Does Scale Really Matter?:

Ultra-Large-Scale Systems Seven Years after the Study

Linda Northrop
Chief Scientist
Software Solutions Division
Software Engineering Institute
May 24, 2013

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **MAY 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Does Scale Really Matter? Ultra-Large-Scale Systems Seven Years after the Study**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Carnegie Mellon University ,Software Engineering Institute,Pittsburgh,PA,15213**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
presented at the 35th International Conference on Software Engineering (ICSE 2013), 18-26 May, San Francisco, CA and was published by IEEE Computer Society Press.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**102**	

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

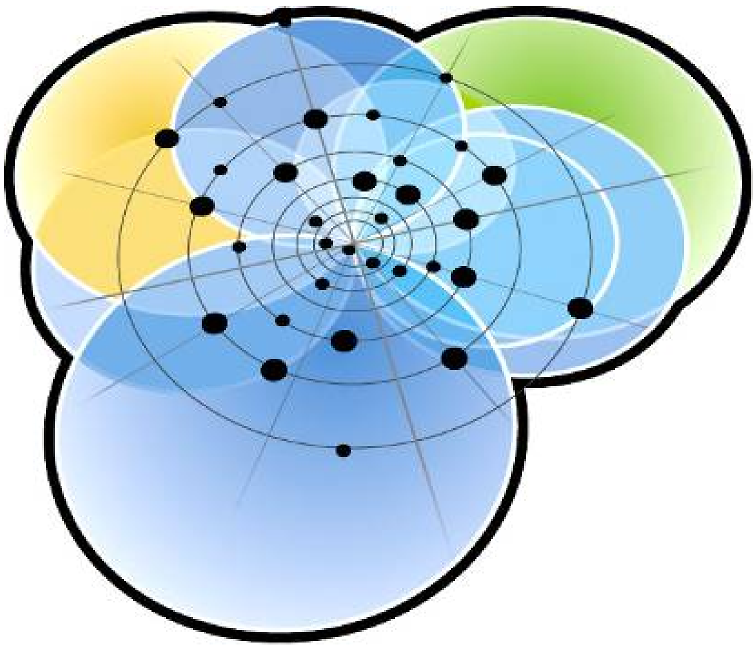
Current Climate

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

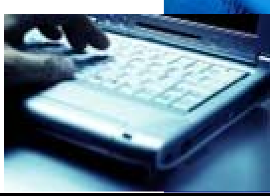
Safety and security

Transportation



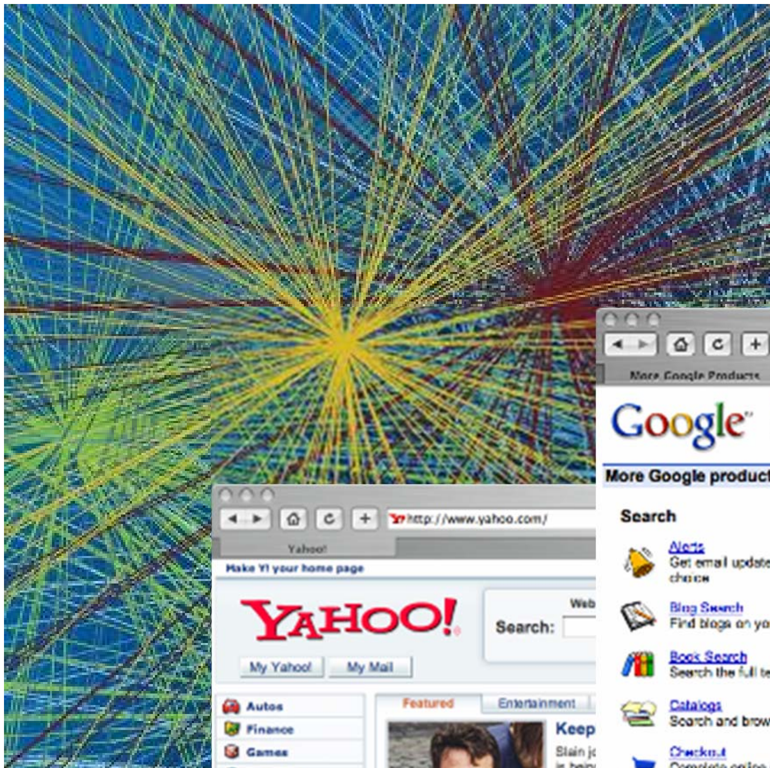


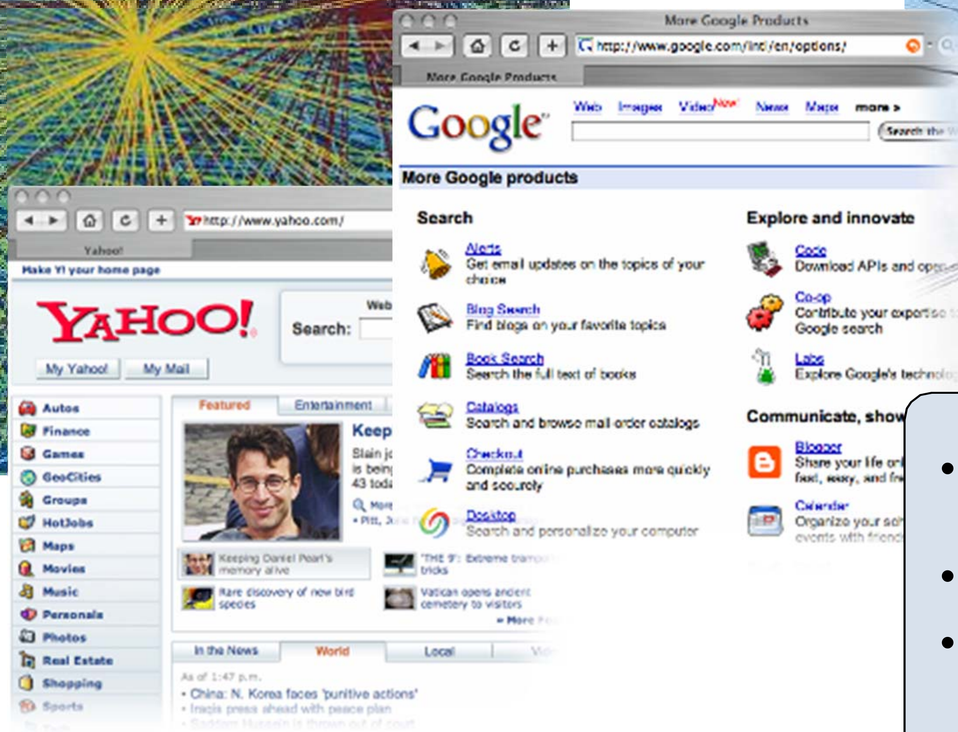




Society’s Dependence on Software

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

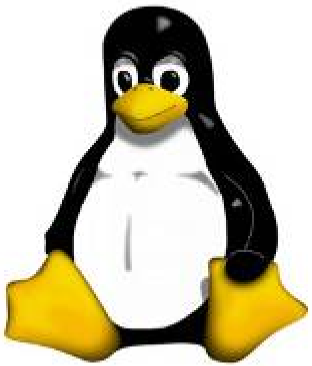
John Lehoczky
Carnegie Mellon University

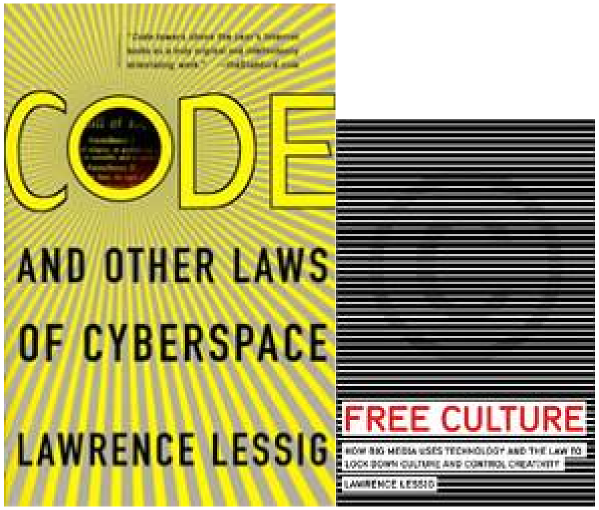
Jack Whalen
PARC

The Journey


2006
SUMMIT
PIKES PEAK
ALTITUDE 14,110 FT.
COG WHEEL ROUTE
A SUMMIT PHOTO IS A LASTING MEMENTO OF
YOUR TRIP TO THIS WORLD-FAMOUS PEAK

Inspiration: Open Source and Cooperative Communities

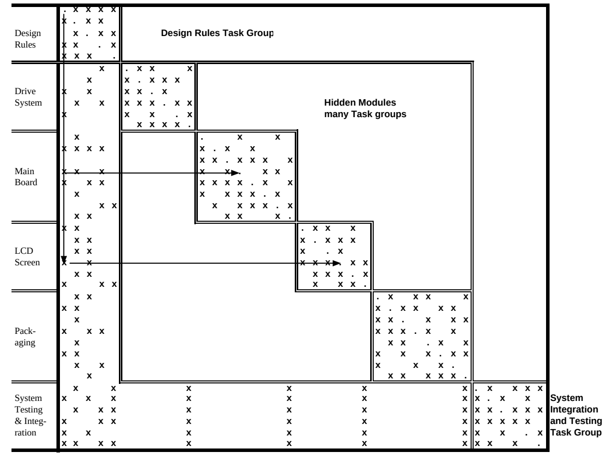




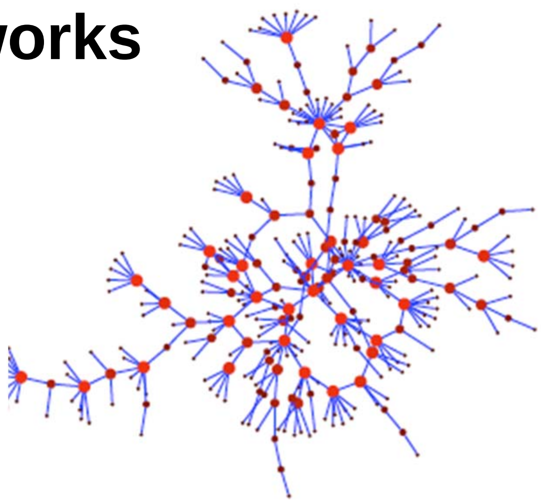
More Inspiration

Game Theory

Economics

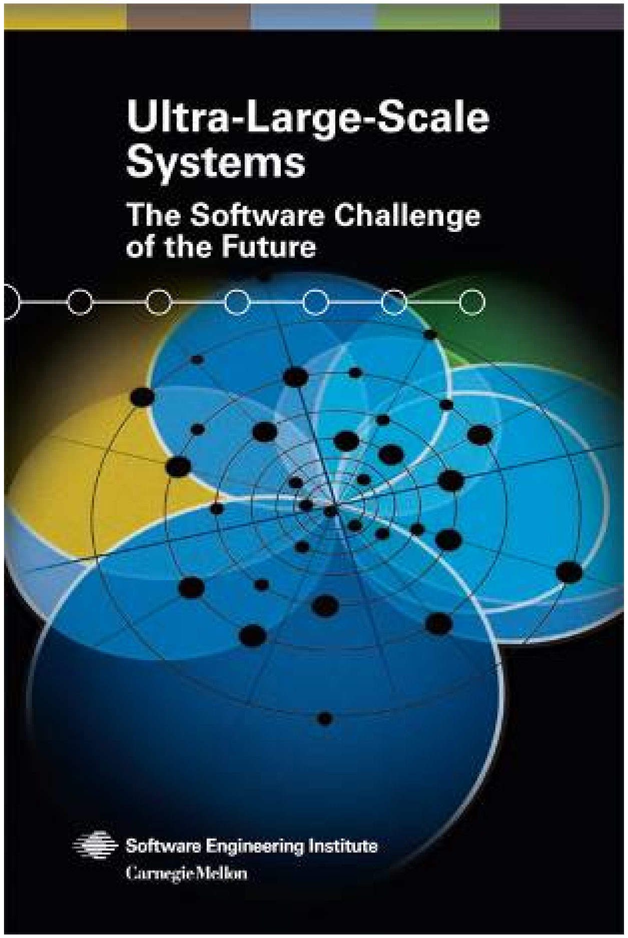


Networks



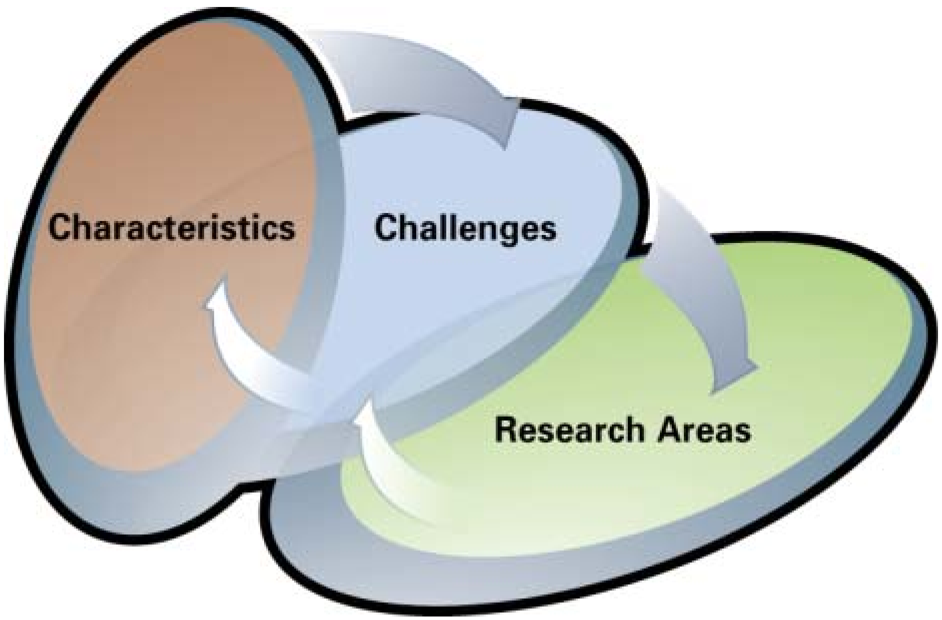
Statistical Mechanics

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

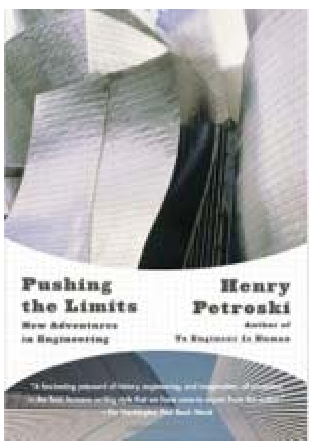
Approaches to Software Development

The Engineering Perspective

The Agile Perspective

A New Perspective is Required

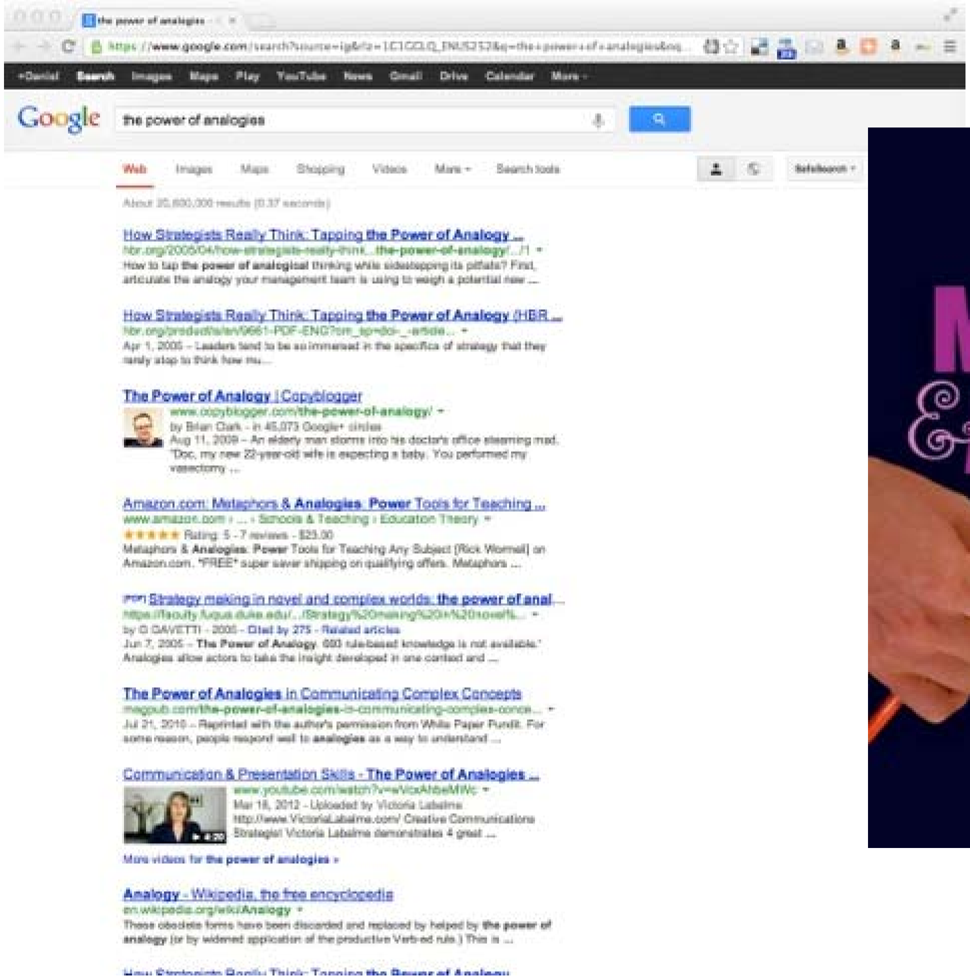
“The older is not always a reliable model for the newer, the smaller for the larger, or the simpler for the more complex…Making something greater than any existing thing necessarily involves going beyond experience.”

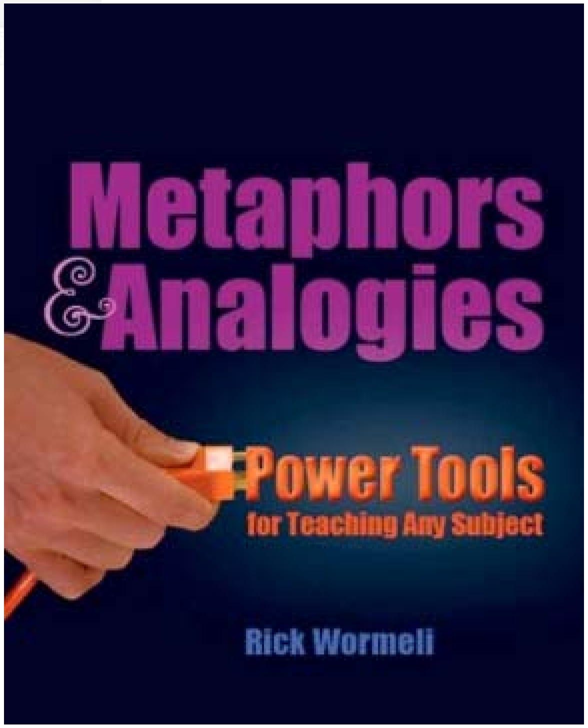


Henry Petroski

Pushing the Limits: New Adventures in Engineering

Analogies are Useful

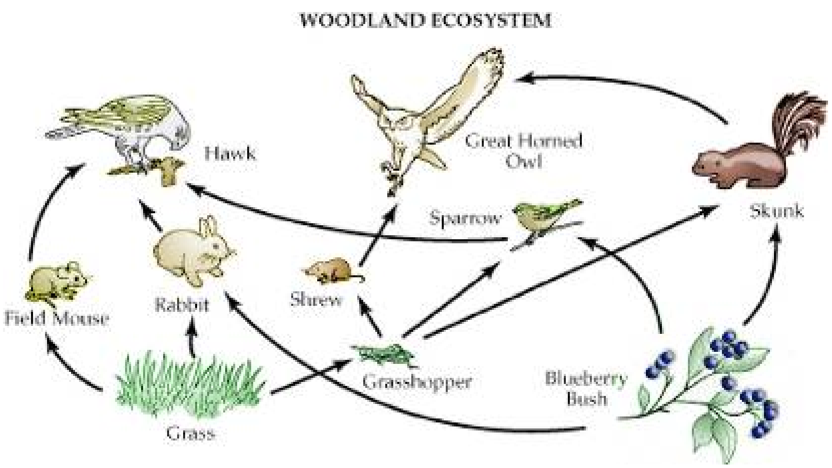




Think Cities not Buildings

“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

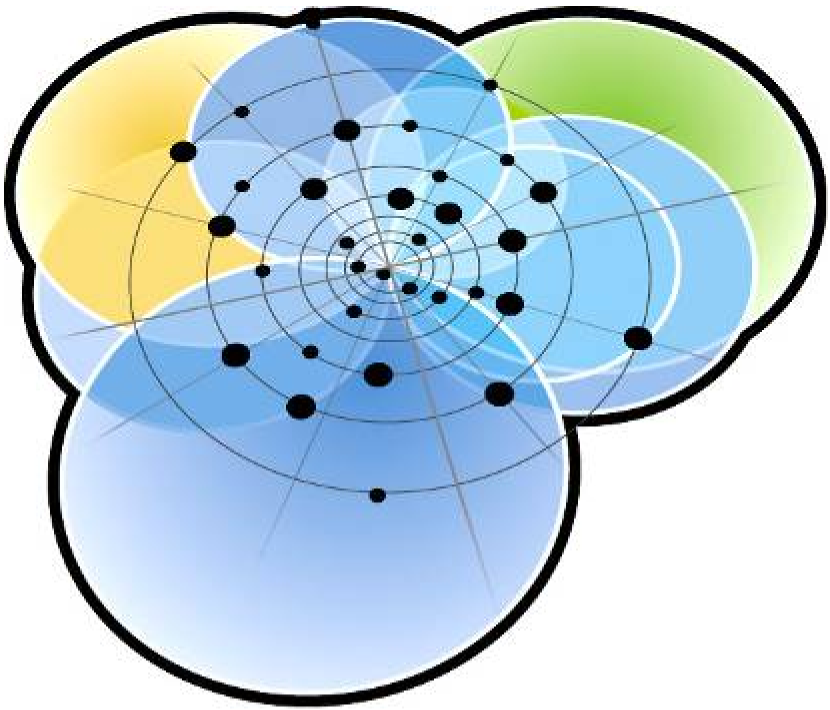
Has:

- 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.

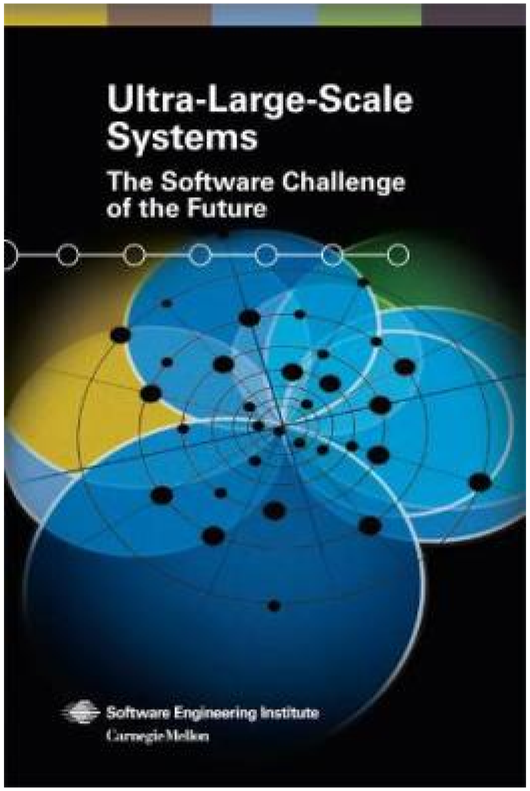
These changes undermine the assumptions we routinely make in traditional software engineering approaches.

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.”



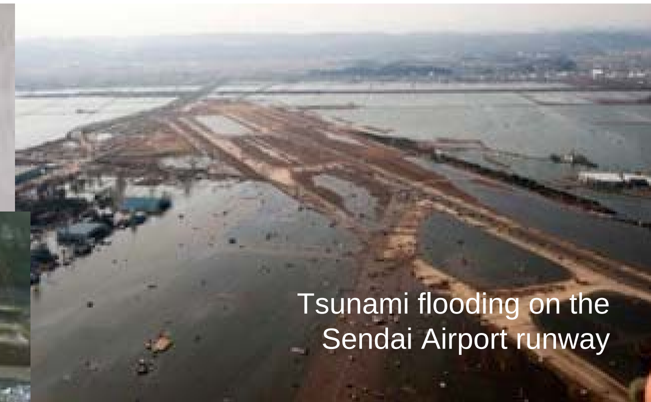
Early Post-Study Observations

- 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.

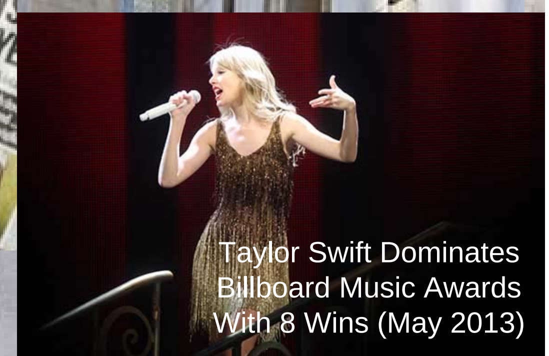
Seven Years Later

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

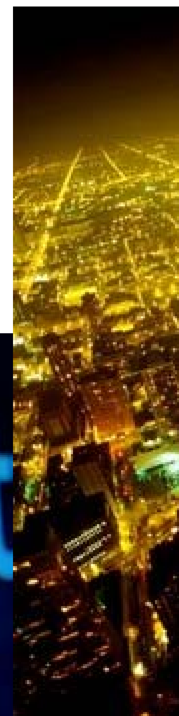
Powering our civilization

Disease, epidemics, and health care

Livable megacities

Safety and security

Transportation



Software is Ubiquitous and Often Transparent

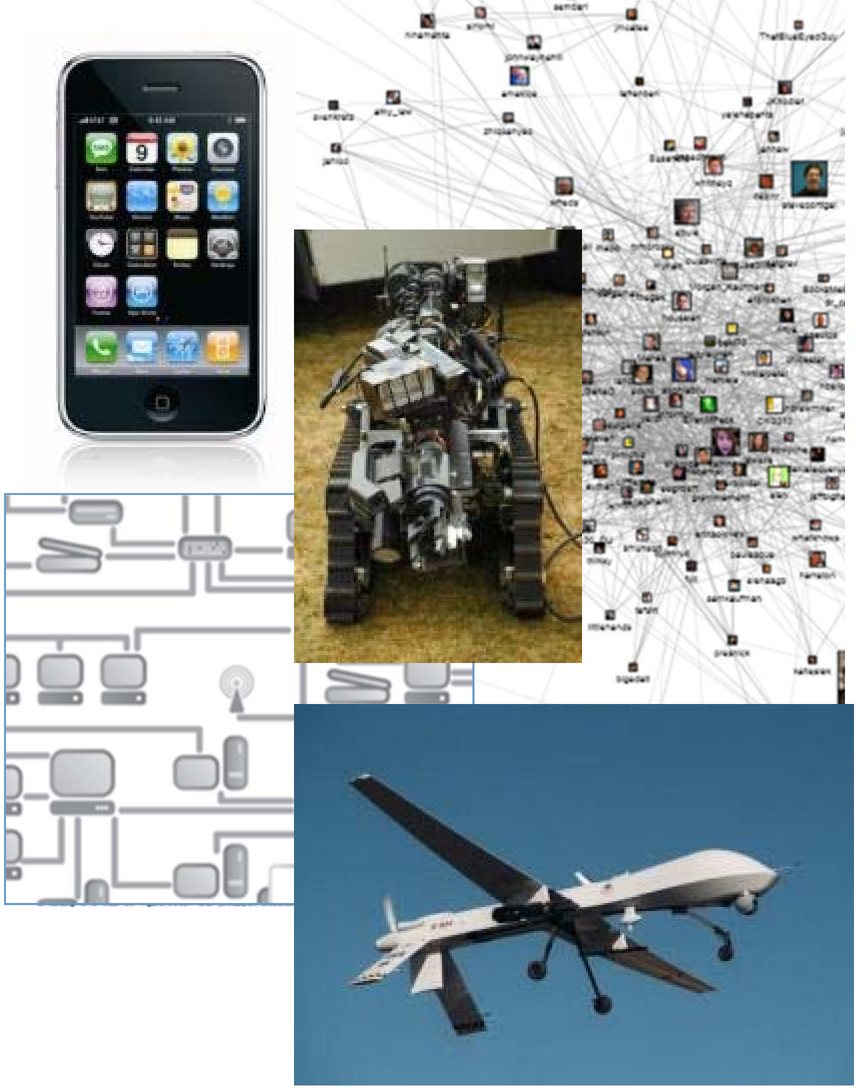
Software-Reliant Systems: What HAS Changed?

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


HEADLINES
"CYBERSECURITY STARTS IN HIGH SCHOOL WITH TOMORROW'S HIRES
CISPA CYBERSECURITY BILL BACKERS HOPE SECOND TIME'S A
WHAT CAN BE DONE ABOUT THE CYBERSECURITY SKILLS SHORTAGE?
WHAT COMES AFTER THE CYBER SECURITY STRATEGY?
GOVERNMENT TO SHARE CYBER SECURITY INFORMATION WITH
TOP US ADMIRAL PUTS CYBER SECURITY ON THE
US INVESTMENT IN CYBER-SECURITY EQUAL TO
GLOBAL CYBER DEFENSE EXPERTS TAKE ON
AIR FORCE HACKERS WIN NSA'S 13TH ANNUAL
CURTIS LEVINSON, UNITED STATES
JAPAN, U.S. CONCLUDE 1ST DIALOGUE
ROCHESTER INSTITUTE OF
GOVERNMENT TO SHARE
INCREASE COOPERATION
NEW SOFTWARE SPOTS,
CARS' INTERNET
KERALA GETS FIVE
HACKING
RECENT
MILLENNIAL
GENERATION
TIME
THE
ME ME ME
GENERATION
Millennials are lazy, entitled narcissists who still live with their parents
Why they'll save us all
The Power of Organizing Without Organizations
HERE COMES EVERYBODY
Revolution doesn't happen when society adopts new technology, it happens when society adopts new behaviors
CLAY SHIRKY
author of COGNITIVE SURPLUS
WITH AN UPDATED EPILOGUE

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.

Industrial Shift

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?

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

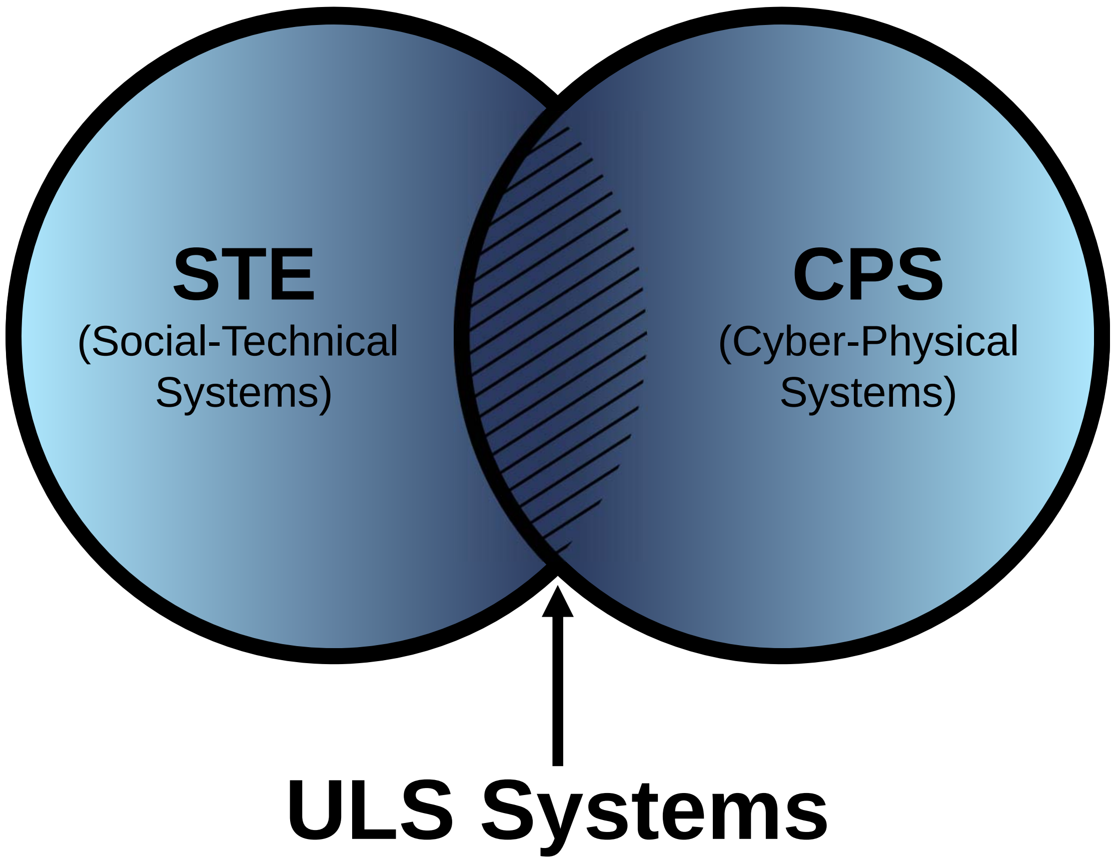
http://blog.johnrooksby.org/post/1329670 33/notes-on-ultra-large-scale-systems

John Rooksby

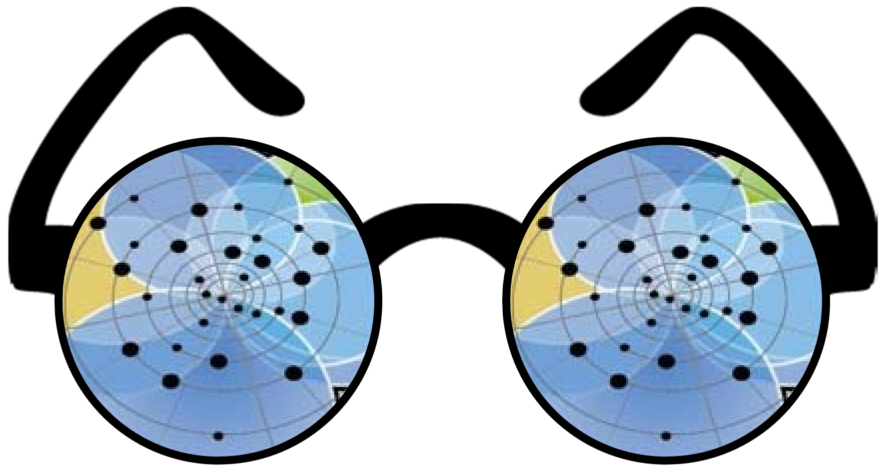
University of Glasgow

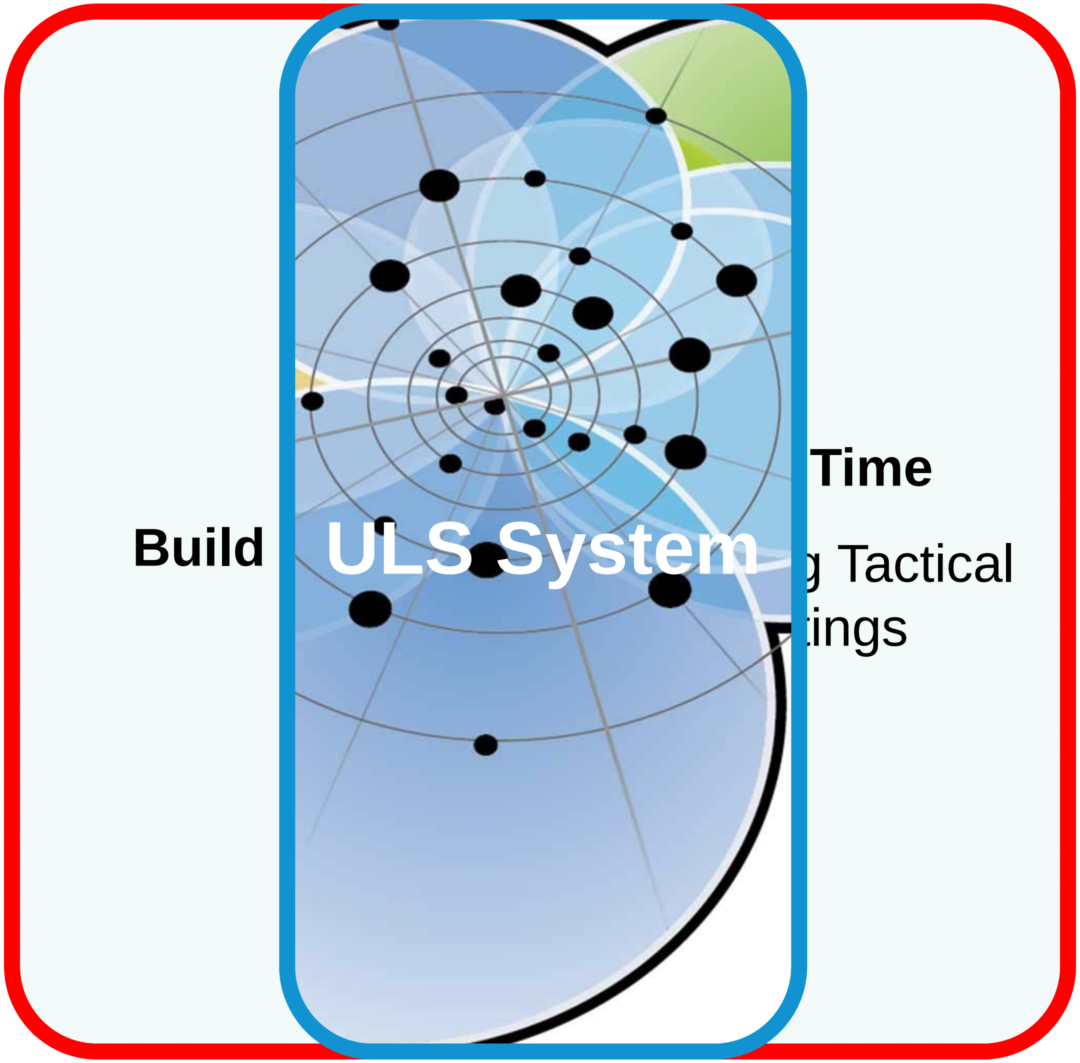
"True to national stereotypes the Americans were asking *how can we build the biggest systems in the world*? The British were asking *how can we stop screwing up when we try to build the biggest systems in the world*?"

Upon Reflection



ULS System Perspective

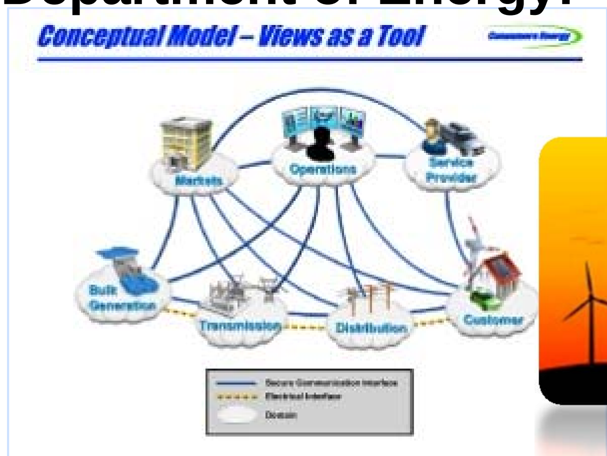


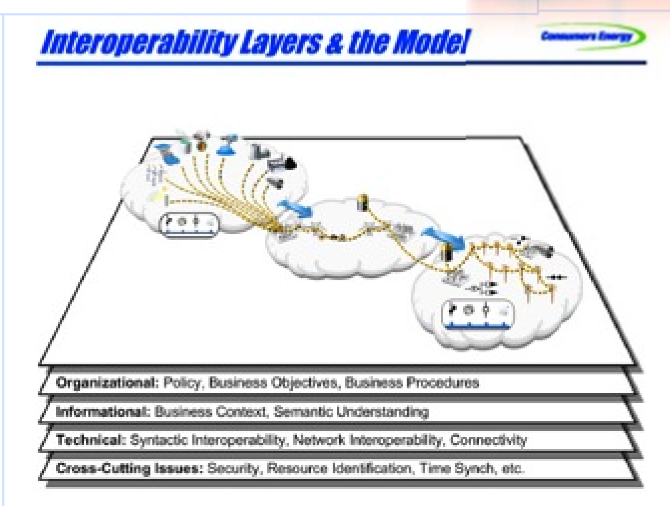

Build
ULS System
Time
g Tactical
tings

Selected Experiences with Systems at Scale:

Nibbling at the Edges

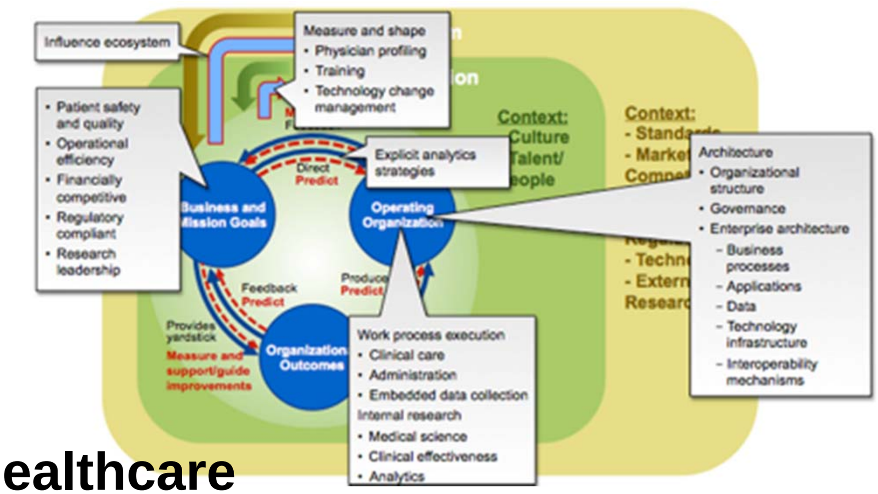
Department of Energy: Smart Grid





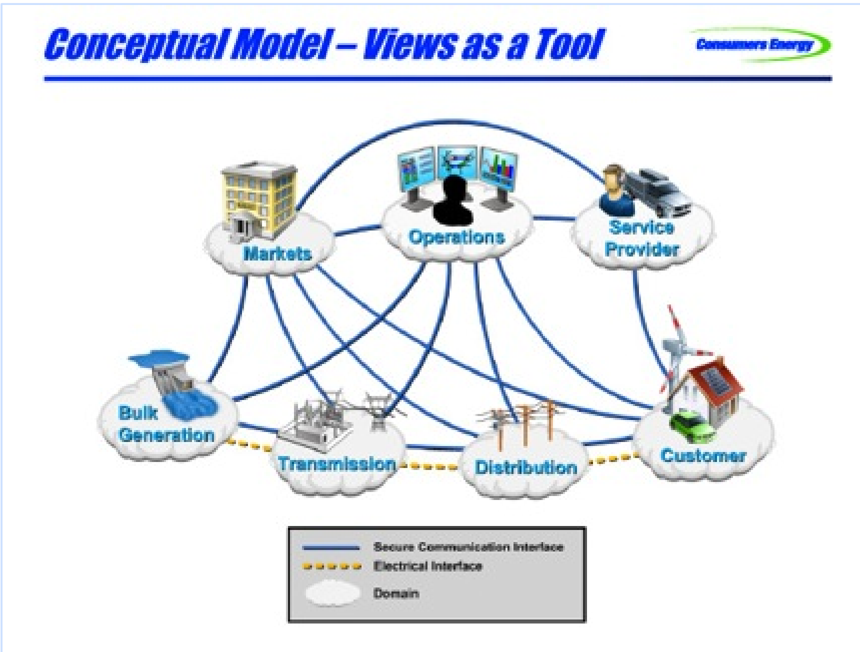
Diagrams courtesy of
Wayne Longcore
Consumers Energy

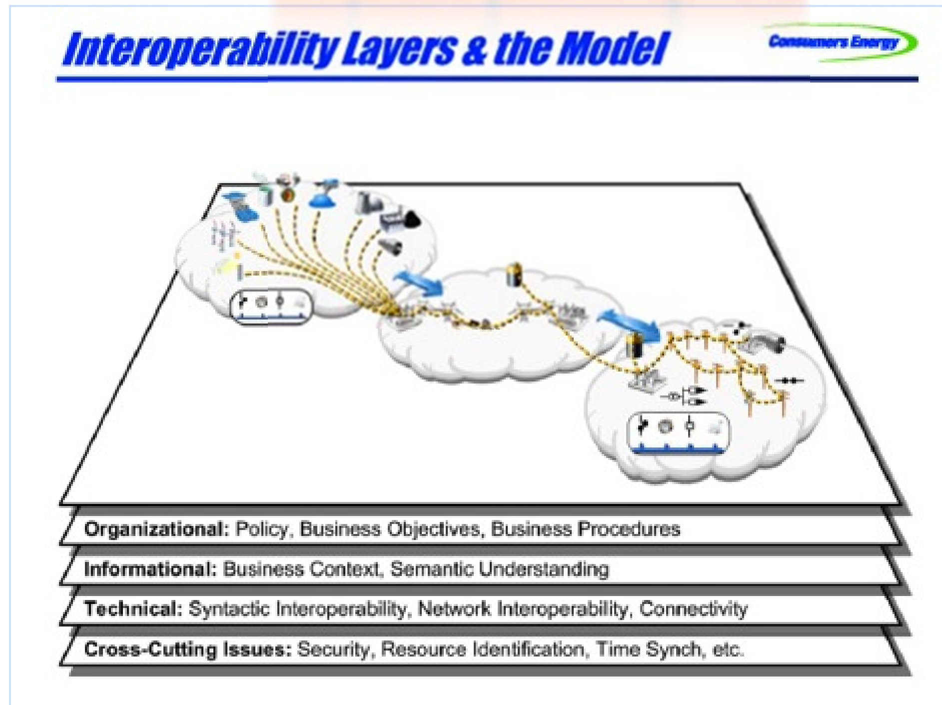
The eXtreme Science and Engineering Discovery Environment (XSEDE) enhances the productivity of scientists and engineers.



Healthcare Analytics

Smart Grid – A ULS System





Diagrams courtesy of

Wayne Longcore

Consumers Energy

Specific Problem and Technical Approach

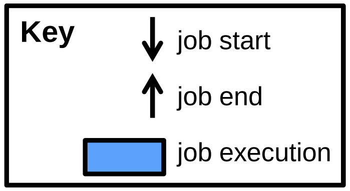
Problem

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.

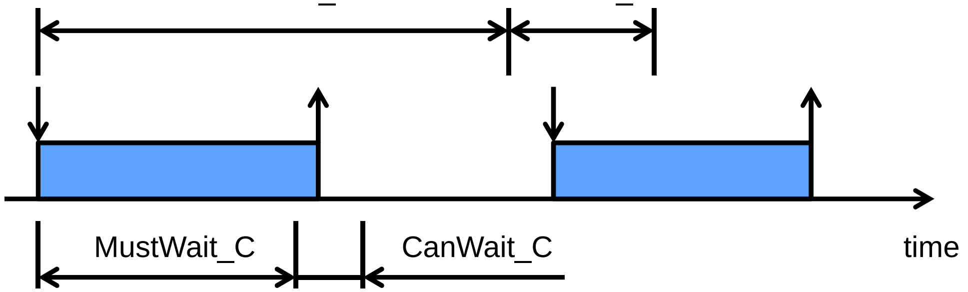
Intelligent Electronic Devices (devices deployed to control field equipment) exhibit several desirable characteristics



- 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
- ..

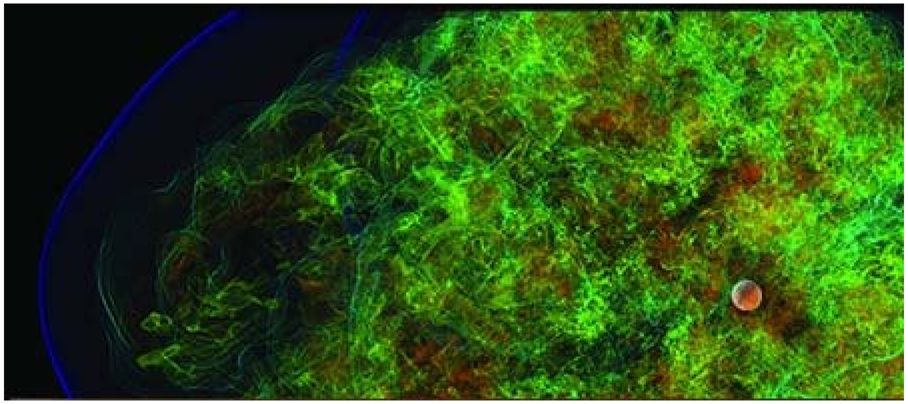
XSEDE

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.

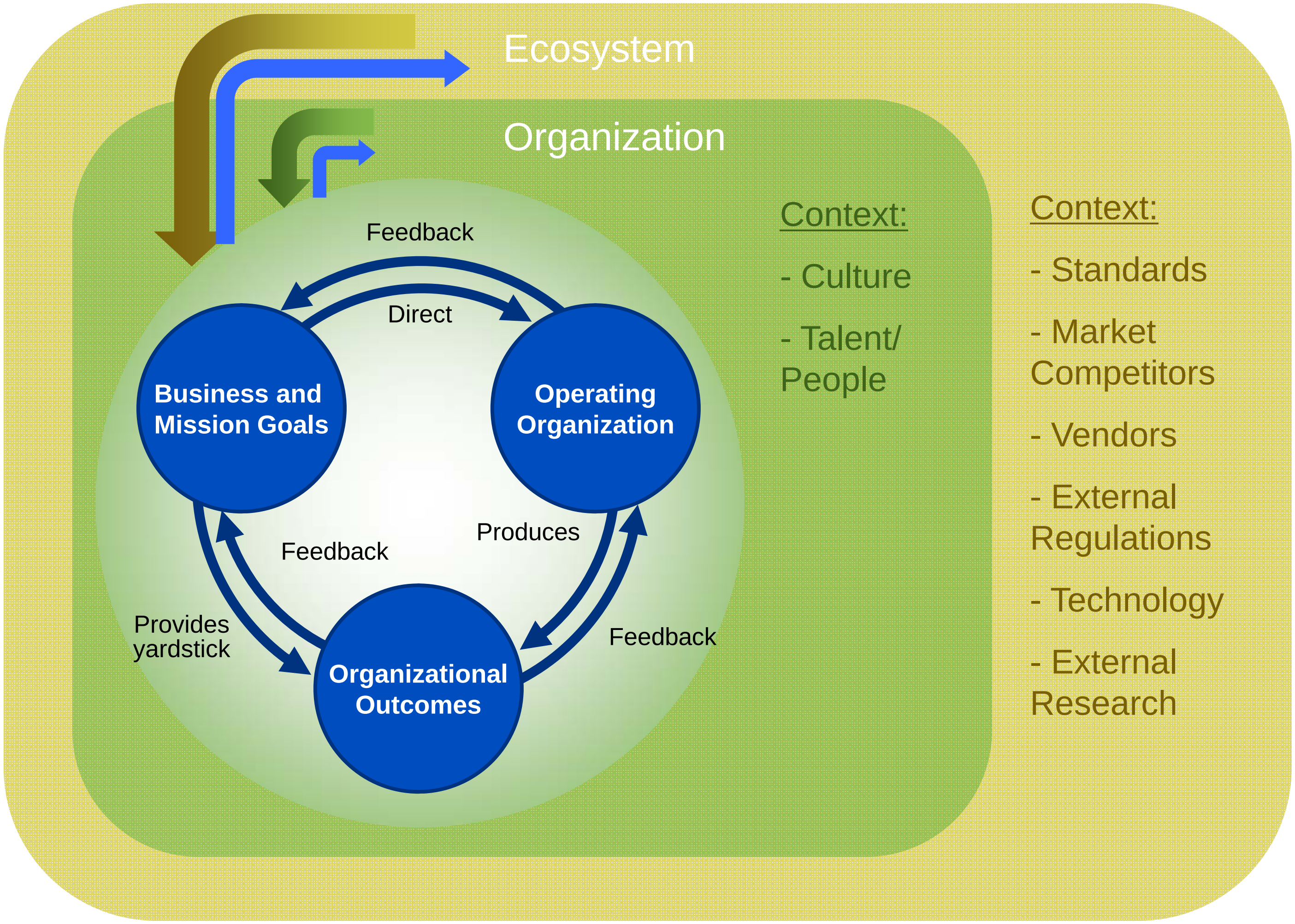
Healthcare Analytics

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

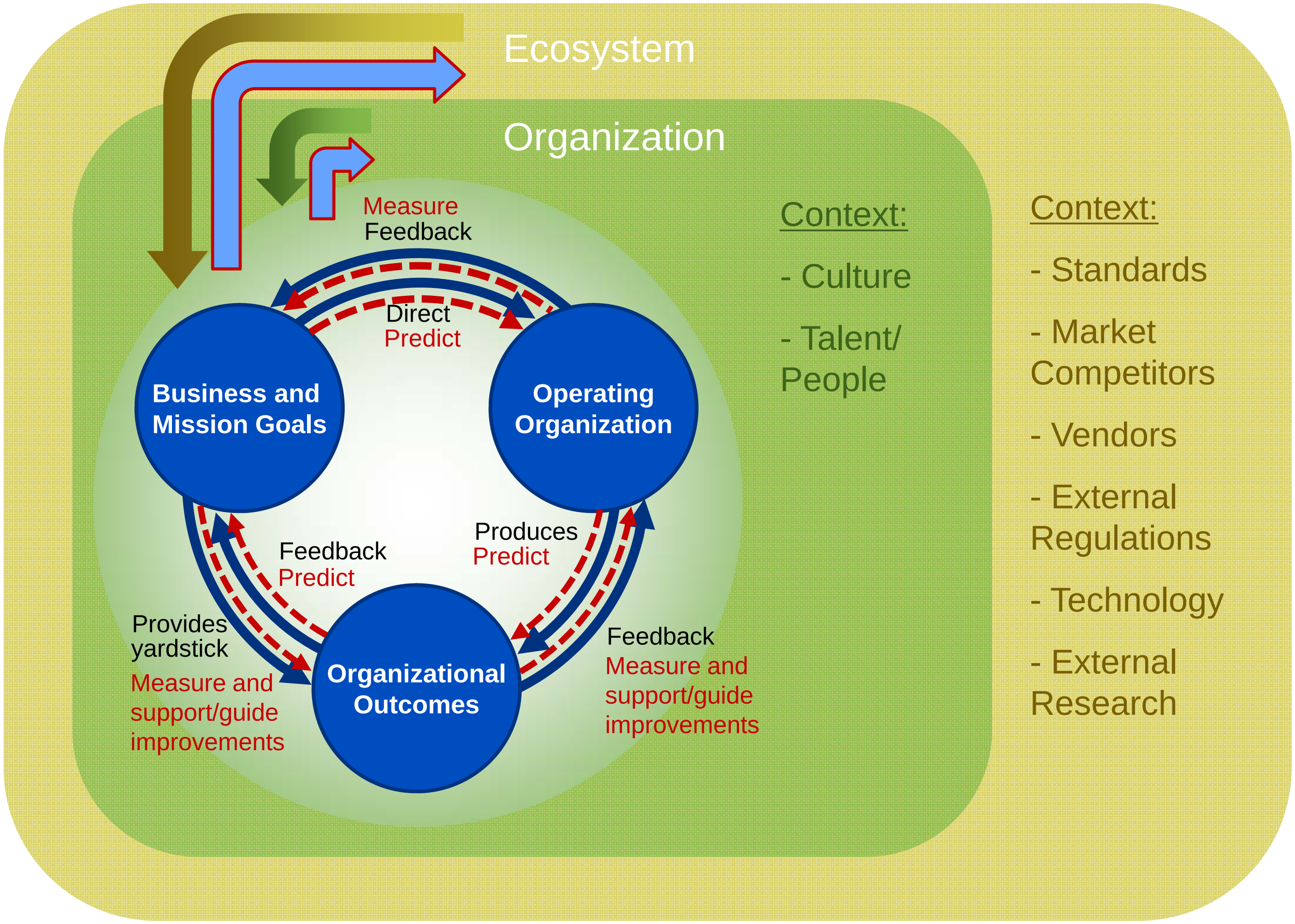
Healthcare Infrastructure

Approach: Define an analytics framework.

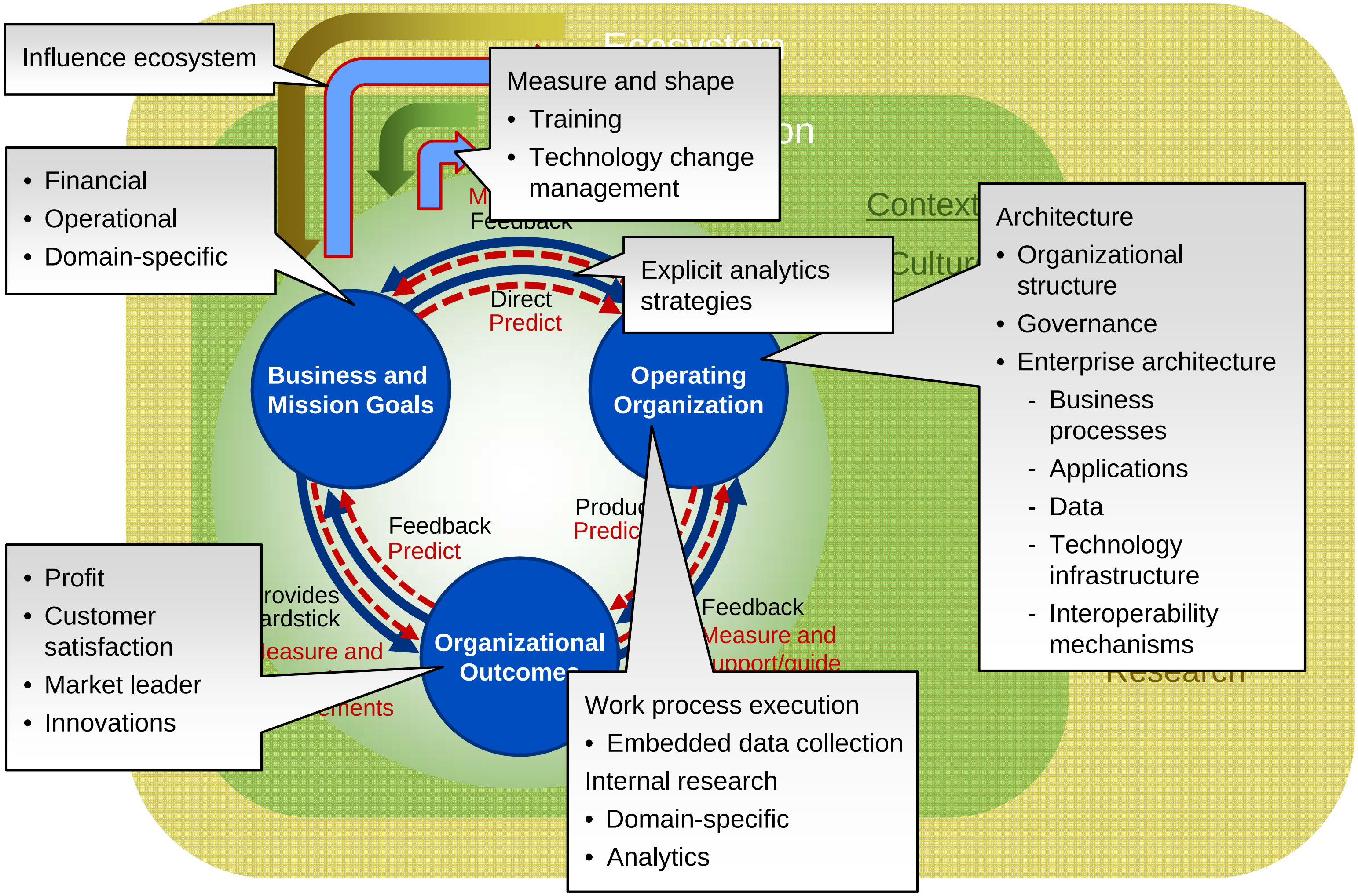
Organizational Dynamics



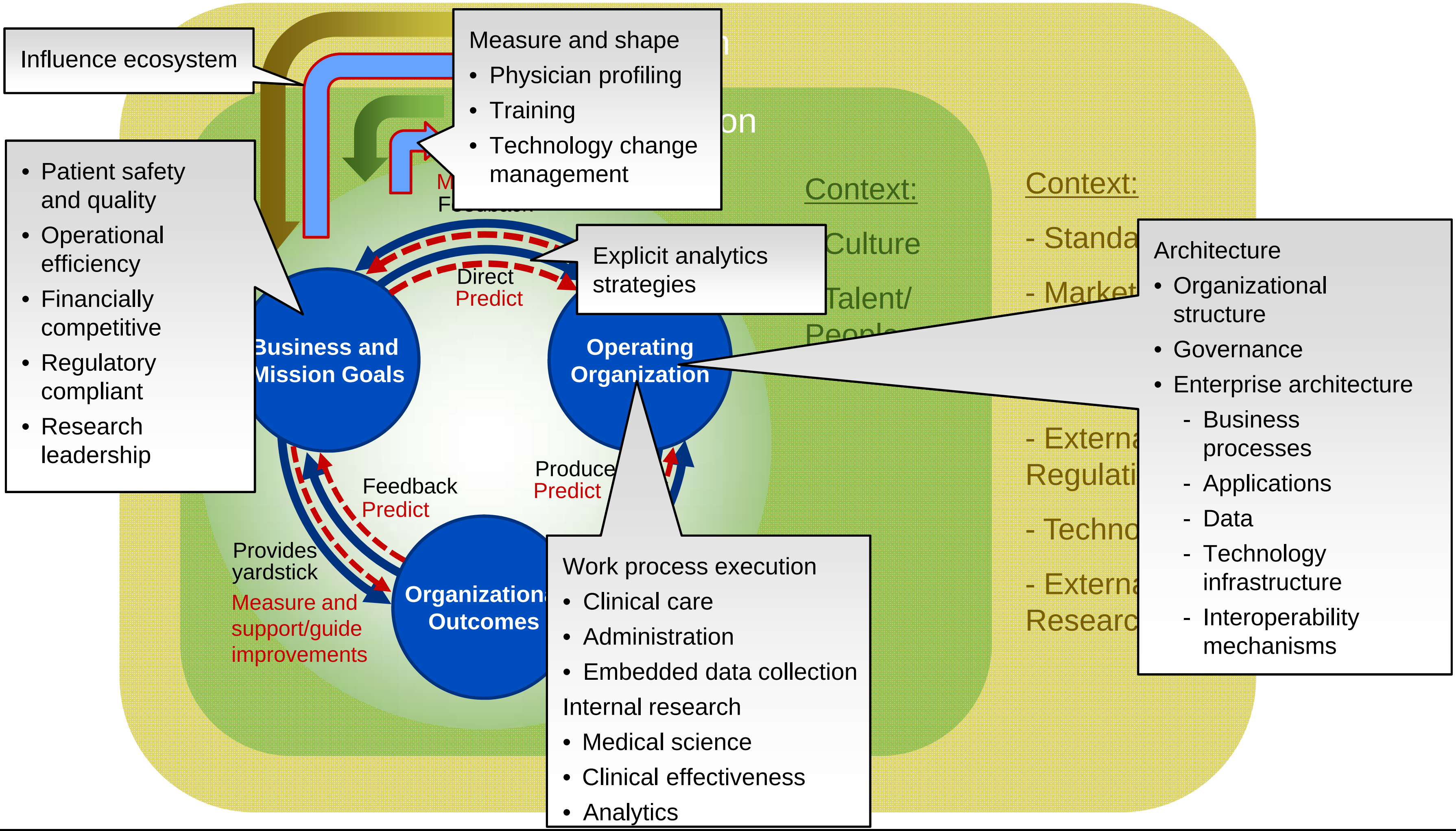
Adding Analytics



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

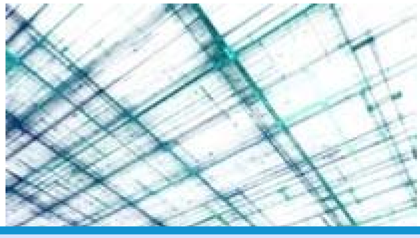
Selected SEI Research Targeted at ULS Systems: More Nibbling

Some SEI Research In ULS Systems

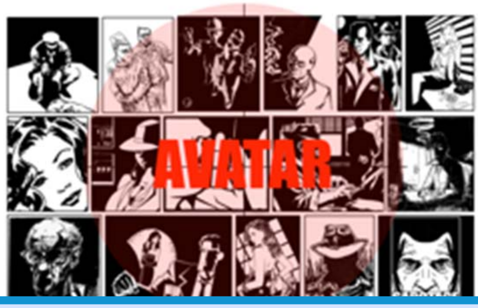
Socio-Adaptive Systems Using Computational Mechanism Design and Adaptive QoS

High-Confidence Cyber-Physical Systems

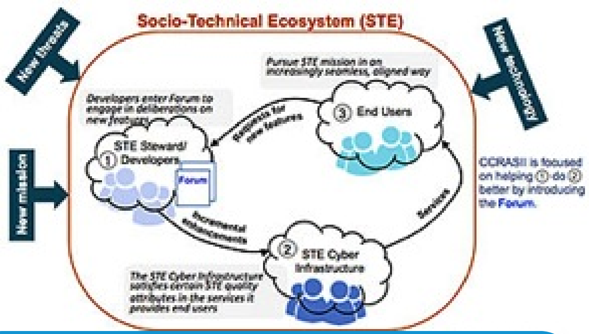
Edge-Enabled Tactical Systems



Architecture in ULS Systems Context

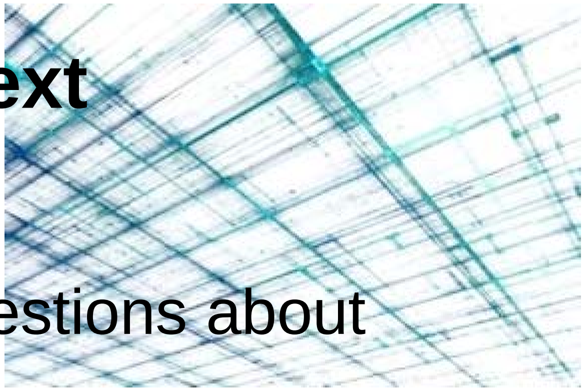


Augmented and Virtual Actors for Threat Abatement Readiness



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)

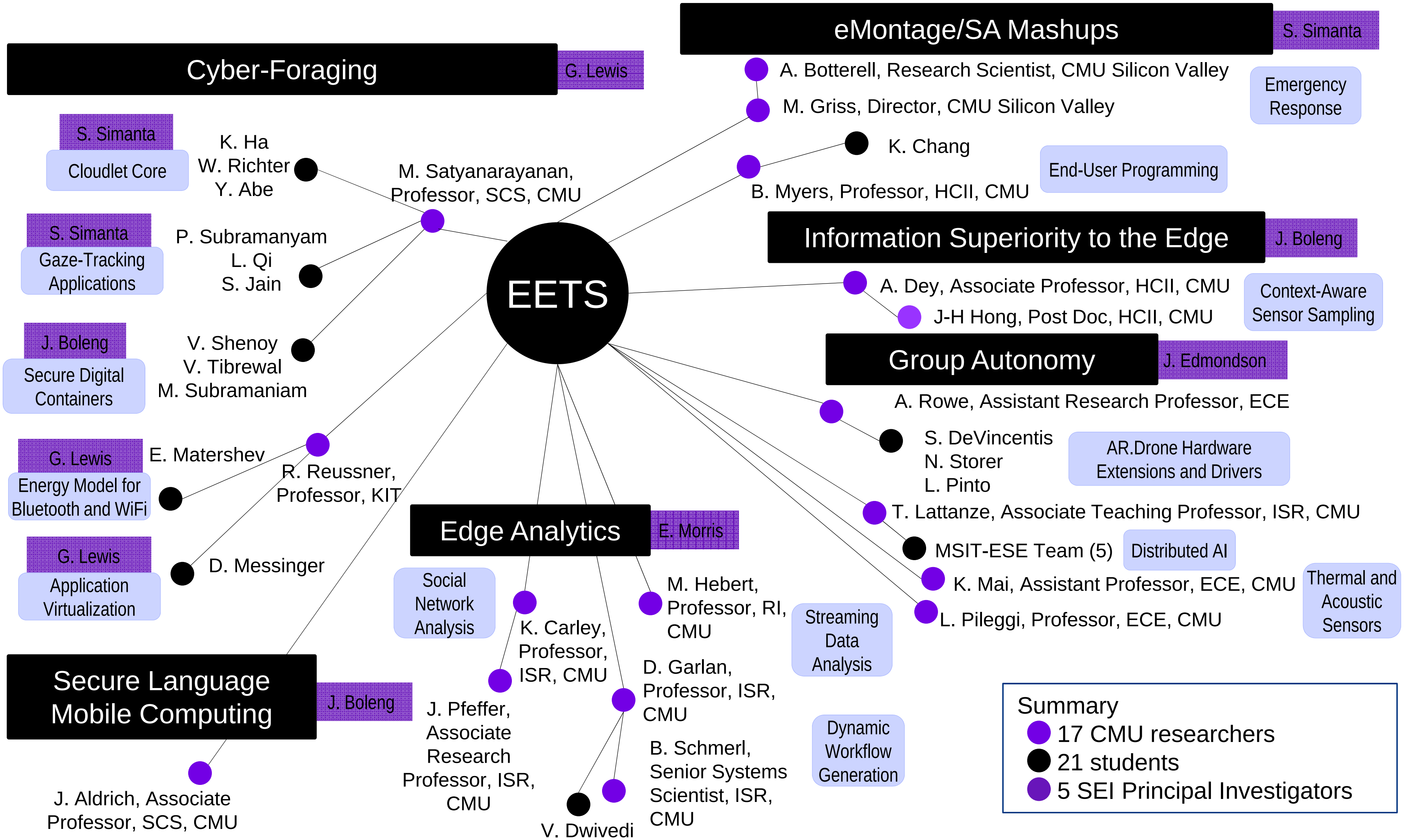
Investigates architectures and technologies that adapt new generations of mobile devices and sensors to support humans operating in demanding edge environments

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.

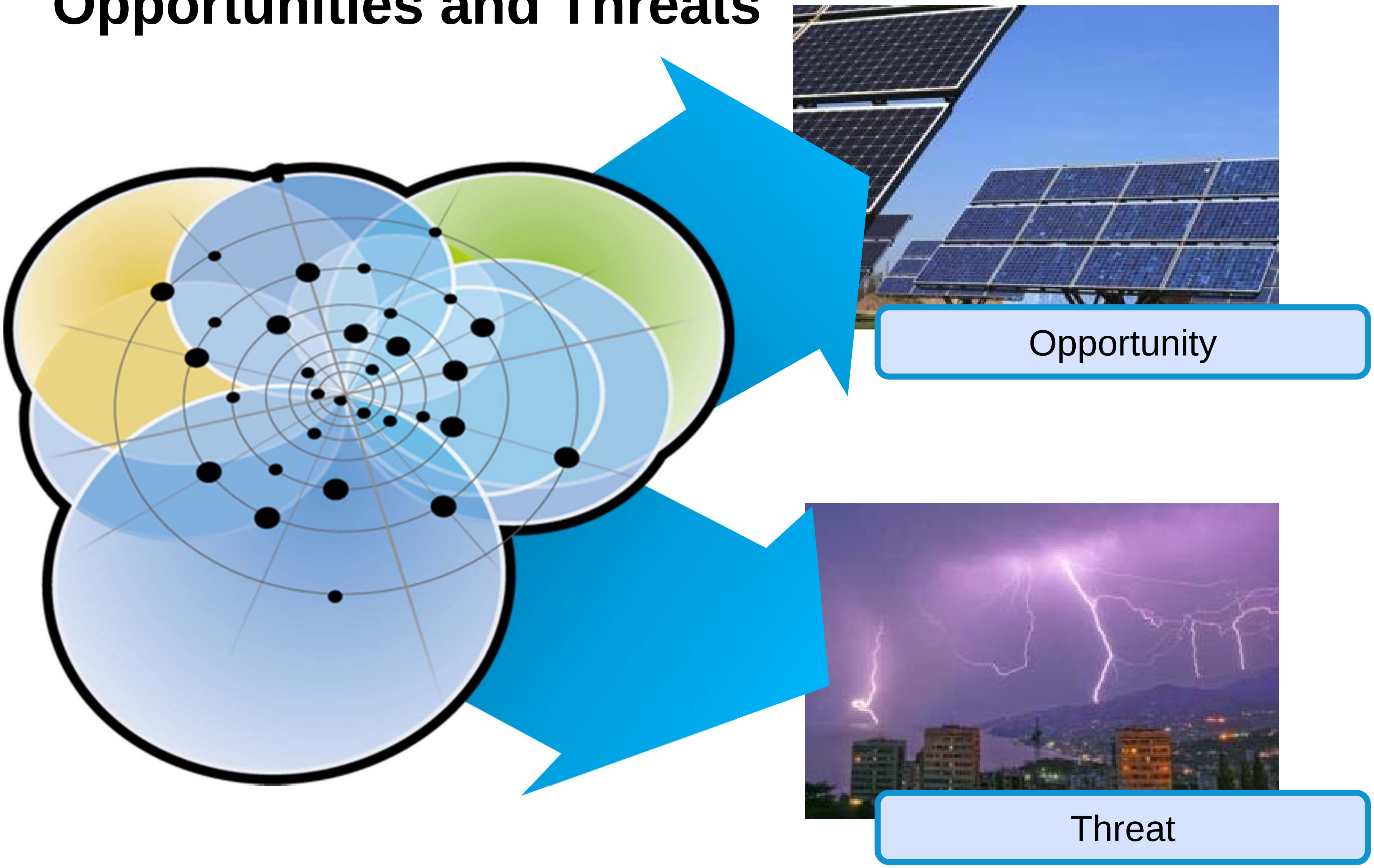
Climate Change (term used by David West at Code Freeze 2013)

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

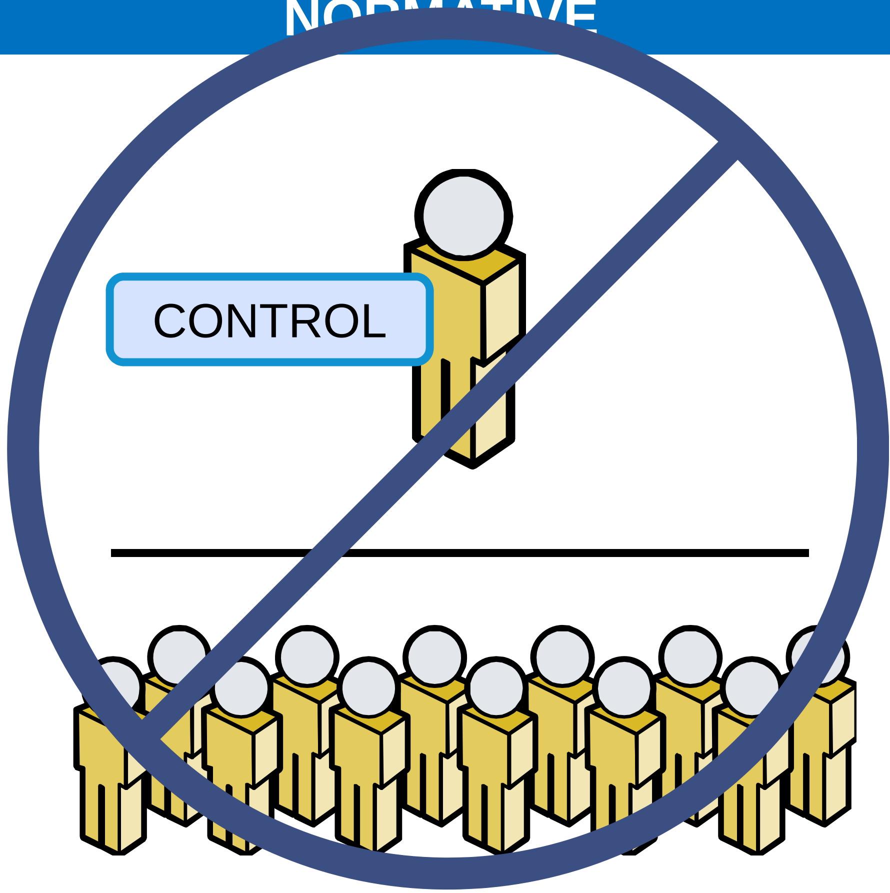
These are real.

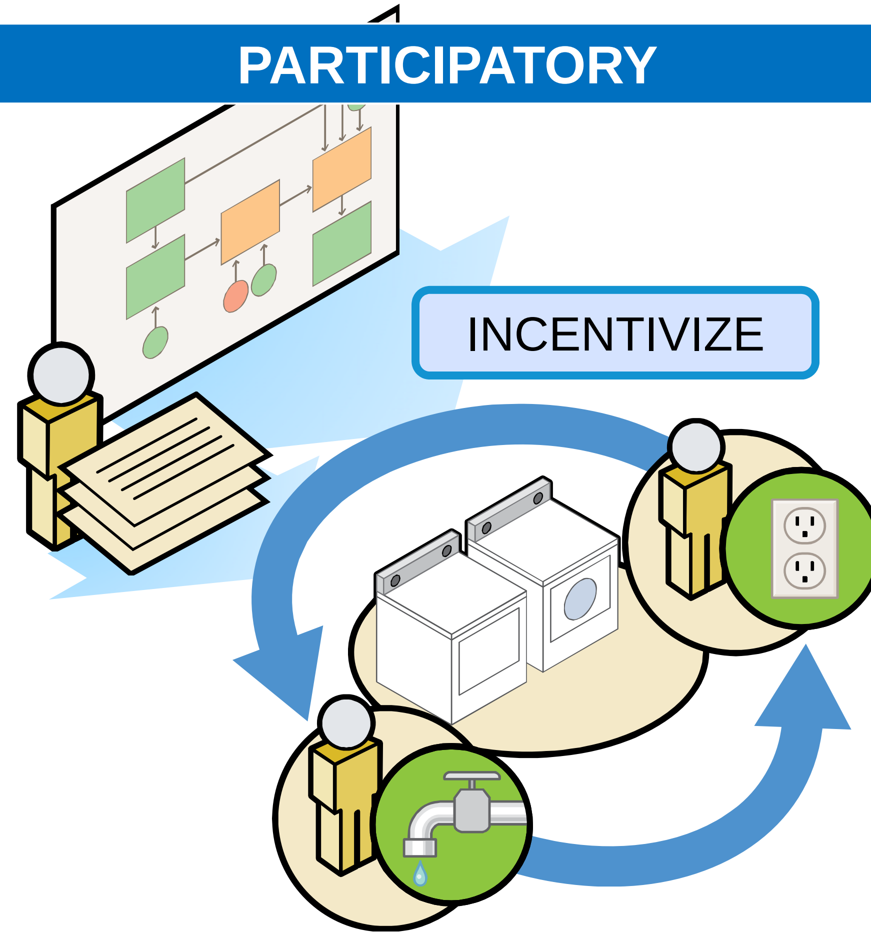
Opportunities and Threats



Implications for How We Do Our Work

NORMATIVE	PARTICIPATORY





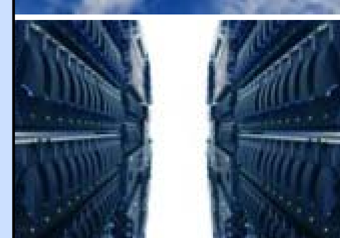
SYSTEMS MUST BE: Responsible | Responsive | Adaptive - SO MUST WE

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

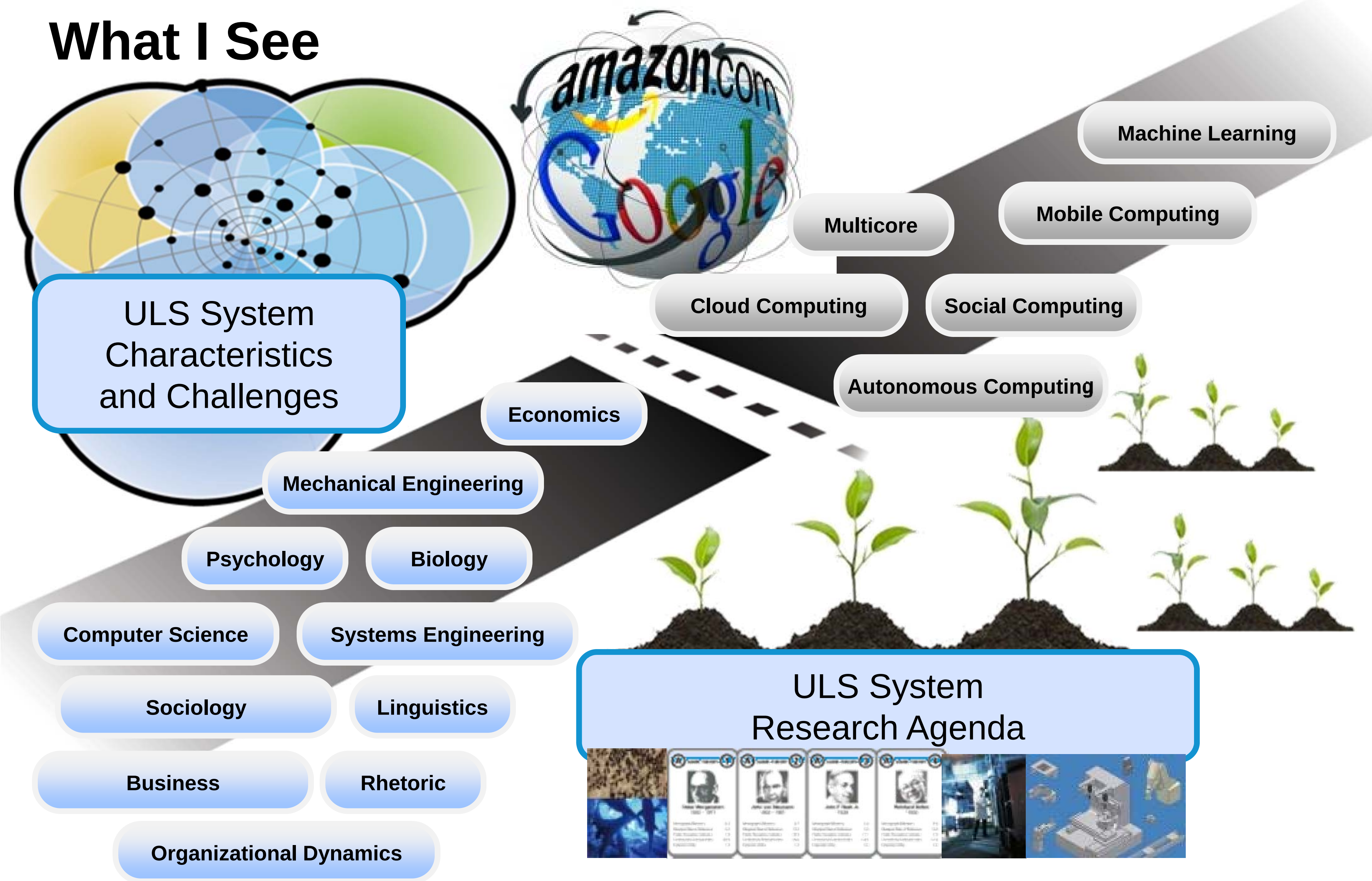
Research Progress – My Assessment

- ✓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


amazon.com
Google
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

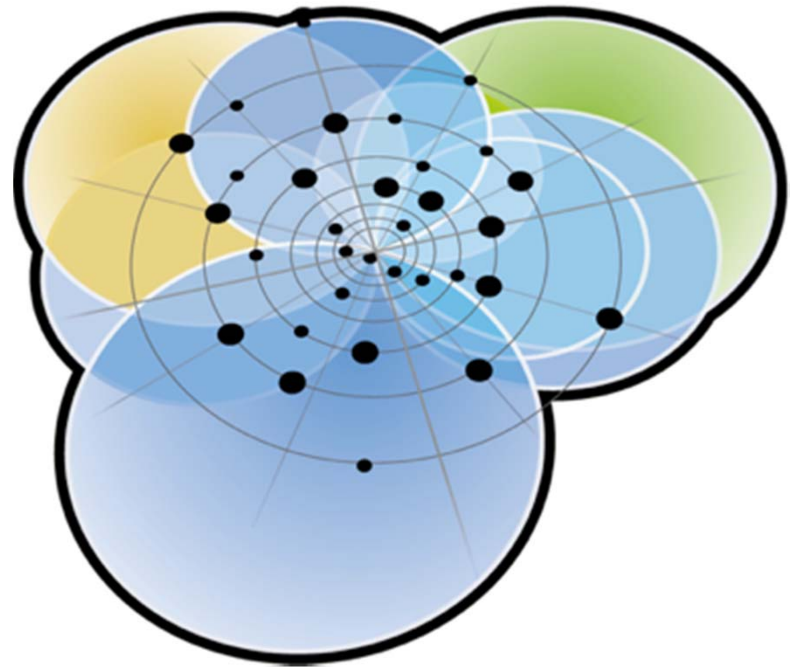
Summing It Up

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?



Thanks To Many Who Made The Study Possible

Report Author Team:

Peter Feiler, Richard P. Gabriel, John Goodenough, Rick Linger, Tom Longstaff, Rick Kazman, Mark Klein, Douglas Schmidt, Kevin Sullivan, Kurt Wallnau, Bill Pollak (Chief Editor), Daniel Pipitone (Information Designer)

2006 Support System:

Hon Claude Bolton, Paul Nielsen (SEI CEO), Clyde Chittister (SEI COO), Hal Stevens (2006 SEI/Army Liaison), Jim Linnehan (2006 Army/SEI Liaison)

Thanks To The Entire ULS System Study Team

Thanks To My SEI and Campus Colleagues

In particular:

Felix Bachmann, Jeff Boleng, Gene Cahill, James Edmondson, Ian Gorton, Jim Herbsleb, Scott Hissam, Carolyn Kernan, John Klein, Mark Klein, Mike Konrad, Grace Lewis, John McGregor, Gabriel Moreno, Ed Morris, Daniel Pipitone, Bill Pollak, James Root, Mary Shaw, Soumya Simanta, Kurt Wallnau

A Special Thank You and Tribute

thank you

Interaction

Contact Information

Linda Northrop
SEI Fellow
Chief Scientist
Software Solutions Division
Telephone: 412-268-7638
Email: lmn@sei.cmu.edu
Website: http://www.sei.cmu.edu/uls/

U.S. Mail:
Software Engineering Institute
Carnegie Mellon University
Pittsburgh, PA 15213-3890

SEI Fax: 412-268-5758

References for Slides 65-66

References - 1

Azim Sharifloo, Amir, Mehdi Mirakhorli, and Fereidoon Shams. "How Could ULS Systems Achieve Architecture Benefits?." In Proceedings of the 2nd International Workshop on Ultra-large-scale Software-intensive Systems, pp. 41-44. ACM, 2008.

Bacon, David F.; Bokelberg, Eric; Chen, Yiling; Kash, Ian A.; Parkes, David C.; Rao, Malvika; Sridharan, Manu. “Software Economies “ In Proceedings of the FSE/SDP Workshop on the Future of Software Engineering Research, FoSER 2010, p 7-11, 2010.

Barki, Henri, Suzanne Rivard, and Jean Talbot. "Toward an assessment of software development risk." Journal of Management Information Systems (1993): 203-225.

Bezemer, Cor-Paul, and Andy Zaidman. "Server Overload Detection and Prediction Using Pattern Classification}." In Proceedings of the 8th International Conference on Autonomic Computing (ICAC)}, pp. 163-165. ACM}, 2011.

Breivold, Hongyu Pei, Ivica Crnkovic, and Magnus Larsson. "A systematic review of software architecture evolution research." Information and Software Technology 54, no. 1 (2012): 16-40.

Broy, Manfred, María Victoria Cengarle, and Eva Geisberger. "Cyber-physical Systems: Imminent Challenges." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 1-28. Springer Berlin Heidelberg, 2012.

References - 2

Bryant, Barrett R., Jeff Gray, and Marjan Mernik. "Domain-specific Software Engineering." In Proceedings of the FSE/SDP Workshop on Future of Software Engineering research, pp. 65-68. ACM, 2010.

Calinescu, Radu, Shinji Kikuchi, and Kenneth Johnson. "Compositional Reverification of Probabilistic Safety Properties for Large-scale Complex IT Systems." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 303-329. Springer Berlin Heidelberg, 2012.

Canfora, Gerardo, and Corrado Aaron Visaggio. "Does enforcing anonymity mean decreasing data usefulness?." In Proceedings of the 4th ACM workshop on Quality of protection, pp. 15-22. ACM, 2008.

Canfora, Gerardo, Elisa Costante, Igino Pennino, and Corrado Aaron Visaggio. "A three-layered model to implement data privacy policies." Computer Standards & Interfaces 30, no. 6 (2008): 398-409.

Castro-Herrera, Carlos, Chuan Duan, Jane Cleland-Huang, and Bamshad Mobasher. "A recommender system for requirements elicitation in large-scale software projects." In Proceedings of the 2009 ACM symposium on Applied Computing, pp. 1419-1426. ACM, 2009.

References - 3

Cataldo, Marcelo, and James D. Herbsleb. "Architecting in Software Ecosystems: Interface Translucence as an Enabler for Scalable Collaboration." In Proceedings of the Fourth European Conference on Software Architecture: Companion Volume, pp. 65-72. ACM, 2010.

Chen, Bangdao, and A. W. Roscoe. "Social Networks for Importing and Exporting Security." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 132-147. Springer Berlin Heidelberg, 2012.

Cheng, Betty HC, and Joanne M. Atlee. "Research Directions in Requirements Engineering." In 2007 Future of Software Engineering, pp. 285-303. IEEE Computer Society, 2007.

Cheng, Betty HC, Rogerio De Lemos, Holger Giese, Paola Inverardi, Jeff Magee, Jesper Andersson, Basil Becker et al. Software Engineering for Self-adaptive Systems: A Research Roadmap. Springer Berlin Heidelberg, 2009.

Cinque, Marcello, Catello Di Martino, and Christian Esposito. "On Data Dissemination for Large-scale Complex Critical Infrastructures." Computer Networks 56, no. 4 (2012): 1215-1235.

Cleland-Huang, Jane, and Bamshad Mobasher. "Using data mining and recommender systems to scale up the requirements process." In Proceedings of the 2nd international Workshop on Ultra-large-scale Software-intensive Systems, pp. 3-6. ACM, 2008.

References - 4

Clements, Paul, and Mary Shaw. "" The Golden Age of Software Architecture" Revisited." IEEE Software 26, no. 4 (2009): 70-72.

Cliff, Dave, and Linda Northrop. "The Global Financial Markets: an Ultra-Large-Scale Systems Perspective." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 29-70. Springer Berlin Heidelberg, 2012.

Cukier, Daniel, and Joseph W. Yoder. "The artist in the computer scientist: more humanity to our research." In Proceedings of the 10th SIGPLAN Symposium on New ideas, New Paradigms, and Reflections on Programming and Software, pp. 129-136. ACM, 2011.

Dawson, Dylan, Ron Desmarais, Holger M. Kienle, and Hausi A. Müller. "Monitoring in Adaptive Systems Using Reflection." In Proceedings of the 2008 International Workshop on Software engineering for Adaptive and Self-Managing Systems, pp. 81-88. ACM, 2008.

Demchak, Barry, Vina Ermagan, Claudiu Farcas, Emilia Farcas, Ingolf H. Krüger, and Massimiliano Menarini. "Rich Services: Addressing Challenges of Ultra Large-Scale Software-Intensive Systems." In Proceedings of the 2nd International Workshop on Ultra-Large-Scale Software-Intensive Systems, pp. 29-32. ACM, 2008.

References - 5

Dorn, Christoph, and Richard N. Taylor. "Co-adapting Human Collaborations and Software Architectures." In Proceedings of the 2012 International Conference on Software Engineering, pp. 1277-1280. IEEE Press, 2012.

Drachova, S., J. O. Hallstrom, J. Hollingsworth, D. P. Jacobs, J. Krone, and M. Sitaraman. "A Systematic Approach to Teaching Abstraction and Mathematical Modeling." (2011).

Dustdar, Schahram, Christoph Dorn, Fei Li, Luciano Baresi, Giacomo Cabri, Cesare Pautasso, and Franco Zambonelli. "A roadmap Towards Sustainable Self-aware Service Systems." In Proceedings of the 2010 ICSE Workshop on Software Engineering for Adaptive and Self-Managing Systems, pp. 10-19. ACM, 2010.

Facelli, Julio C. "An Agenda for Ultra-Large-Scale System Research for Global Health Informatics." ACM SIGHIT Record 2, no. 1 (2012): 12-12.

Faleiro, Jose, Sriram Rajamani, Kaushik Rajan, G. Ramalingam, and Kapil Vaswani. "CScale–A Programming Model for Scalable and Reliable Distributed Applications." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 148-156. Springer Berlin Heidelberg, 2012.

Felfernig, Alexander, Monika Schubert, Monika Mandl, Francesco Ricci, and Walid Maalej. "Recommendation and Decision Technologies for Requirements Engineering." In Proceedings of the 2nd International Workshop on Recommendation Systems for Software Engineering, pp. 11-15. ACM, 2010.

References - 6

Froihofer, Lorenz, Gerhard Glos, Johannes Osrael, and Karl M. Goeschka. "Overview and Evaluation of Constraint Validation Approaches in Java." In Proceedings of the 29th International Conference on Software Engineering, pp. 313-322. IEEE Computer Society, 2007.

Gabriel, Richard P., and Ron Goldman. "Conscientious Software." In ACM SIGPLAN Notices, vol. 41, no. 10, pp. 433-450. ACM, 2006.

Gershenson, Carlos, and Nelson Fernández. "Complexity and information: Measuring emergence, self-organization, and homeostasis at multiple scales." Complexity 18, no. 2 (2012): 29-44.

Goth, Greg. "Ultralarge Systems: Redefining Software Engineering?." IEEE Software 25, no. 3 (2008): 91-94.

Greenwood, Phil, Alessandro Garcia, Yuanfang Cai, Claudio Sant'Anna, Kevin Sullivan, Thomas Cottenier, and James Noble. "3rd Workshop on Assessment of Contemporary Modularization Techniques (ACoM 2009)." In Proceedings of the 24th ACM SIGPLAN Conference Companion on Object Oriented Programming Systems Languages and Applications, pp. 715-716. ACM, 2009.

References - 7

Haber, Arne, Holger Rendel, Bernhard Rumpe, and Ina Schaefer. "Evolving Delta-Oriented Software Product Line Architectures." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 183-208. Springer Berlin Heidelberg, 2012.

Heering, Jan, and Marjan Mernik. "Domain-Specific Languages as Key Tools for ULSSIS engineering." In Proceedings of the 2nd International Workshop on Ultra Large-Scale Software-Intensive Systems, pp. 1-2. ACM, 2008.

Hennicker, Rolf, and Matthias Ludwig. "View-Based Development of a Simulation Framework for Multi-disciplinary Environmental Modeling." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 224-250. Springer Berlin Heidelberg, 2012.

Henningsson, Stefan, and Helle Zinner Henriksen. "Inscription of Behaviour and Flexible Interpretation in Information Infrastructures: The Case of European e-Customs." The Journal of Strategic Information Systems 20, no. 4 (2011): 355-372.

Herold, Sebastian, Holger Klus, Dirk Niebuhr, and Andreas Rausch. "Engineering of it Ecosystems: Design of Ultra-large-scale Software-intensive Systems." In Proceedings of the 2nd International Workshop on Ultra-large-scale Software-intensive Systems, pp. 49-52. ACM, 2008.

References - 8

Hill, James H., Jules White, Sean Eade, Douglas Schmidt, and Trip Denton. "Towards a solution for synchronizing disparate models of ultra-large-scale systems." In Proceedings of the 2nd International Workshop on Ultra-large-scale Software-intensive Systems, pp. 19-22. ACM, 2008.

Holl, Gerald, Paul Grünbacher, and Rick Rabiser. "A systematic review and an expert survey on capabilities supporting multi product lines." Information and Software Technology 54, no. 8 (2012): 828-852.

Huget, Marc-Philippe. "Executing ultra-large software systems with multiagent systems." In Proceedings of the 2nd International Workshop on Ultra-large-scale Software-intensive Systems, pp. 33-36. ACM, 2008.

Johnson, Philip M. "Ultra-automation and Ultra-autonomy for Software Engineering Management of Ultra-large-scale systems." In Proceedings of the International Workshop on Software Technologies for Ultra-Large-Scale Systems, p. 1. IEEE Computer Society, 2007.

Keen, J. “What is a Care Pathway?” In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 81-93. Springer Berlin Heidelberg, 2012.

Lane, Jo Ann, and Ricardo Valerdi. "Synthesizing SoS Concepts for Use in Cost Modeling." Systems Engineering 10, no. 4 (2007): 297-308.

References - 9

Lange, Douglas S., Phillip Verbancsics, Robert S. Gutzwiller, John Reeder, and Cullen Sarles. "Command and Control of Teams of Autonomous Systems." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 81-93. Springer Berlin Heidelberg, 2012.

Lesbegueries, Julien, Amira Ben Hamida, Nicolas Salatgé, Sarah Zribi, and Jean-Pierre Lorré. "Multilevel event-based monitoring framework for the petals enterprise service bus: industry article." In Proceedings of the 6th ACM International Conference on Distributed Event-Based Systems, pp. 48-57. ACM, 2012.

Liang, Peng, Paris Avgeriou, Keqing He, and Lai Xu. "From collective knowledge to intelligence: pre-requirements analysis of large and complex systems." In Proceedings of the 1st Workshop on Web 2.0 for Software Engineering, pp. 26-30. ACM, 2010.

Lim, Soo Ling, and Anthony Finkelstein. "StakeRare: using social networks and collaborative filtering for large-scale requirements elicitation." Software Engineering, IEEE Transactions on 38, no. 3 (2012): 707-735.

Litoiu, Marin, Murray Woodside, Johnny Wong, Joanna Ng, and Gabriel Iszlai. "A business driven cloud optimization architecture." In Proceedings of the 2010 ACM Symposium on Applied Computing, pp. 380-385. ACM, 2010.

References - 10

Lucrédio, Daniel, Ethan K. Jackson, and Wolfram Schulte. "Playing with fire: Harnessing the hottest technologies for ultra-large-scale systems." In 15th Monterey Workshop-Foundations of Computer Software, Future Trends and Techniques for Development. 2008.

McGowan, Julie J., Caitlin M. Cusack, and Meryl Bloomrosen. "The future of health IT innovation and informatics: a report from AMIA's 2010 policy meeting." Journal of the American Medical Informatics Association 19, no. 3 (2012): 460-467.

Mirakhorli, Mehdi, Amir Azim Sharifloo, and Fereidoon Shams. "Architectural Challenges of Ultra Large Scale Systems." In Proceedings of the 2nd International Workshop on Ultra-large-scale Software-intensive Systems, pp. 45-48. ACM, 2008.

Müller, Hausi, Mauro Pezzè, and Mary Shaw. "Visibility of control in adaptive systems." In Second International Workshop on Ultra-Large-Scale Software-Intensive Systems (ULSSIS 2008), ICSE 2008 Workshop. 2008.

Musil, Juergen, Angelika Musil, Dietmar Winkler, and Stefan Biffl. "A first account on stigmergic information systems and their impact on platform development." In Proceedings of the WICSA/ECSA 2012 Companion Volume, pp. 69-73. ACM, 2012.

References - 11

Naqvi, Syed Asad, Ruzanna Chitchyan, Steffen Zschaler, Awais Rashid, and Mario Südholt. "Cross-Document dependency analysis for system-of-system integration." In Foundations of Computer Software. Future Trends and Techniques for Development, pp. 201-226. Springer Berlin Heidelberg, 2010.

Niebuhr, Dirk, and Andreas Rausch. "Guaranteeing Correctness of Component Bindings in Dynamic Adaptive Systems Based on Runtime Testing." In Proceedings of the 4th International Workshop on Services Integration in Pervasive Environments, pp. 7-12. ACM, 2009.

Orlov, Michael, and Moshe Sipper. "Flight of the FINCH through the Java Wilderness." Evolutionary Computation, IEEE Transactions on 15, no. 2 (2011): 166-182.

Paige, Richard F., Phillip J. Brooke, Xiaocheng Ge, Christopher DS Power, Frank R. Burton, and Simon Poulding. "Revealing complexity through domain-specific modelling and analysis." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 251-265. Springer Berlin Heidelberg, 2012.

Polacek, George A., David A. Gianetto, Khaldoun Khashanah, and Dinesh Verma. "On principles and rules in complex adaptive systems: A financial system case study." Systems Engineering 15, no. 4 (2012): 433-447.

Richards, M., A. Ross, D. Hastings, and D. Rhodes. "Survivability Design Principles for Enhanced Concept Generation and Evaluation." In 19th INCOSE Symposium, Suntec, Singapore. 2009.

References - 12

Salehie, Mazeiar, and Ladan Tahvildari. "Self-Adaptive Software: Landscape and Research Challenges." ACM Transactions on Autonomous and Adaptive Systems (TAAS) 4, no. 2 (2009): 14.

Santos, Francielle S., and Hermano P. Moura. "What is wrong with the software development?: Research Trends and a New Software Engineering Paradigm." In Proceedings of the 24th ACM SIGPLAN Conference Companion on Object-Oriented Programming Systems Languages and Applications, pp. 895-900. ACM, 2009.

Scaffidi, Christopher, and Mary Shaw. "Accommodating Data Heterogeneity in ULS Systems." In Proceedings of the 2nd International Workshop on Ultra-large-scale Software-intensive Systems, pp. 15-18. ACM, 2008.

Schaefer, Robert. "Software maturity: design as dark art." ACM SIGSOFT Software Engineering Notes 34, no. 1 (2009): 1-36.

Schäfer, Wilhelm, Mauro Birattari, Johannes Blömer, Marco Dorigo, Gregor Engels, Rehan O'Grady, Marco Platzner, Franz Rammig, Wolfgang Reif, and Ansgar Trächtler. "Engineering Self-coordinating Software Intensive Systems." In Proceedings of the FSE/SDP Workshop on Future of Software Engineering Research, pp. 321-324. ACM, 2010.

References - 13

Shams, Fereidoon, Amir Azim Sharifloo, Mehdi Mirakhorli, and Mostafa Emaeli. "A Service Driven Development Process (sddp) Model for Ultra-Large-Scale Systems." In Proceedings of the 2nd international workshop on Ultra-large-scale software-intensive systems, pp. 37-40. ACM, 2008.

Shaw, Mary. "Continuing Prospects for an Engineering Discipline of Software." Software, IEEE 26, no. 6 (2009): 64-67.

Sim, Susan Elliott, Medha Umarji, Sukanya Ratanotayanon, and Cristina V. Lopes. "How well do search engines support code retrieval on the web?." ACM Transactions on Software Engineering and Methodology (TOSEM) 21, no. 1 (2011): 4.

Sommerville, Ian, Dave Cliff, Radu Calinescu, Justin Keen, Tim Kelly, Marta Kwiatkowska, John Mcdermid, and Richard Paige. "Large-scale Complex IT Systems." Communications of the ACM 55, no. 7 (2012): 71-77.

Stamkopoulos, Konstantinos, Evaggelia Pitoura, Panos Vassiliadis, and Apostolos Zarras. "Accelerating Web service workflow execution via intelligent allocation of services to servers." Journal of Database Management (JDM) 21, no. 4 (2010): 60-90.

Sullivan, Kevin, William Knaus, and Richard Marks. "An Ultra-large-scale Systems Approach to National-scale Health Information Systems." In Proceedings of the FSE/SDP Workshop on Future of Software Engineering Research, pp. 365-368. ACM, 2010.

References - 14

Valerdi, Ricardo, Elliot Axelband, Thomas Baehren, Barry Boehm, Dave Dorenbos, Scott Jackson, Azad Madni, Gerald Nadler, Paul Robitaille, and Stan Settles. "A Research Agenda for Systems of Systems Architecting." International Journal of System of Systems Engineering 1, no. 1 (2008): 171-188.

von Hanxleden, Reinhard, Edward A. Lee, Christian Motika, and Hauke Fuhrmann. "Multi-view Modeling and Pragmatics in 2020." In Large-Scale Complex IT Systems. Development, Operation and Management, pp. 209-223. Springer Berlin Heidelberg, 2012.

Wang, Hongchun, Keqing He, Bing Li, and Jinhu Lü. "On some recent advances in complex software networks: Modeling, Analysis, Evolution and Applications." International Journal of Bifurcation and Chaos 22, no. 02 (2012).

Wang, Jian, Keqing He, Ping Gong, Chong Wang, Rong Peng, and Bing Li. "RGPS: A Unified Requirements Meta-modeling Frame for Networked Software." In Proceedings of the 3rd International Workshop on Applications and Advances of Problem Frames, pp. 29-35. ACM, 2008.

Ward, Jonathan Stuart, and Adam Barker. "Semantic based data collection for large scale cloud systems." In Proceedings of the Fifth International Workshop on Data-Intensive Distributed Computing Date, pp. 13-22. ACM, 2012.

References - 15

White, Jules, Brian Doughtery, and Douglas C. Schmidt. "Ascent: An Algorithmic Technique for Designing Hardware and Software in Tandem." Software Engineering, IEEE Transactions on 36, no. 6 (2010): 838-851.

Xu, Xiwei, Liming Zhu, Yan Liu, and Mark Staples. "Resource-oriented Business pProcess Modeling for Ultra-large-scale Systems." In Proceedings of the 2nd international Workshop on Ultra-large-scale Software-intensive Systems, pp. 65-68. ACM, 2008.

Yoakum-Stover, S., and T. Malyuta. "Unified Data Integration for Situation Management." In Military Communications Conference, 2008. MILCOM 2008. IEEE, pp. 1-7. IEEE, 2008.

Zhang, Charles. "FlexSync: An Aspect-oriented Approach to Java Synchronization." In Proceedings of the 31st International Conference on Software Engineering, pp. 375-385. IEEE Computer Society, 2009.

Zhu, Liming, and Ian Gorton. "UML Profiles for Design Decisions and Non-functional Requirements." In Proceedings of the Second Workshop on SHAring and Reusing architectural Knowledge Architecture, Rationale, and Design Intent, p. 8. IEEE Computer Society, 2007.

References - 16

Zhu, Liming, and Yan Liu. "Model Driven Development with Non-Functional Aspects." In Aspect-Oriented Requirements Engineering and Architecture Design, 2009. EA'09. ICSE Workshop on, pp. 49-54. IEEE, 2009.

Zhu, Liming, Len Bass, and Xiwei Xu. "Data Management Requirements for a Knowledge Discovery Platform." In Proceedings of the WICSA/ECSA 2012 Companion Volume, pp. 169-172. ACM, 2012.