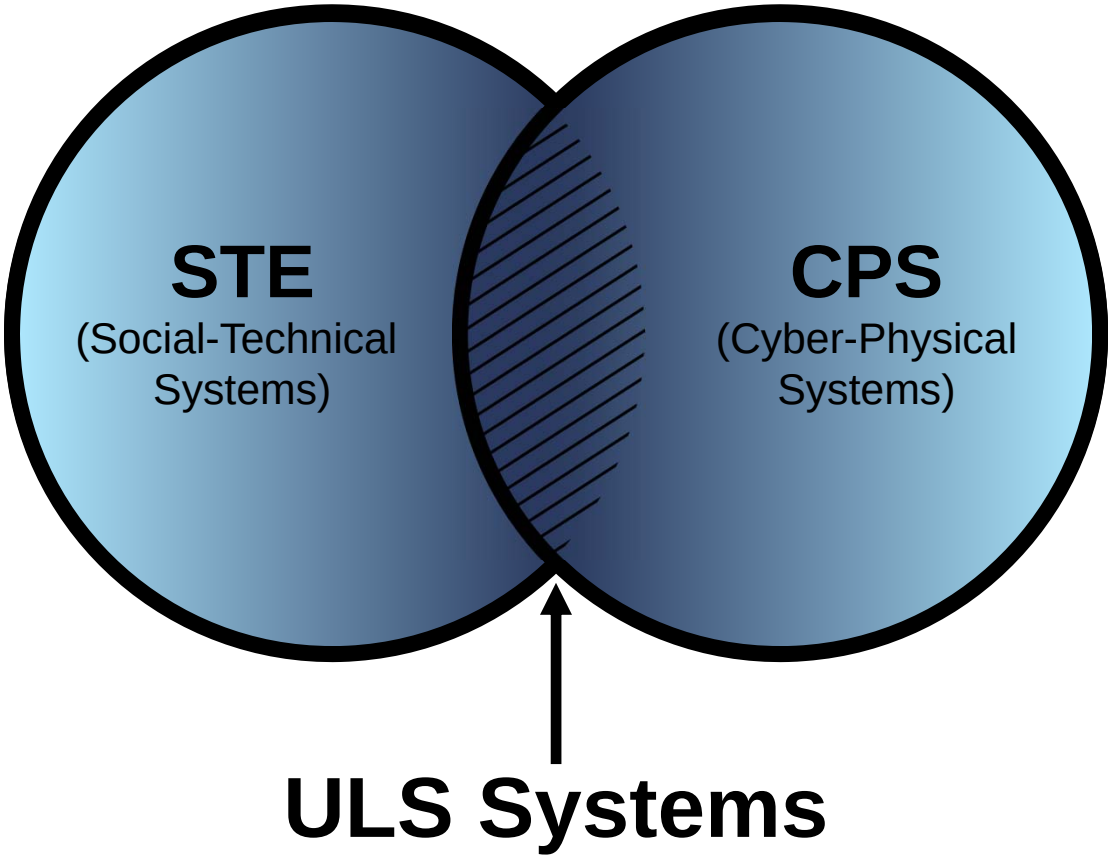
http://blog.johnrooksby.org/post/132967033/notes-on-ultra-large-scale-systems

John Rooksby

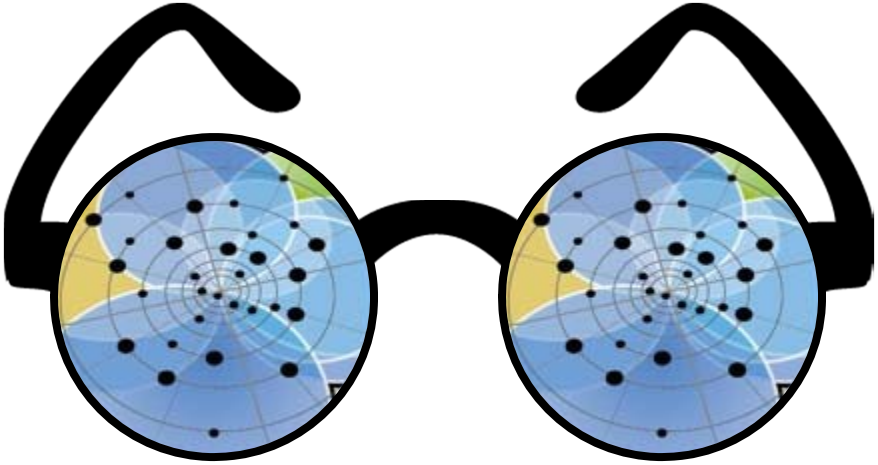
University of Glasgow

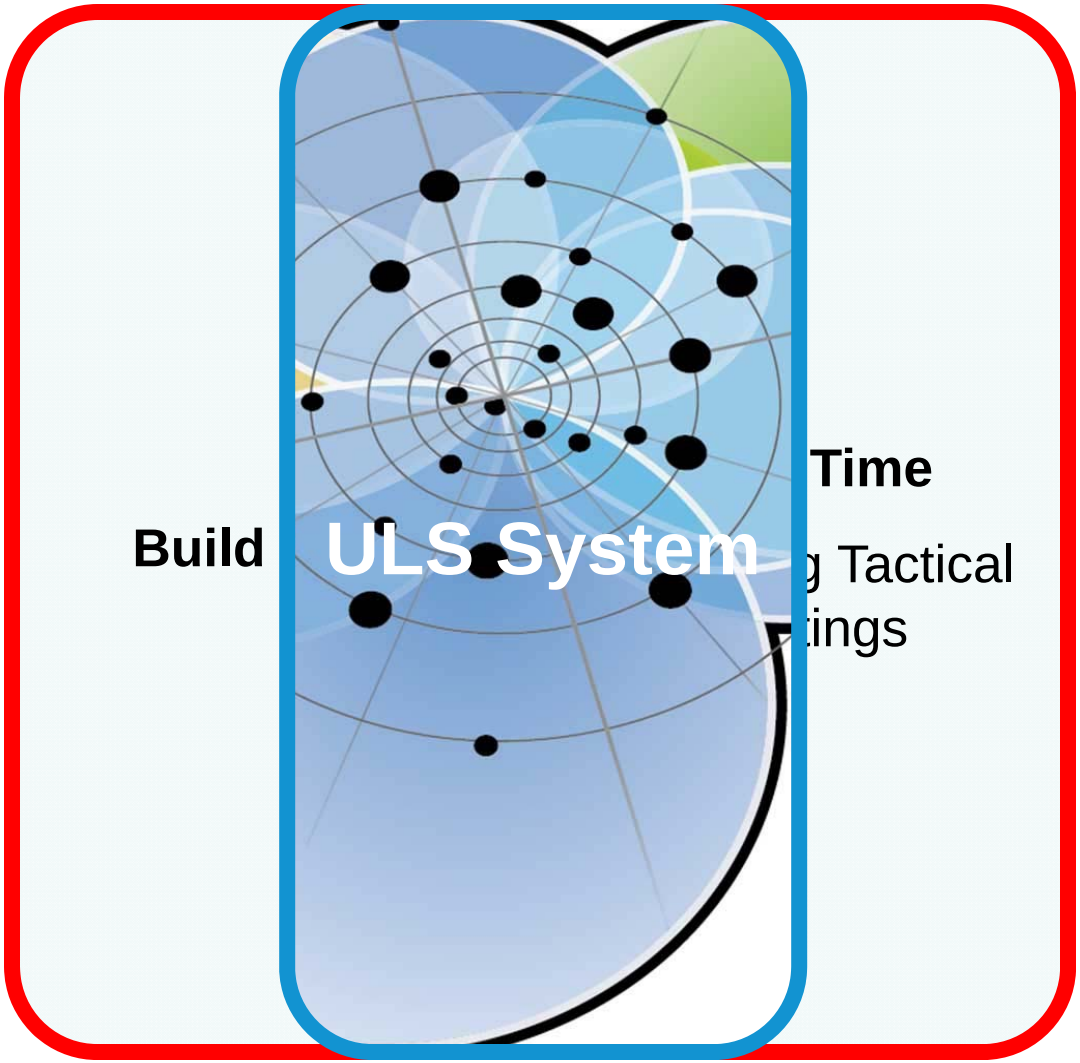
"True to national stereotypes the Americans were asking *how can we build the biggest systems in the world*? The British were asking *how can we stop screwing up when we try to build the biggest systems in the world*?"

Upon Reflection



ULS System Perspective

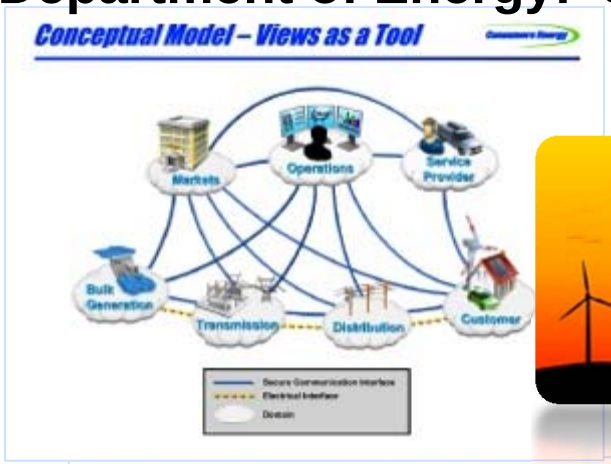


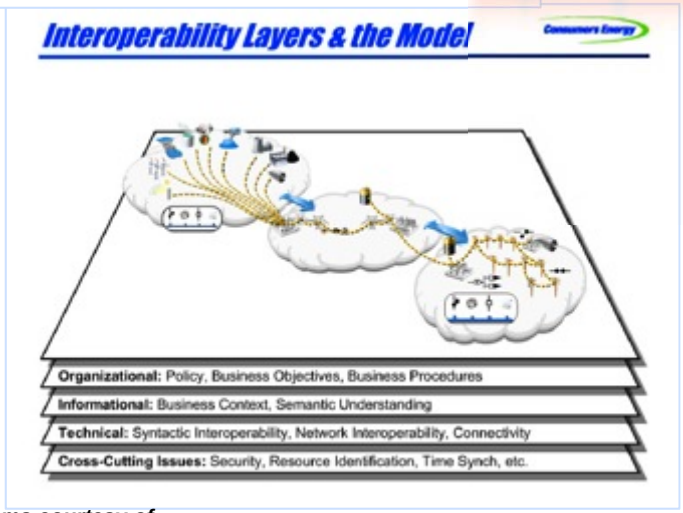


Selected Experiences with Systems at Scale:

Nibbling at the Edges

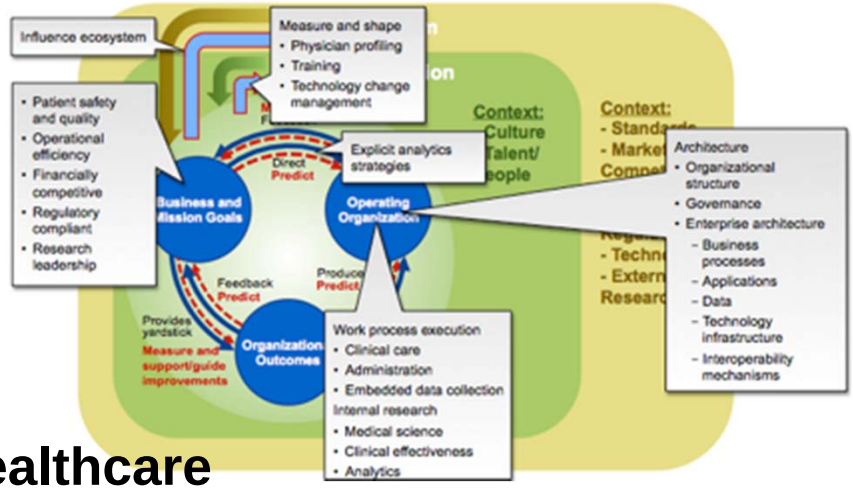
Department of Energy: Smart Grid





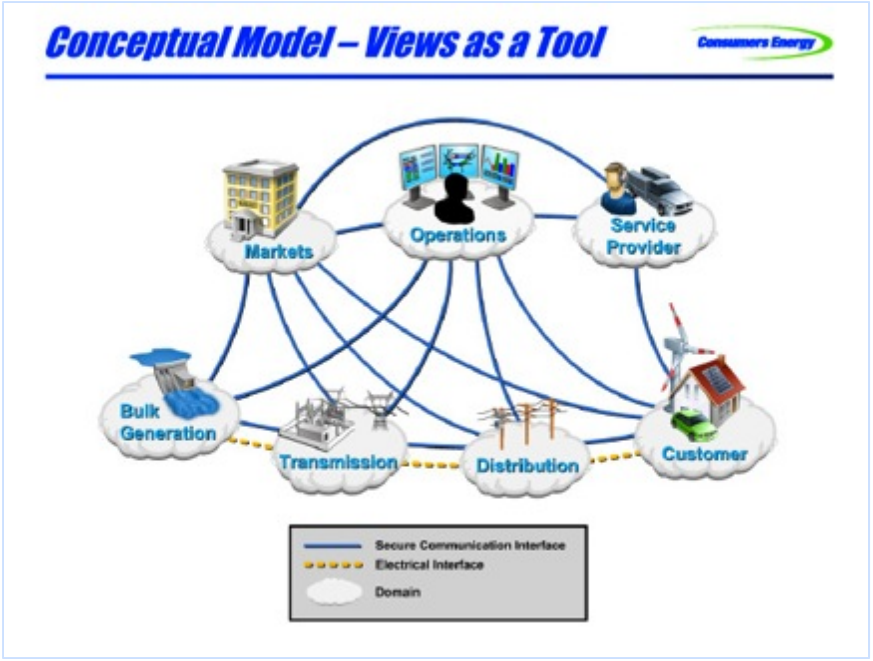
Diagrams courtesy of Wayne Longcore Consumers Energy

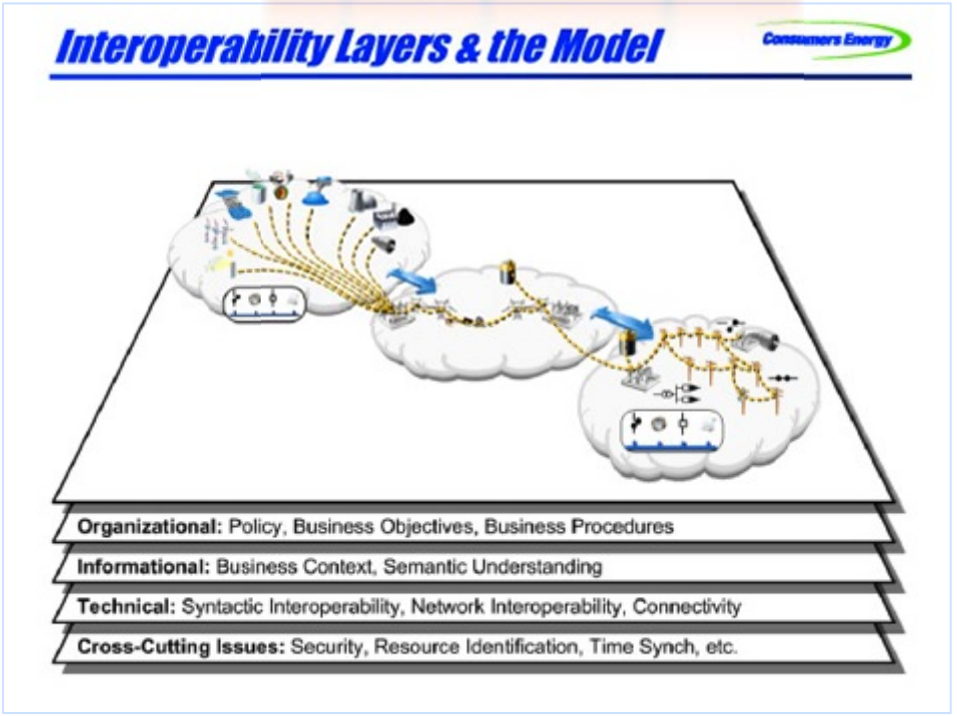
The eXtreme Science and Engineering Discovery Environment (XSEDE) enhances the productivity of scientists and engineers.



Healthcare Analytics

Smart Grid – A ULS System





Diagrams courtesy of
Wayne Longcore
Consumers Energy

Specific Problem and Technical Approach

Problem

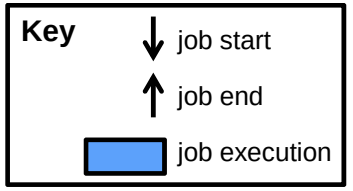
Create a capability to discover if an intruder is executing foreign code in the systems running US critical infrastructure (e.g., Stuxnet).

Approach

Exploit known performance characteristics of critical devices *(timing profiles)* and monitor run-time behavior for deviations.

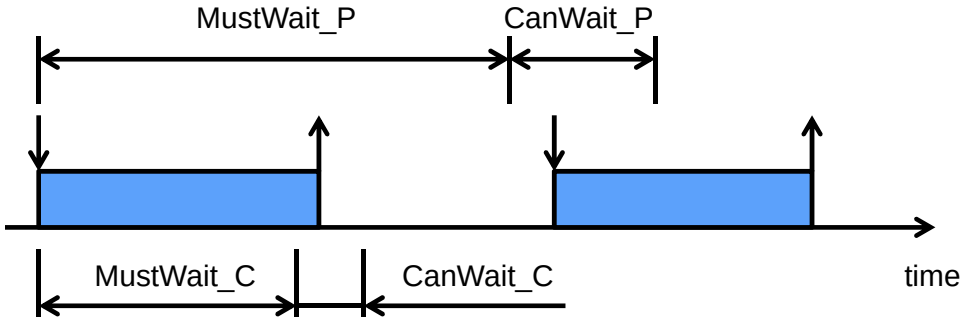
Intelligent Electronic Devices (devices deployed to control field equipment) exhibit several desirable characteristics

- are real-time systems
- are deployed in known, stable configurations
- react to a reasonably small number of kinds of stimulus



A timing violation occurs when

- job execution is too short or too long
- job release period is too short or too long



Broader ULS System Impact

The expansion of communication among diverse devices being seen in the Smart Grid is also happening in other ULS systems and raises the same concerns for a capability to detect this class of intrusions.

Other real-time systems with knowable timing profiles where the technique could be used to enhance intrusion detection include

- sensors
- fire control systems
- vehicle and engine controllers
- avionics systems
- ..

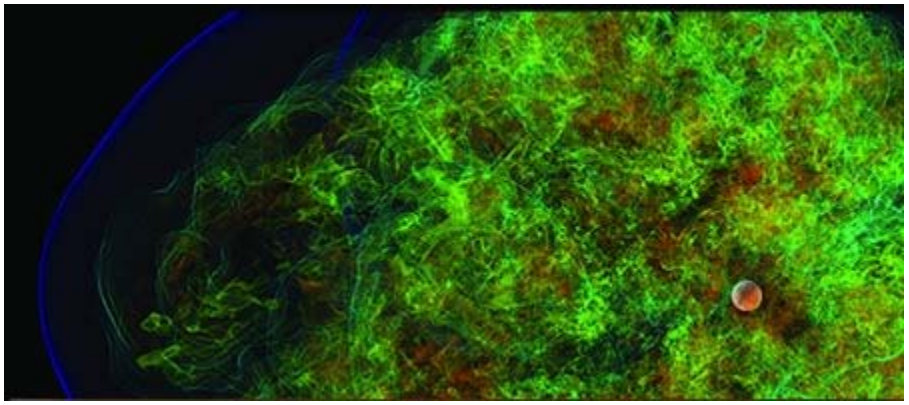
XSEDE

Extreme Science and Engineering Discovery Environment

The eXtreme Science and Engineering Discovery Environment (XSEDE) enhances the productivity of scientists and engineers.

XSEDE is the framework for a national cyber-infrastructure ecosystem, serving as a platform for multiscale cyber-infrastructure integration for scientific collaboration.

XSEDE's innovative, open standards-based architecture facilitates an unparalleled level of integration.



Enabling this architecture are XSEDE's professional systems engineering approach and technology insertion efforts, which ensure robustness and security while continuously incorporating new technologies.

Technical problem: XSEDE needs well-defined software development and software management practices across the XSEDE partner network before it can embrace practices more appropriate for a socio-technical ecosystem.

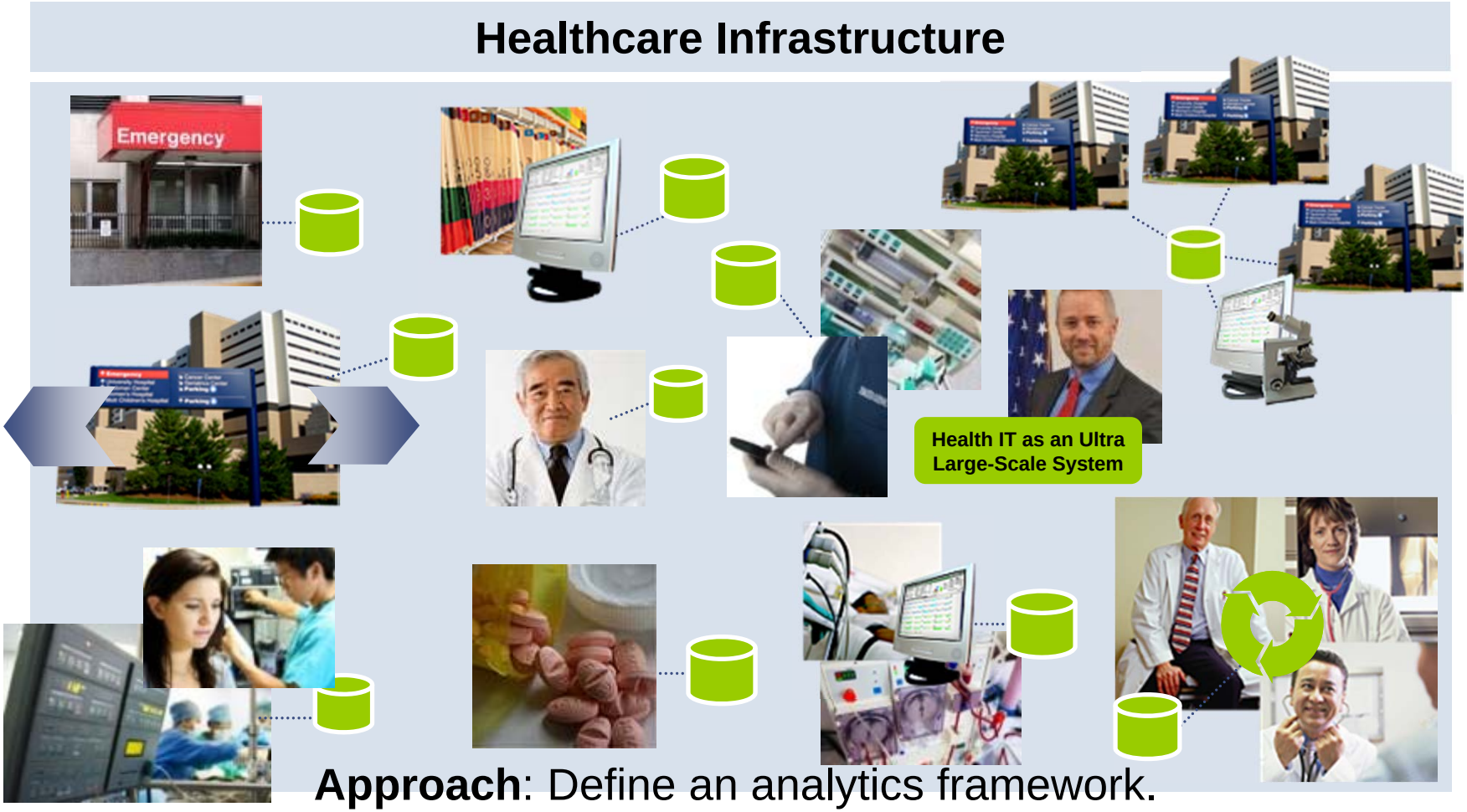
Approach:

- Identify and coach XSEDE community in adopting a variant of architecture-centric practices suitable for their collaborative ecosystem
- Apply automated text and social network analyses to data gathered from XSEDE with the goal of providing automated infrastructure support for ensuring that the right people get the right information at the right time.

Impact: Enabling the evolution of the nation's scientific computing grid via architecture-centered practices and serving as an exemplar for socio-technical ecosystems.

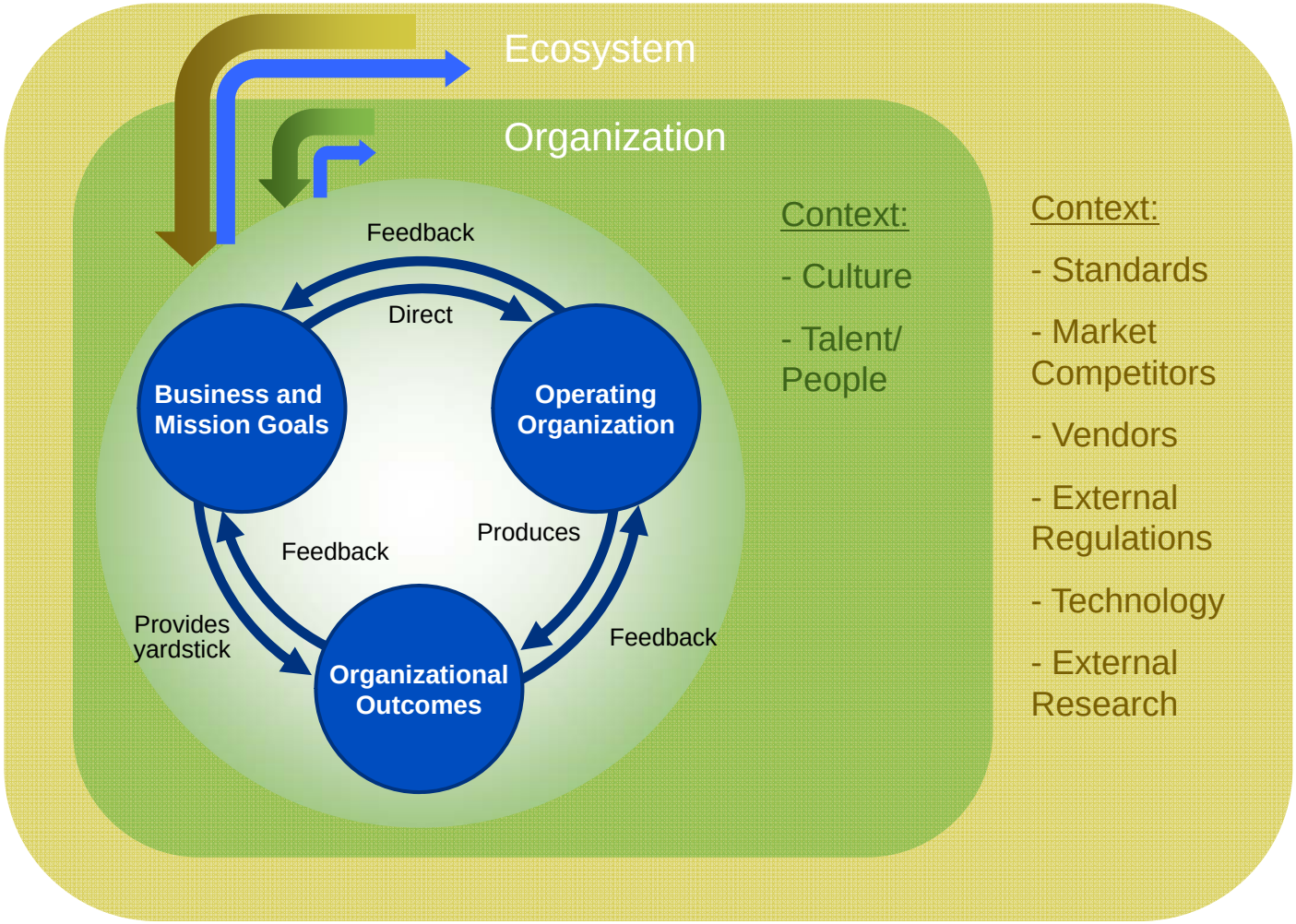
Healthcare Analytics

Problem: Define healthcare analytics from technical and organizational perspectives needed to achieve intelligent healthcare.

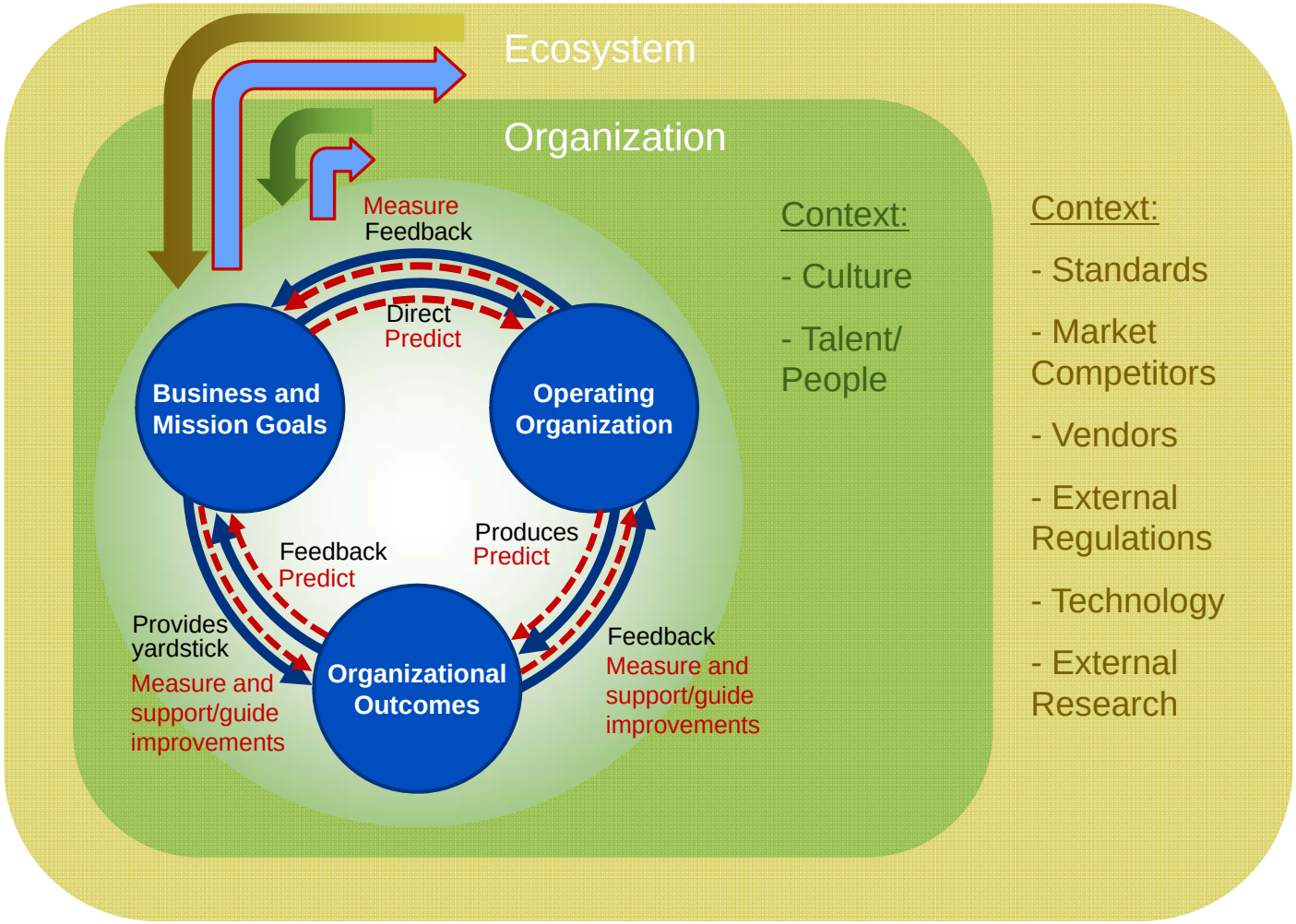


Approach: Define an analytics framework.

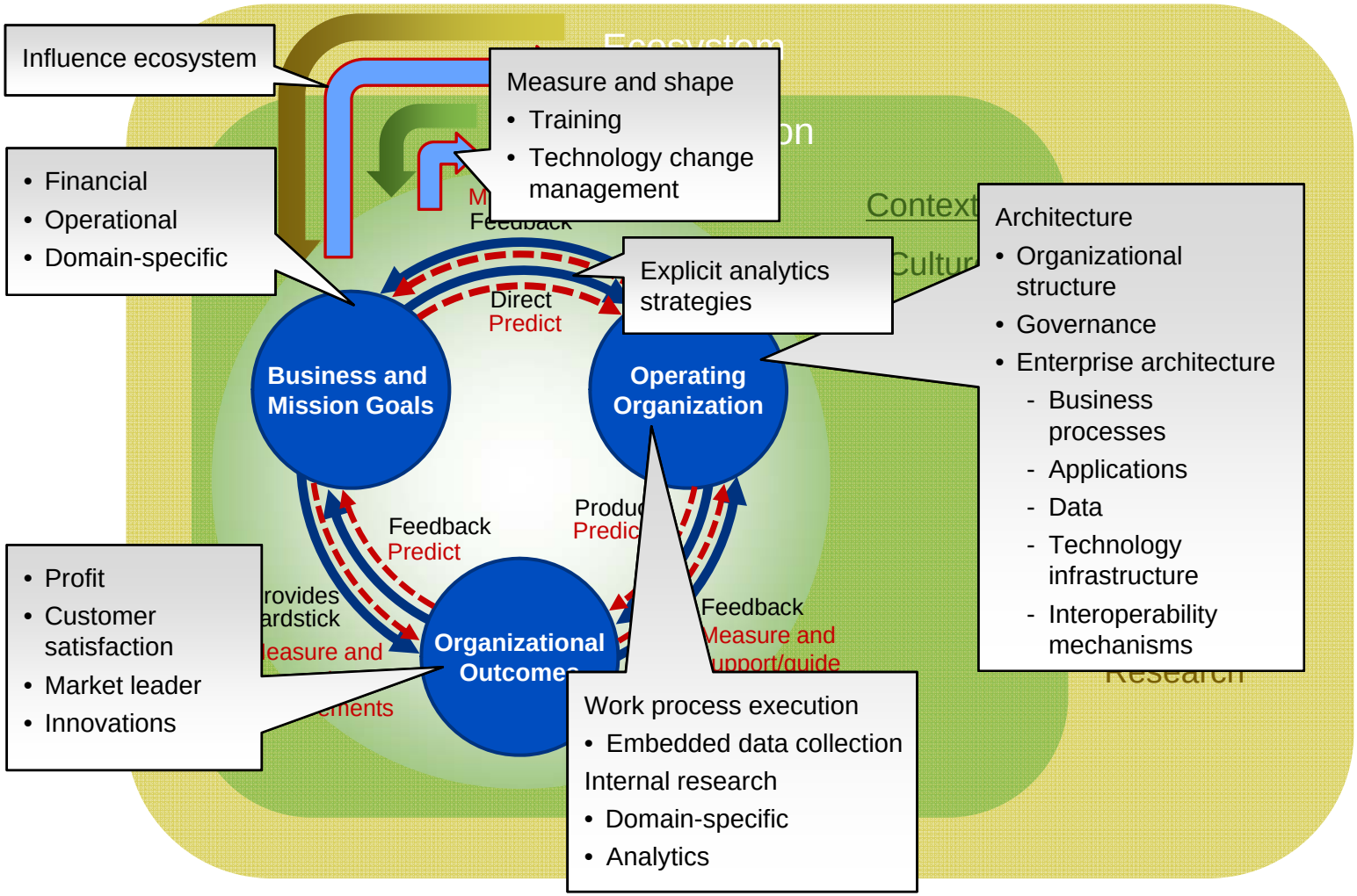
Organizational Dynamics



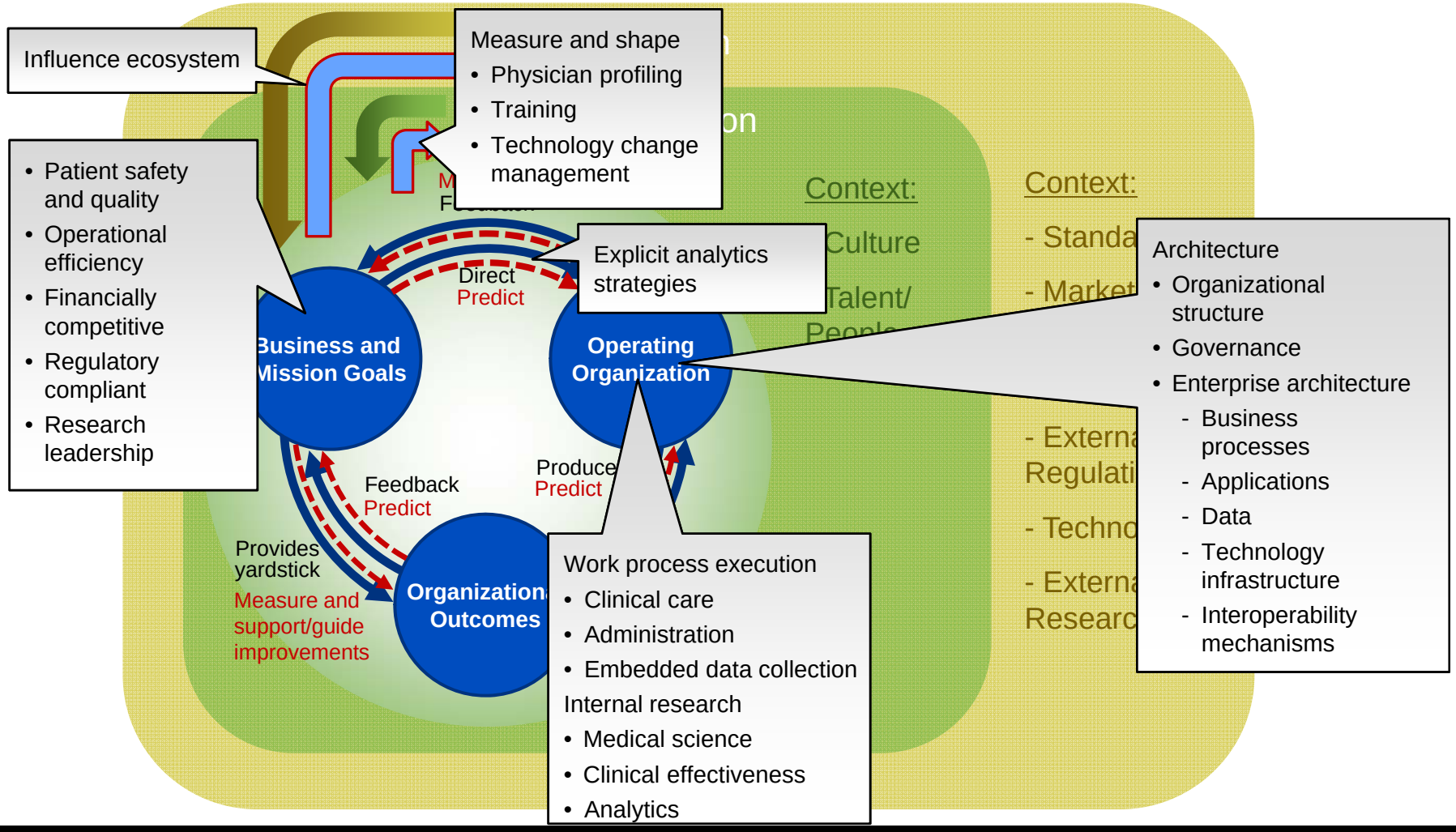
Adding Analytics



Best in Class Analytics Organizations: Learning Organizations



Best in Class Healthcare Analytics Organizations: Learning Organizations



Selected ULS-Systems-Related Research

Sample Published Work

Contextual Design

Collaboration and Coordination in Large-Scale Socio-technical Ecosystems

Social Network Analysis

James Herbsleb et al, Carnegie Mellon University

Ecosystem Modeling

John McGregor et al, Clemson University

Machine Learning

Socio Linguistics

Natural Language Processing

Crowdsourcing Requirements

Stakeholder Analysis

Data Intelligence

Data Privacy

Data Heterogeneity

Self* computing

Self-Coordinating Systems

Self-Adaptive Systems

Dynamic Adaptive Systems

Complex Adaptive Systems

Architecture Mechanisms for Diagnosis and Adaptation

SEAMS Community and others

Architecting ULS Systems

End-User Architecting

Middleware for ULS Systems

Domain-Specific Engineering

Model-based Approaches to ULS Systems

Multi-Product Lines

Multi-Sided Markets

Data-Intensive Large-Scale Systems

Cloud Computing in the ULS Space

NOTE: References at the end

Domain Specific Work

Climate Modeling

NASA JPL

Climate Informatics

**Steve Easterbrook,
University of Toronto**

Financial Markets

**Dave Cliff,
University of Bristol**

Disaster Management

**Martin Griss,
Carnegie Mellon Silicon Valley**

Intelligent Transportation

**Intel
University of Taiwan**

Intelligent River®

Clemson University

Health Information Systems

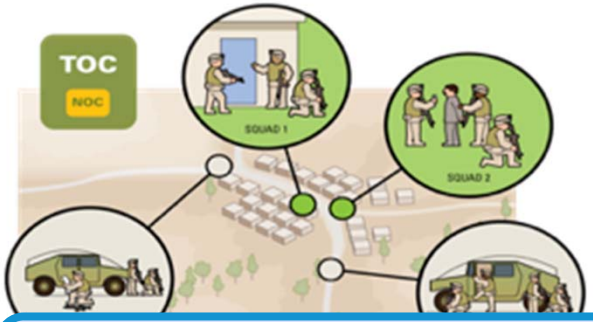
**Kevin Sullivan,
University of Virginia**

Software Defect Analysis in Smart Grid Applications

**M. Ancaari,
Norwegian University of Science and Technology**

Selected SEI Research Targeted at ULS Systems: More Nibbling

Some SEI Research In ULS Systems



Socio-Adaptive Systems Using Computational Mechanism Design and Adaptive QoS

High-Confidence Cyber-Physical Systems

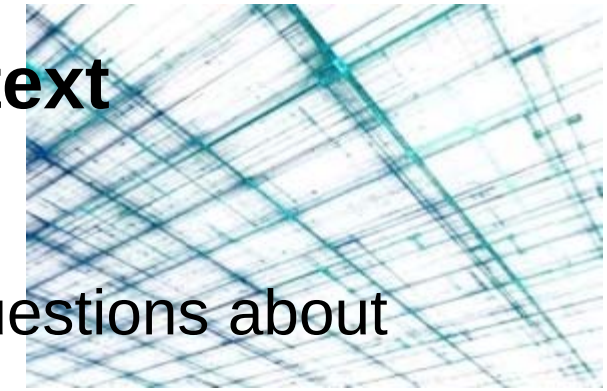
Edge-Enabled Tactical Systems

Augmented and Virtual Actors for Threat Abatement Readiness

Architecture in ULS Systems Context

Concurrent Crowdsourcing of Requirements and Architectures for Socio-Technical Infrastructure Improvement

Architecture in ULS System Context



ULS system characteristics inspire key questions about systems at scale.

- What new quality attributes arise due to scale?
- What types of analyses are required to understand and design systems with these characteristics?
- What new architecture design principles needed?
  - E.g., synergy of concerns instead of separation of concerns?
- What are the associated architectural tactics, patterns, mechanisms?
- What types of analyses and design strategies are needed to design all levels of systems at scale?
  - E.g., population dynamics, connectedness/communication
- And what expertise is required for this design?

Edge-Enabled Tactical Systems (EETS)

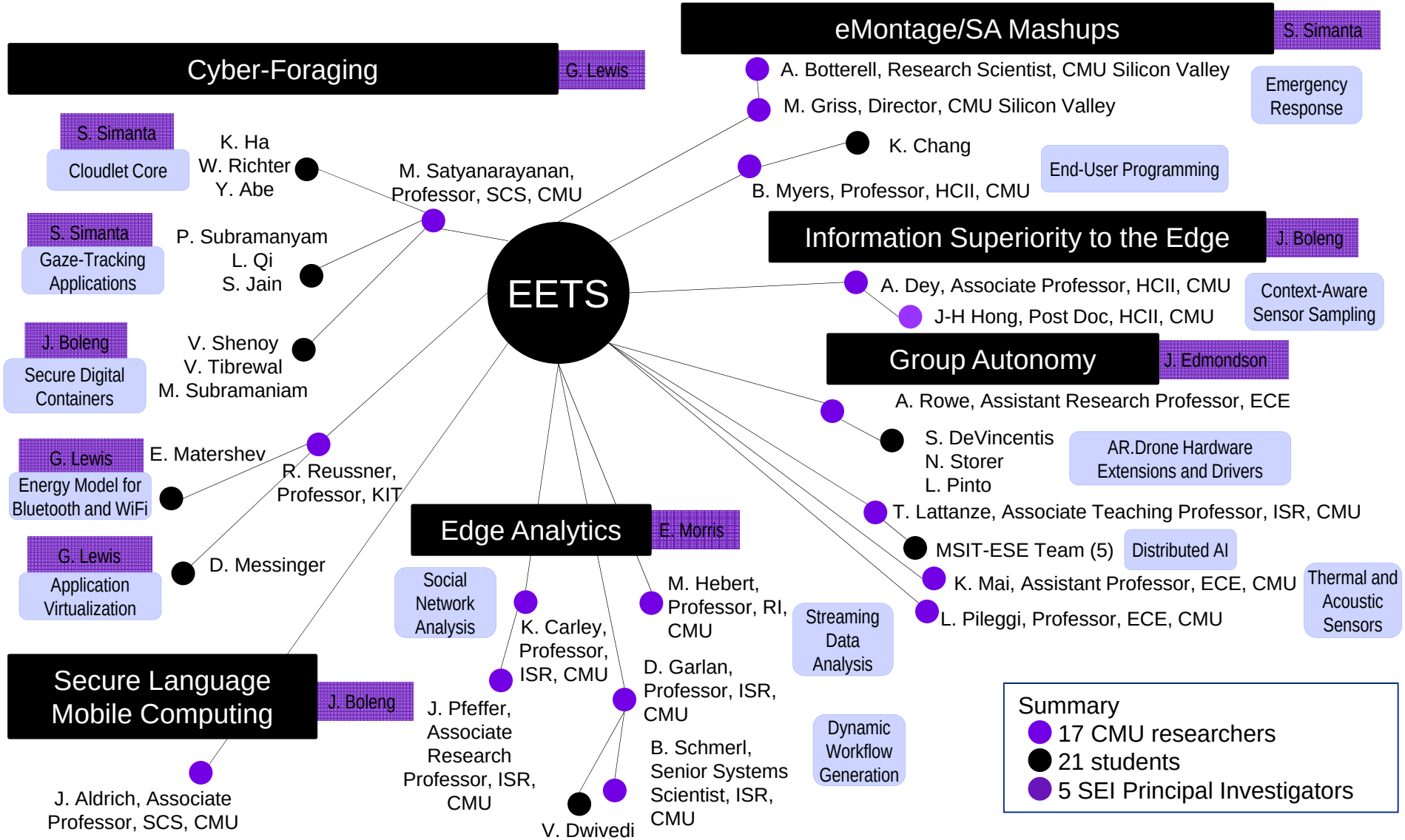
Investigates architectures and technologies that adapt new generations of mobile devices and sensors to support humans operating in demanding edge environments

Mobile technologies can enhance the manner in which people operate in tactical environments

- Local data caching with reach back when available
- Cyber-foraging to enhance handheld and sensor device capabilities
- Flexible deployment and rapid adaptation for new missions
- Context-aware computing to reduce cognitive load and conserve resources
- Local, edge analytics to provide rapid data analysis
- Increased use of autonomy (drones, robots, sensors)

What architectures and technologies support soldiers and other edge users in customizing systems to unique needs, finding information that matters, and to continue processing in uncertain computing environments?

SEI and Broader Carnegie Mellon Collaboration



Reflection:
The Future is Here

So, Where Are We?

The report has been widely distributed via the web and hard copy.

Relevant research is being conducted all over the world.

The confluence of new technology is making ULS systems today.

- with a profound impact on the way society is structured and how society behaves
- substantial engineering challenges are becoming widely recognized if still poorly understood.
  - reliance on *autonomous* behavior
  - increased interaction and interdependence of socio-technical ecosystems
  - increased tempo of change across the spectrum of human behavior – driven by human demand

There is a wide range of technical and non-technical perspectives and approaches that can be brought to bear.

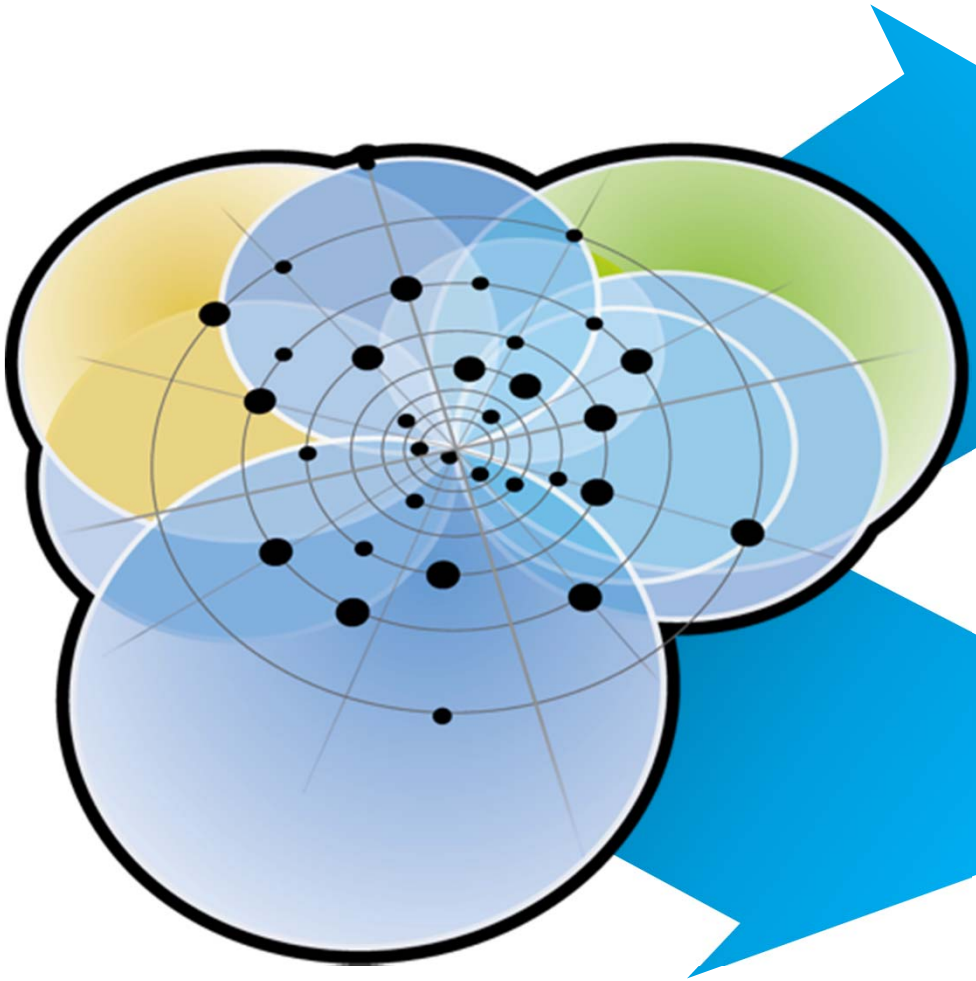
Climate Change (term used by David West at Code Freeze 2013)

Characteristics of ULS systems arise because of their scale.

- Decentralization
- Inherently conflicting, unknowable, and diverse requirements
- Continuous evolution and deployment
- Heterogeneous, inconsistent, and changing elements
- Erosion of the people/system boundary
- Normal failures
- New paradigms for acquisition and policy

These are real.

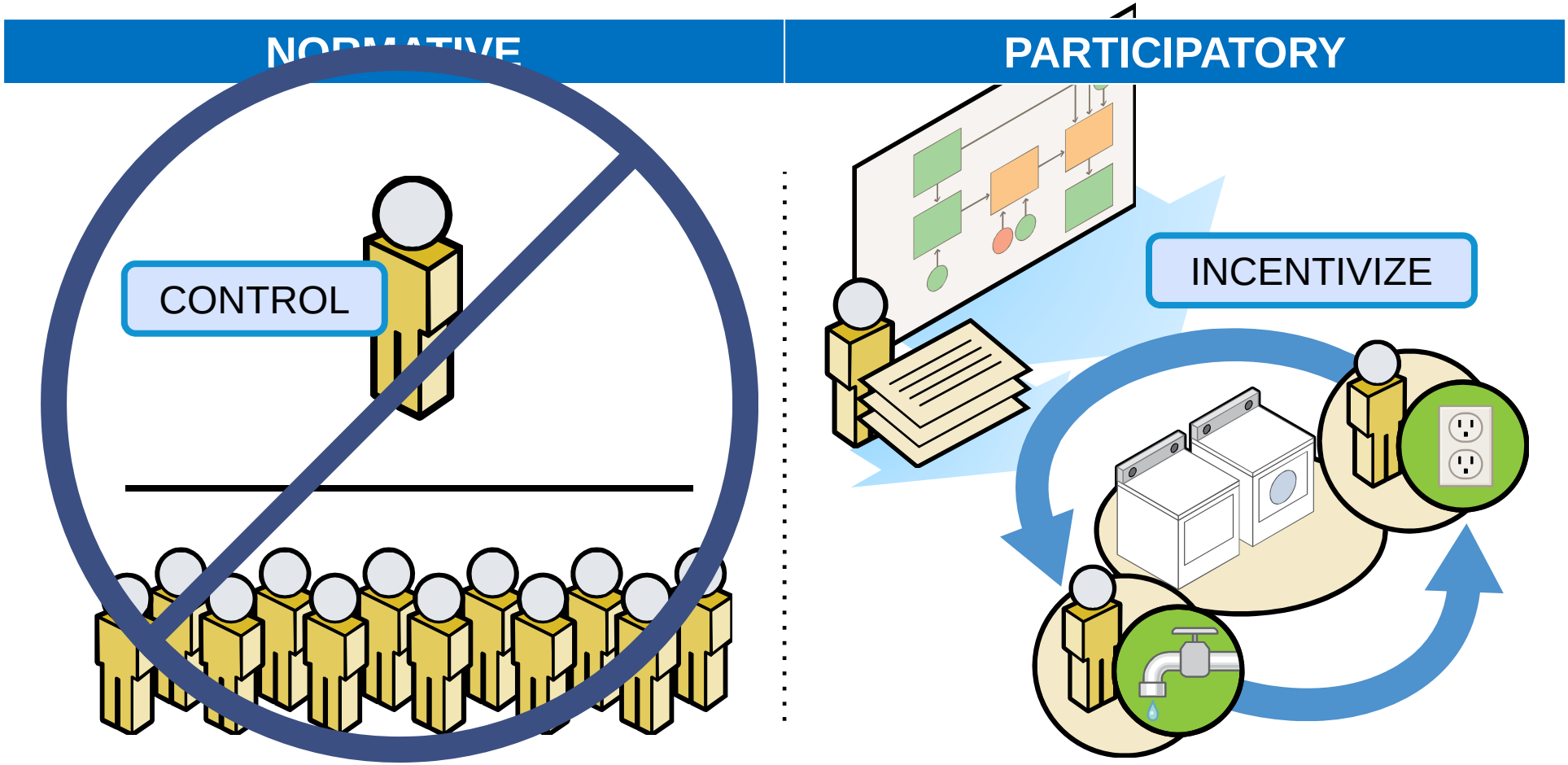
Opportunities and Threats



Opportunity

Threat

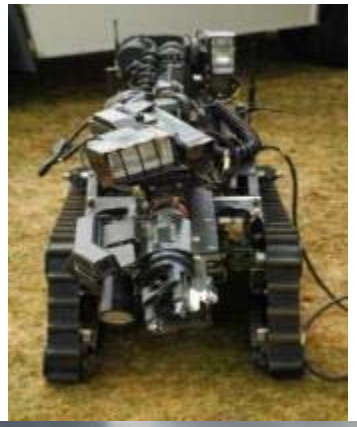
Implications for How We Do Our Work

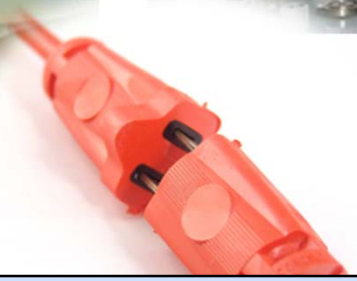


SYSTEMS MUST BE: Responsible | Responsive | Adaptive - SO MUST WE

Putting Technology to Work: a Few Take Aways







Context is key

- Computation needs to be organic with human incentives and human workflow
- Technology standards do not ensure interoperability
- Multi-disciplinary approach is essential

Big data and machine learning don't help without an analytics framework, feedback loops, and analytics-driven sensing

Humans, computational, and autonomous entities are peers

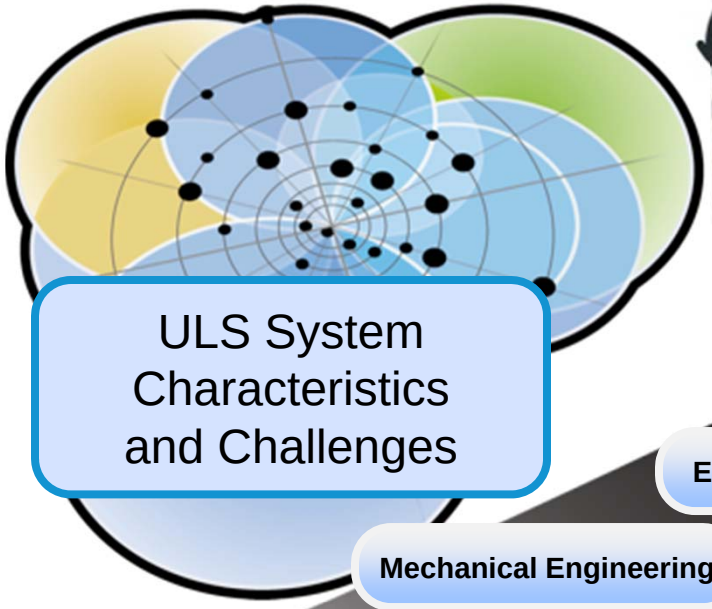
Research Progress – My Assessment

- ✓6.1 Human Interaction
- ✓6.2 Computational Emergence
- ✓6.3 Design
- ✓6.4 Computational Engineering
- ✓6.5 Adaptive System Infrastructure
- ✓6.6 Adaptable and Predictable System Quality
- ✓6.7 Policy, Acquisition, and Management

Progress has been made on all these fronts and others.

And yet…there is a fast growing gap between our research and reality.

What I See



ULS System Characteristics and Challenges

Machine Learning

Mobile Computing

Multicore

Cloud Computing

Social Computing

Autonomous Computing

Economics

Mechanical Engineering

Psychology

Biology

Computer Science

Systems Engineering

Sociology

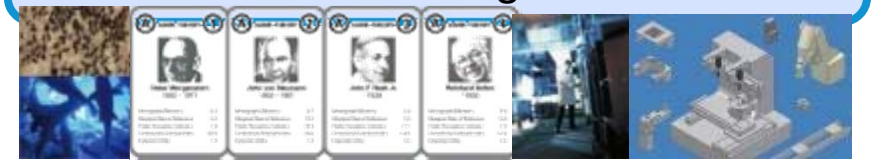
Linguistics

Business

Rhetoric

Organizational Dynamics

ULS System Research Agenda



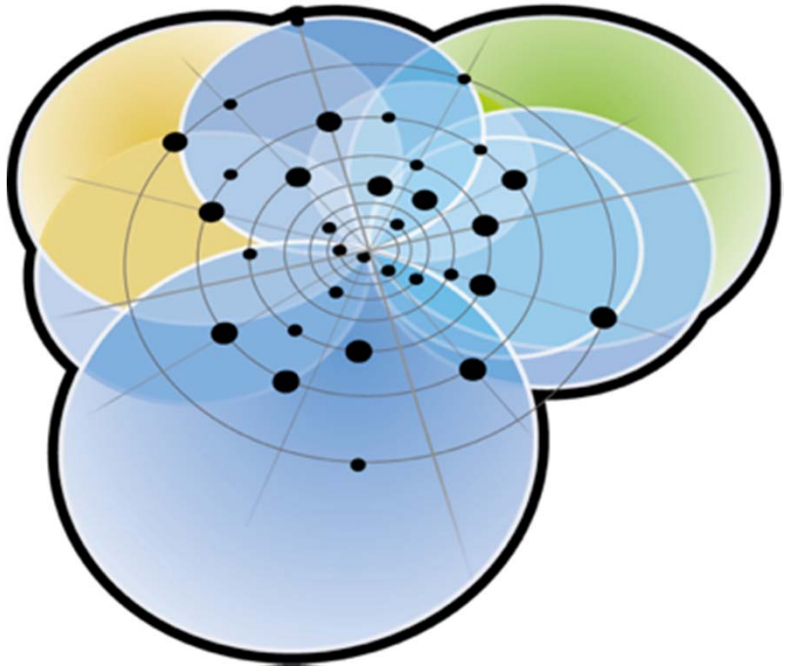
Summing It Up

Scale Matters

- ULS systems are in our midst and the changes to our social fabric and institutions are significant.
- In hindsight, we were probably too conservative in our report.
- Recent technologies have exacerbated the pace of scale growth – allowing us to transcend time and space.
- There are great opportunities.

Food for Thought

- Is our research a match?
- Do we have the right incentives and mindset for the needed multi-disciplinary approach?
- Will we, the software engineering research community, make a difference?



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thank you

Interaction

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