Drivers for Interdisciplinary Research:

Designing Exceptional Systems

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University of Michigan, Integrative Systems and Design Oct 21, 2016

Outline

NASA Background

Interdisciplinary Research

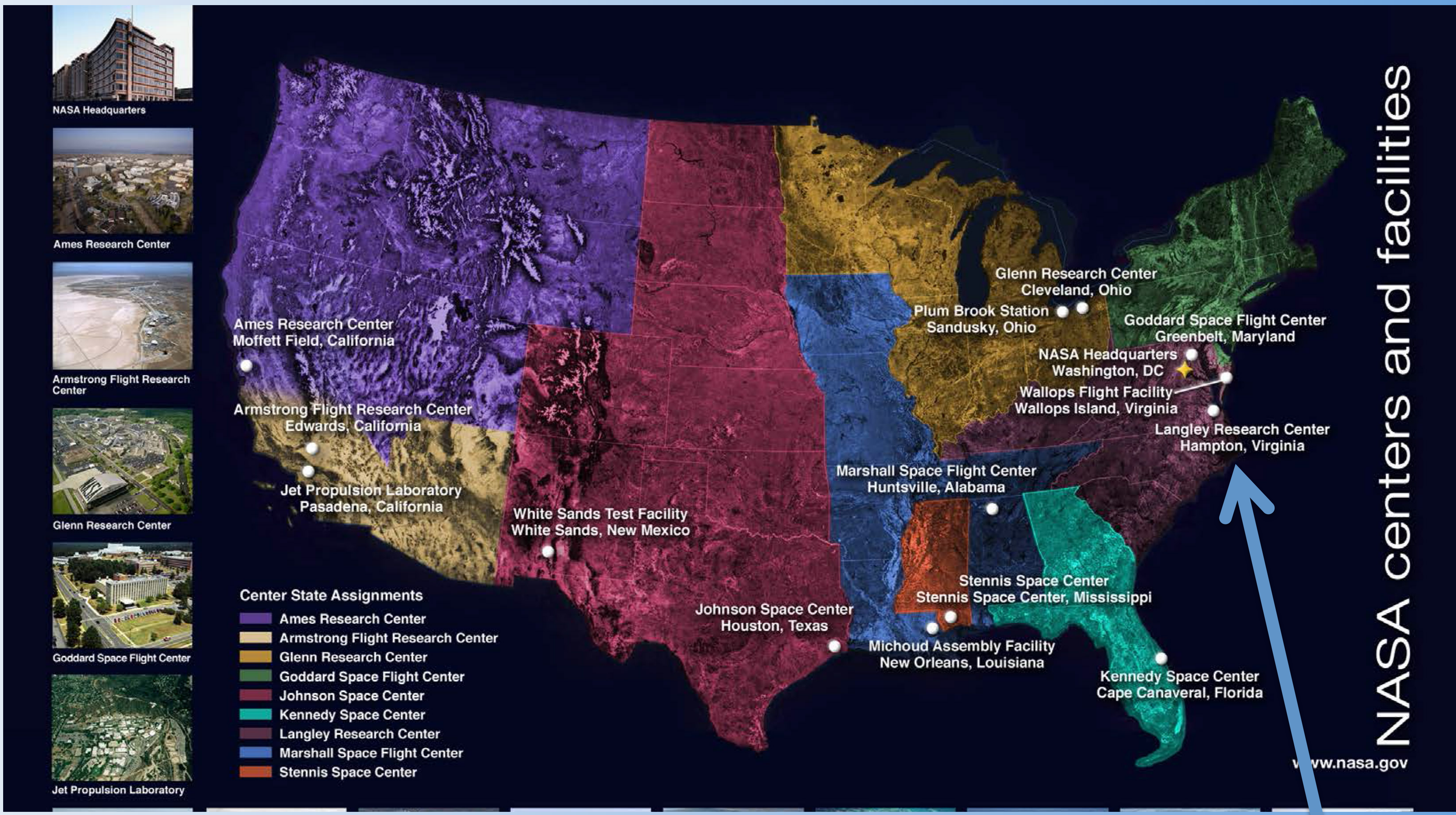
Examples in Large-Scale Systems

Using Interdisciplinary Research to Design

Exceptional Systems

Discussion

NASA Overview with Map



NASA Langley at a Glance (2016)

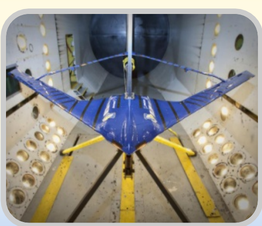
As of 4/30/16

Langley's Economic Impact (2015)

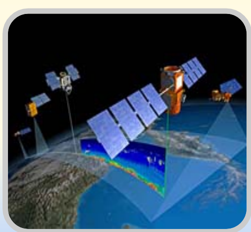
- National economic output of ~$2.3b and generates over 17,400 high-tech jobs
- Virginia economic output of ~$1.1b and generates over 8,800 high-tech jobs
- Within Virginia, executed $155m or 49% of obligations to small businesses

PY2016 Budget Estimate	**~$928m**
NASA Langley Budget	**~$905m**
External Business	~$23m
Workforce	**~3,400**
Civil Servants	~1,800
Contractors (on/near-site)	~1,600
Infrastructure/Facilities	
156 Buildings	764 acres
Replacement Value	~$3.6b

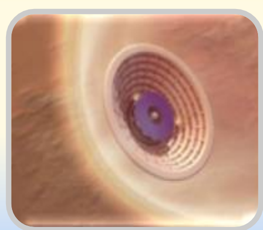
AERONAUTICS $214m



SCIENCE $235m



SPACE TECH $29m



HUMAN EXPLORATION $41m

EDUCATION $3m

SAFETY, SECURITY & MISSION SERVICES & CONSTRUCTION/ENVIRONMENTAL COMPLIANCE & RESTORATION

Center Management & Operations
(Facilities, IT, Engineering, Tech Authority, B&P, IRAD, Safety/Mission Assurance, Legal, Finance, Procurement, Human Resources)

Agency Management & Operations
(NASA Engineering & Safety Center, Office of Chief Engineer, Agency IT)

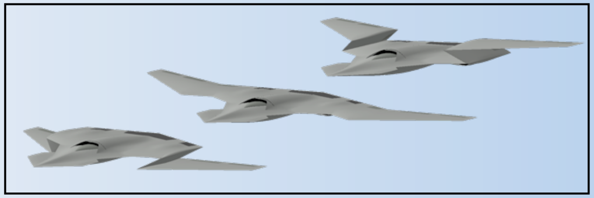
Construction Environmental Compliance & Restoration
(Revitalization Plan)

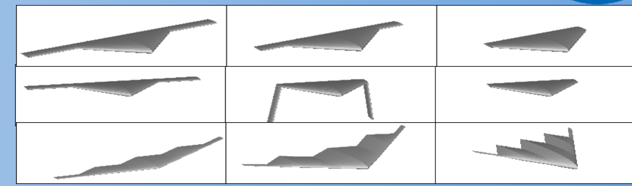
Interdisciplinary Research

Integrating the Natural and Social Sciences

that Integrates the Natural and Social Sciences?

Multidisciplinary Analysis & Design





Generate Concepts

Candidate Concepts

Parameterized Models

~~MDO~~

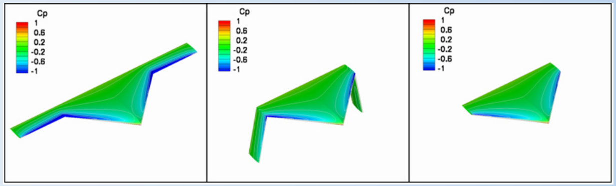
Generate Aerodynamic Database (MATLAB & CMARC/CFD)

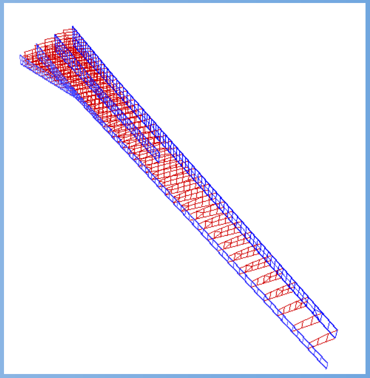
Aero Database

Analyze Nonlinear Multibody System (Virtual Lab & DYMORE)

~~Flexibility~~

Generate and Analyze Structural Models (OptWing & NASTRAN)





Morphing Performance Metrics

- Weight penalties
- Actuator concepts
- Loads; Load Paths

Integrated Aerodynamic/Structural/Dynamic Analyses of Aircraft with Large Shape Changes, Pawel Chwalowski, Jamshid A. Samareh, Lucas G. Horta, David J. Piatak, Anna-Maria R. McGowan, AVT-168 Symposium on Morphing Vehicles, Portugal, 2009

Terminology

Cross-disciplinary

Multidisciplinary
(Multiple)

Interdisciplinary
(Between)

Transdisciplinary
(Transcend)

All Approaches Seek to Overcome Disciplinary Monism, But With Different Approaches Towards That End

Multidisciplinary

Uniqueness: Each Discipline (and Researcher) Preserves its Methodologies and Assumptions (and Understanding) Without Significant Modification

- Klein (2010): “an approach that juxtaposes disciplines. Juxtaposition fosters wider knowledge, information, and methods. Yet, disciplines remain separate, **disciplinary elements retain their original identity, any existing structure of knowledge is not questioned**.”

- Repko (2012): “More than a single discipline in which each discipline makes a separate contribution”

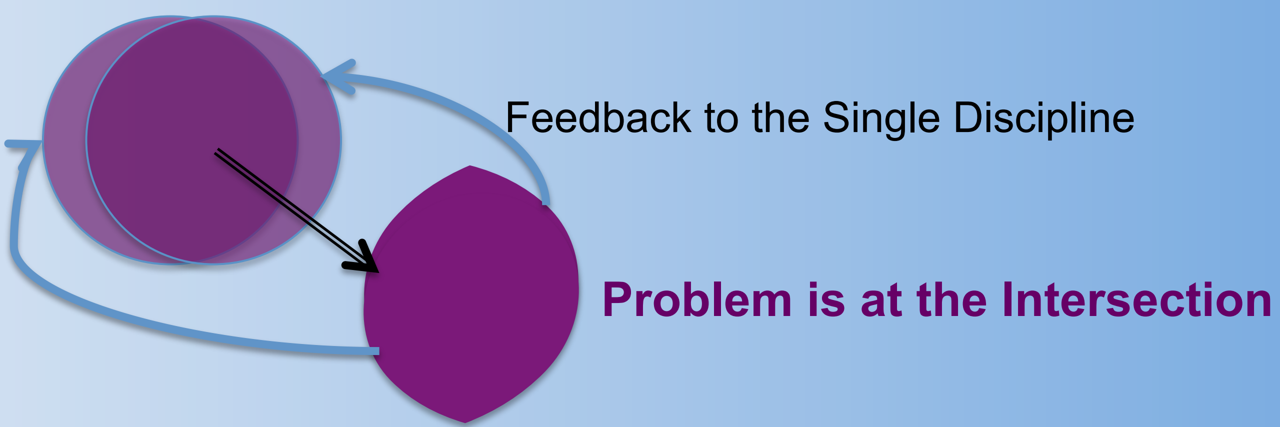
- Augsburg (2006): The relationship between the disciplines “may be mutual and cumulative but not interactive.”

A + B + C = Sys

Interdisciplinary

Uniqueness: The *Interdependence* of Disciplines = Inherently Interactive, Disciplinary Understanding Changes

- Rafols & Meyer (2009): "Understood as knowledge integration, interdisciplinarity is not the opposite of specialization."
- Lattuca (2001): The problem of interest may "lack a compelling disciplinary basis, and a critique of disciplinary understanding is often implied."
- Repko (2012): "Drawing on disciplinary insights (including stakeholder views) and integrating them."

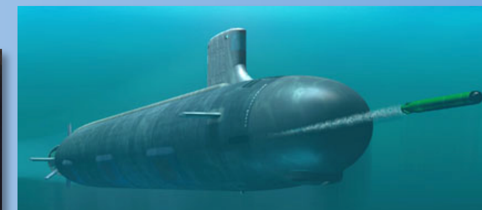


Large-Scale Complex Engineered Systems

Major Civil Infrastructures, Aerospace, Large Maritime, Nuclear

Large-Scale Complex Engineered Systems

- Large number of interconnected subsystems
- Interoperability (legacy and advanced systems)
- Multiple interfaces (Hardware, Software, People) at multiple levels create innumerable interdependencies
- Extended development and operational timelines
- Tremendous increase in operational states and interdependencies that cannot be fully explored
- Failures can have collateral impacts
- Large number of people and organizations involved
- Inherently socio-technical
- Government participation



Large-Scale Complex Engineered Systems

- **Provide critical infrastructure functions**
  - Such as defense, transportation, energy, weather and environmental data, etc.
  - Government is usually involved at some level
- **Performance requirements often necessitate some degree of "complexity" (difficult to "simplify")**
- **These systems have a unique blend of extremes in terms of:**
  - Costs
  - Risks & Interoperability
  - Multiple Organizations
  - Design Cycle
  - Operational Timeline
- ***Blend of extremes challenges the direct application of many existing methods***

Inter-Agency Cooperation

Inter-Agency Working Group for Engineering of Complex Systems

- Develop common understanding of problems
- Collaborate, share expertise and resources

• Position Paper at: http://www.acq.osd.mil/se/outreach/pubs.html

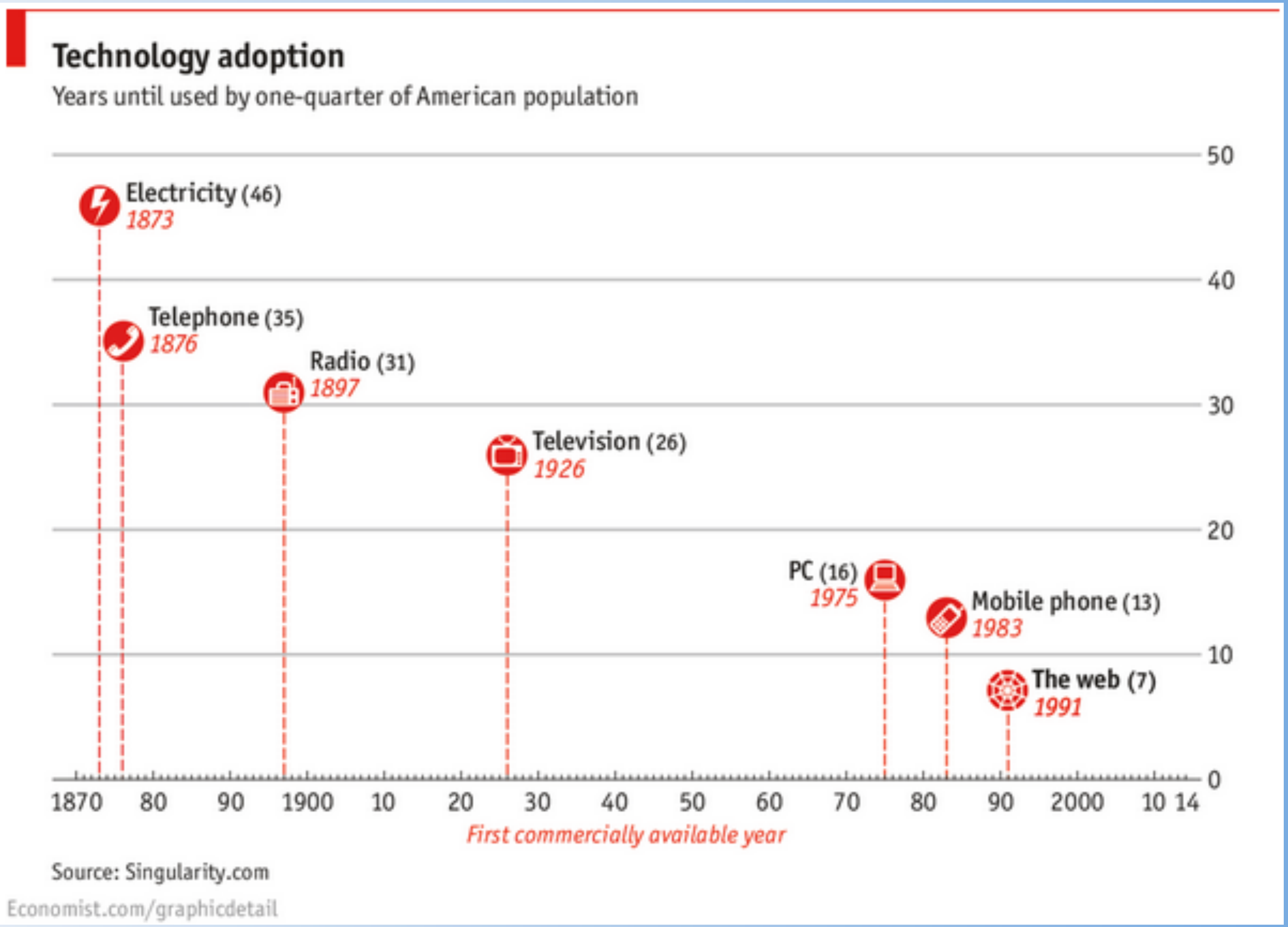
Current Participants:

- National Science Foundation
- National Aeronautics and Space Administration
- Department of Defense
- National Institute of Standards and Technology
- Department of Energy
- Department of Transportation
- Department of Homeland Security
- Federal Aviation Administration
- Veterans Administration
- National Oceanic and Atmospheric Administration

"We need to investigate the core principles of engineering & science that lay the foundation for significant, next generation advances in cross-discipline engineering practice and education in multi-scale environments."

IAWG Joint Statement

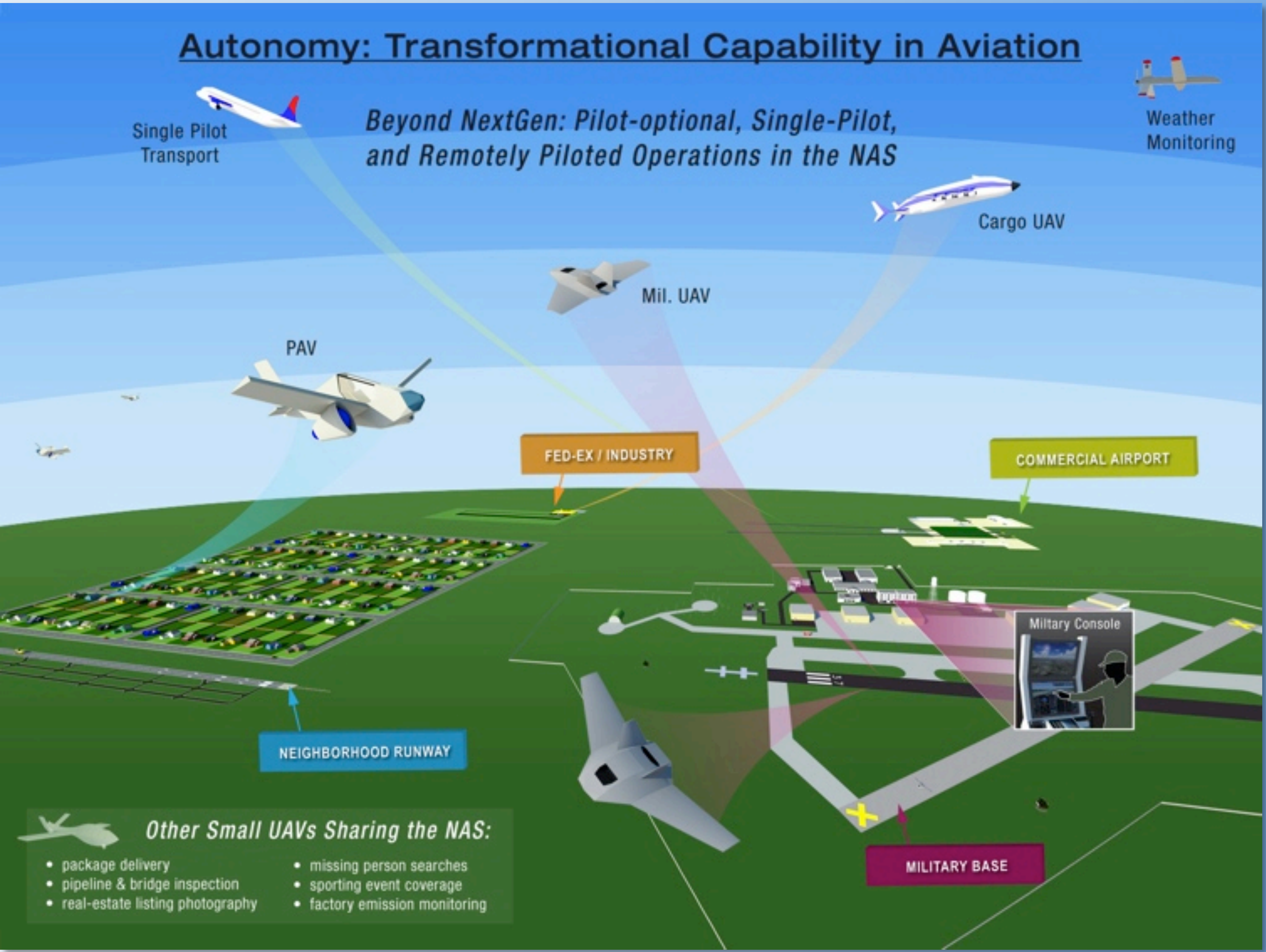
Pace of Technological Change



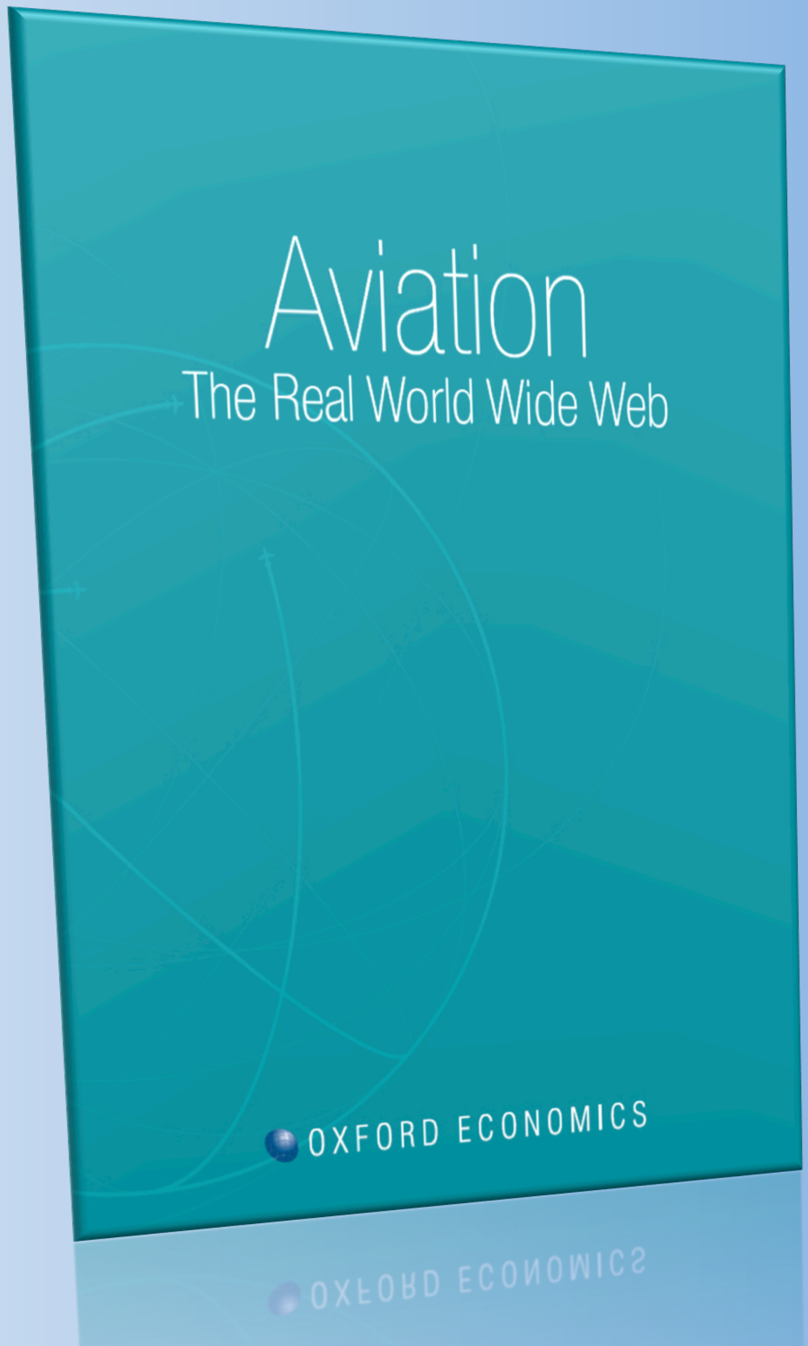
System Designers challenged to respond to rapidly changing technological and global changes


Office


K
EL →

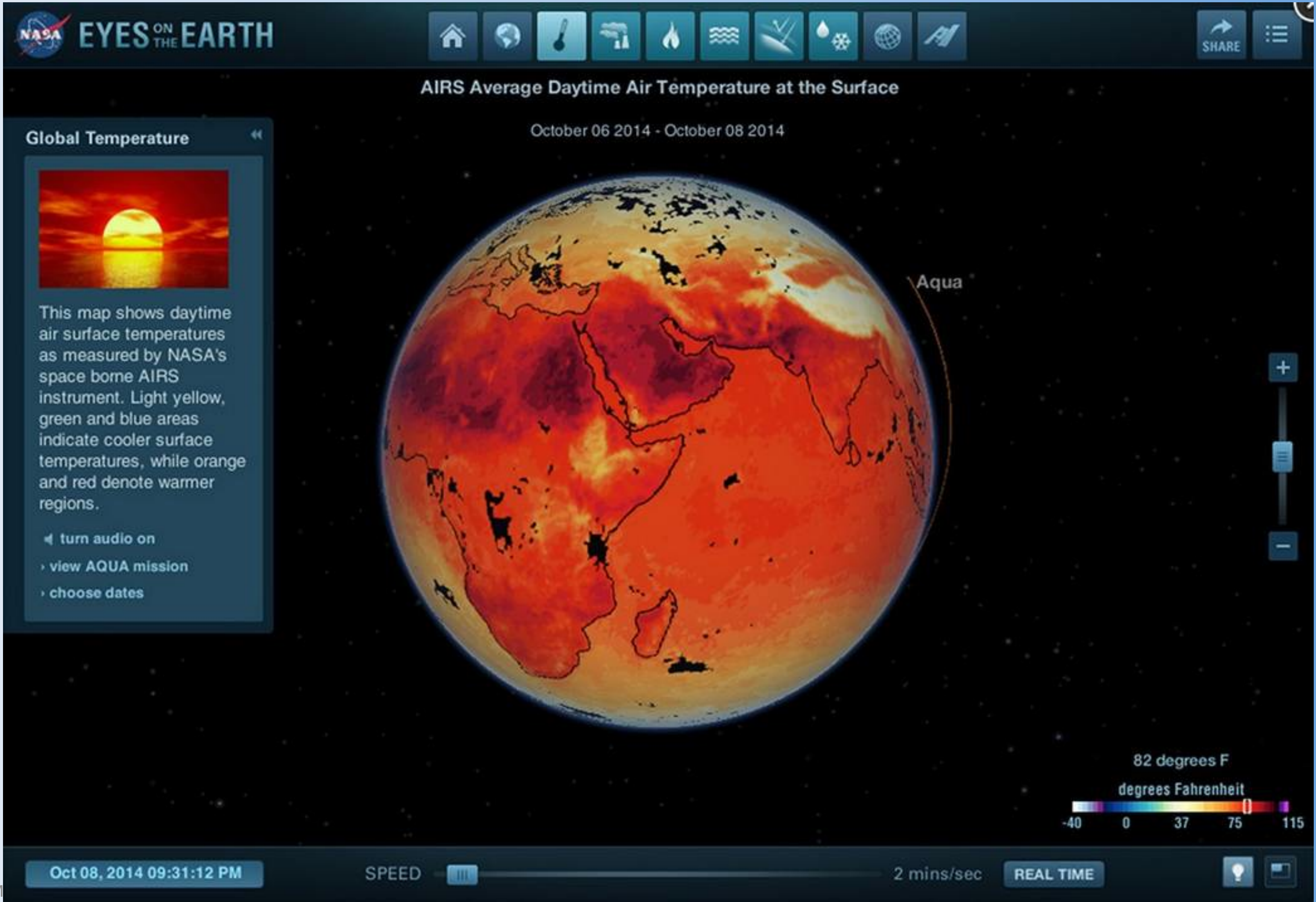


Performance requirements often necessitate some degree of "complexity" (difficult to "simplify")


Aviation
The Real World Wide Web
OXFORD ECONOMICS


PARCEL DELIVERY

NASA Earth Science



What Is the Real System?

Stronger Interdependencies

Within and Outside the Engineered System

Context is Essential to Engineering Complex Systems

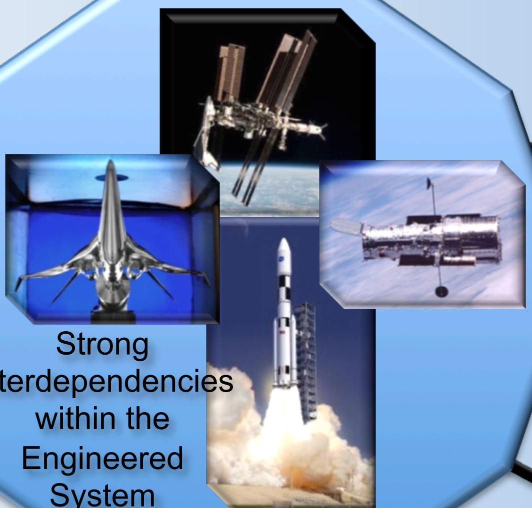
System is defined as much by the ***interactions between components*** as the components themselves

Stronger Interdependencies

Within and Outside the Engineered System

Context is Essential to Engineering Complex Systems

Engineered System



Strong Interdependencies within the Engineered System

Strong Interdependencies

Operational System

Operational Environment

Changing Scenarios

Cyber Security

Interoperability

Machine Operators

Manufacturing

Organizational System

Organizational Environment

Engineering and Organizational Processes and Policies

Org Structure

Incentives

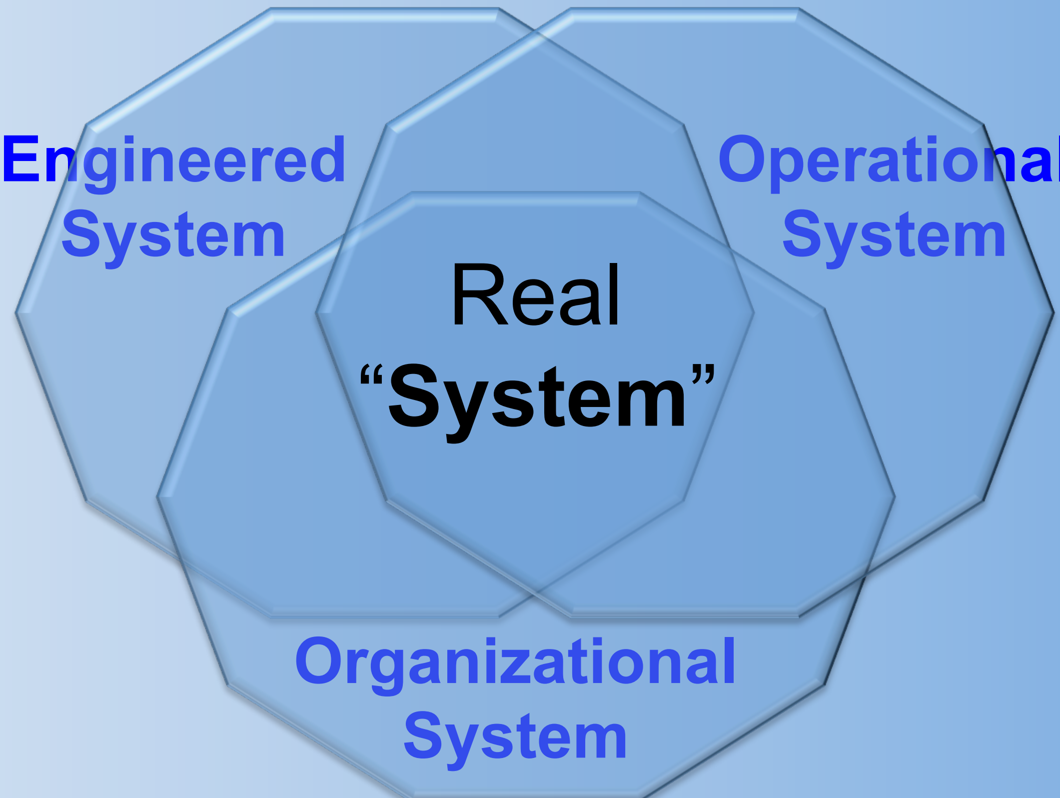
Stakeholders

System is defined as much by the ***interactions between components*** as the components themselves

Stronger Interdependencies

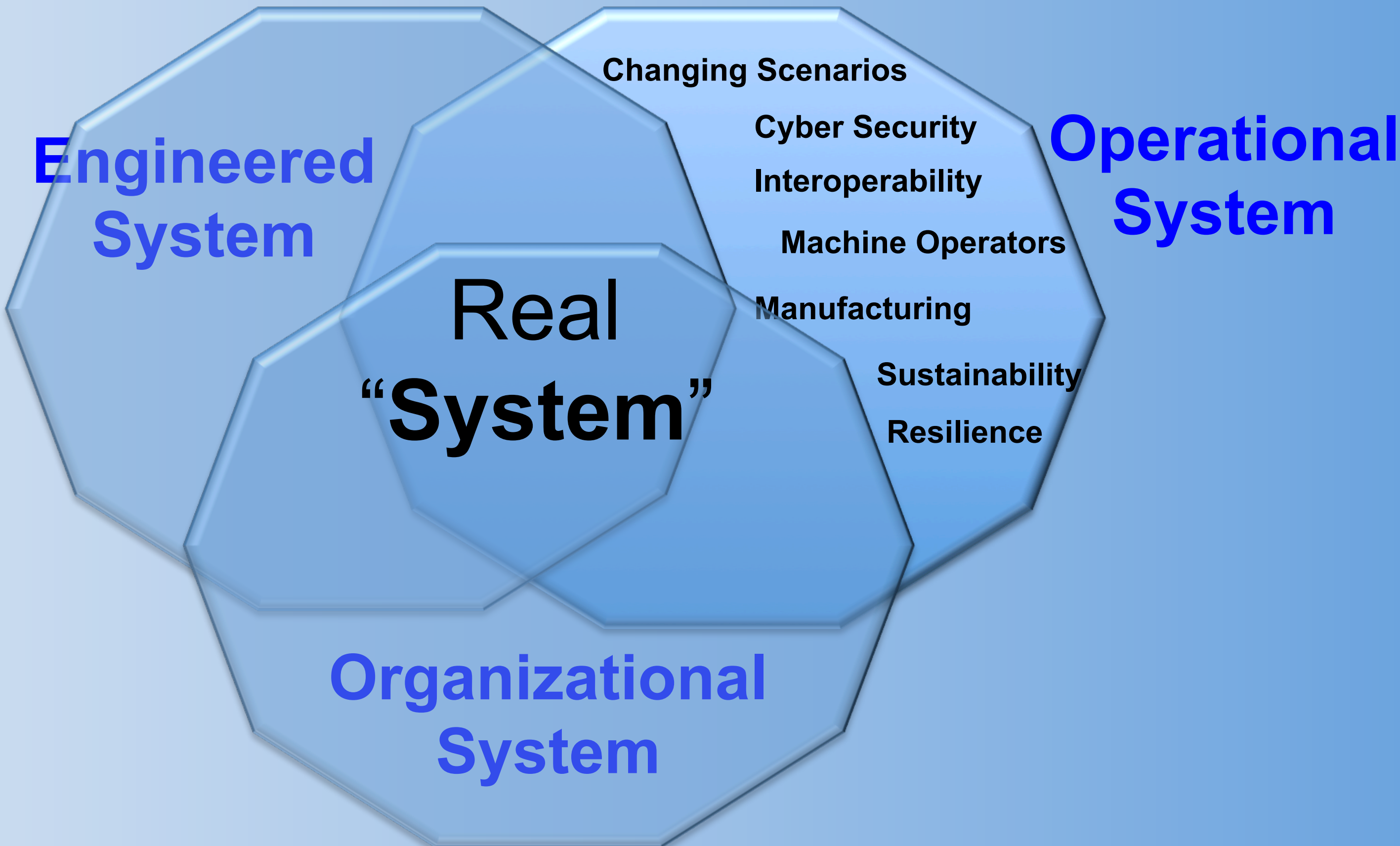
Within and Outside the Engineered System

Context is Essential to Engineering Complex Systems



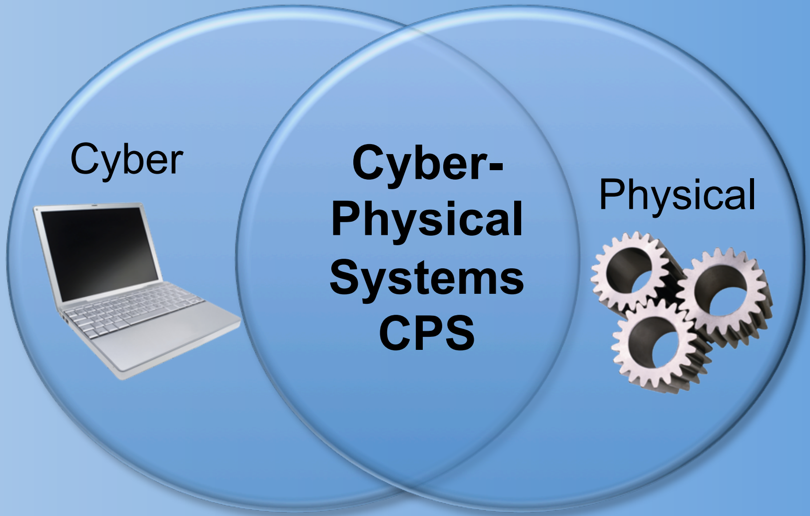
System is defined as much by the ***interactions between components*** as the components themselves

Some Aspects of the **Operational Context**



Cyber-Physical Systems

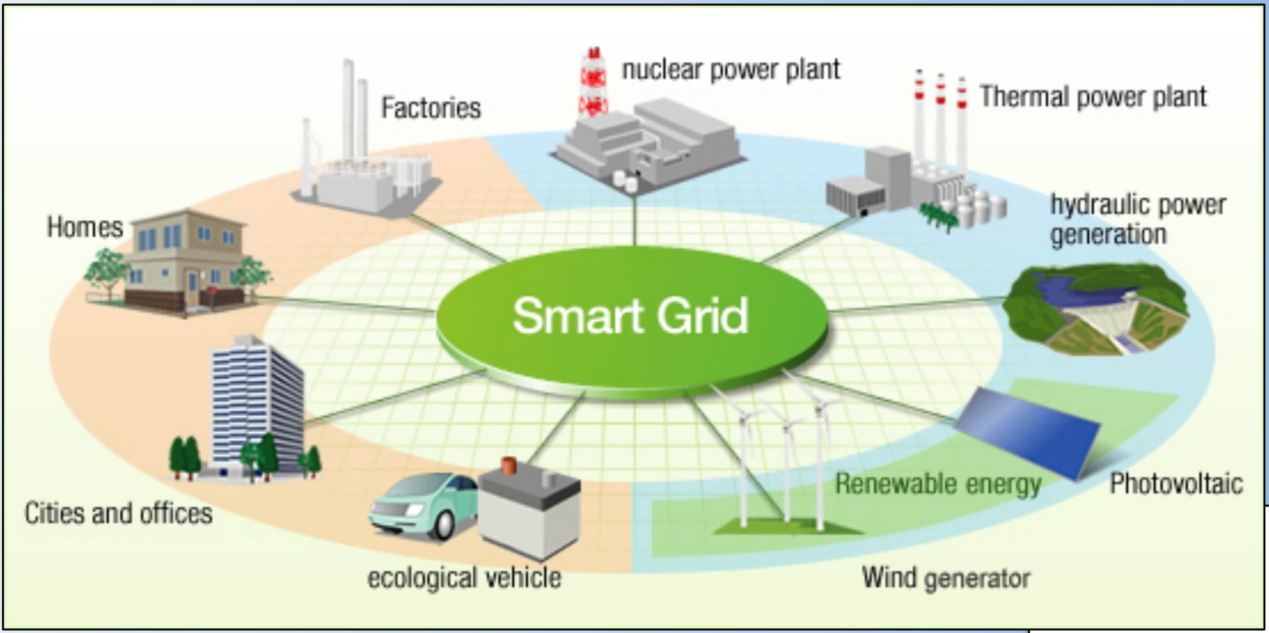
http://www.nist.gov/cps/



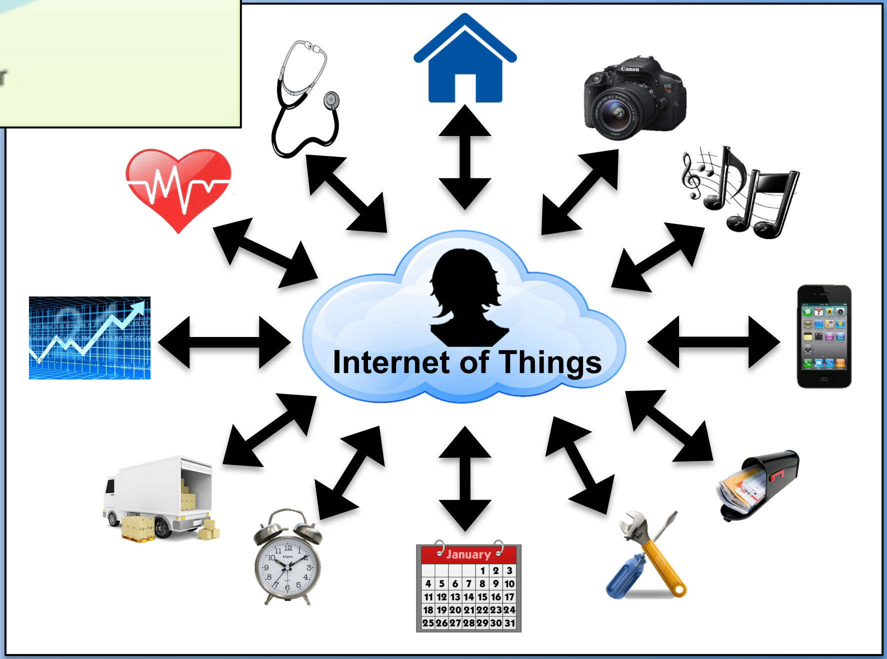
Interconnected Information

http://www.wired.com/2015/07/hackers-remotely-kill-jeep-highway/

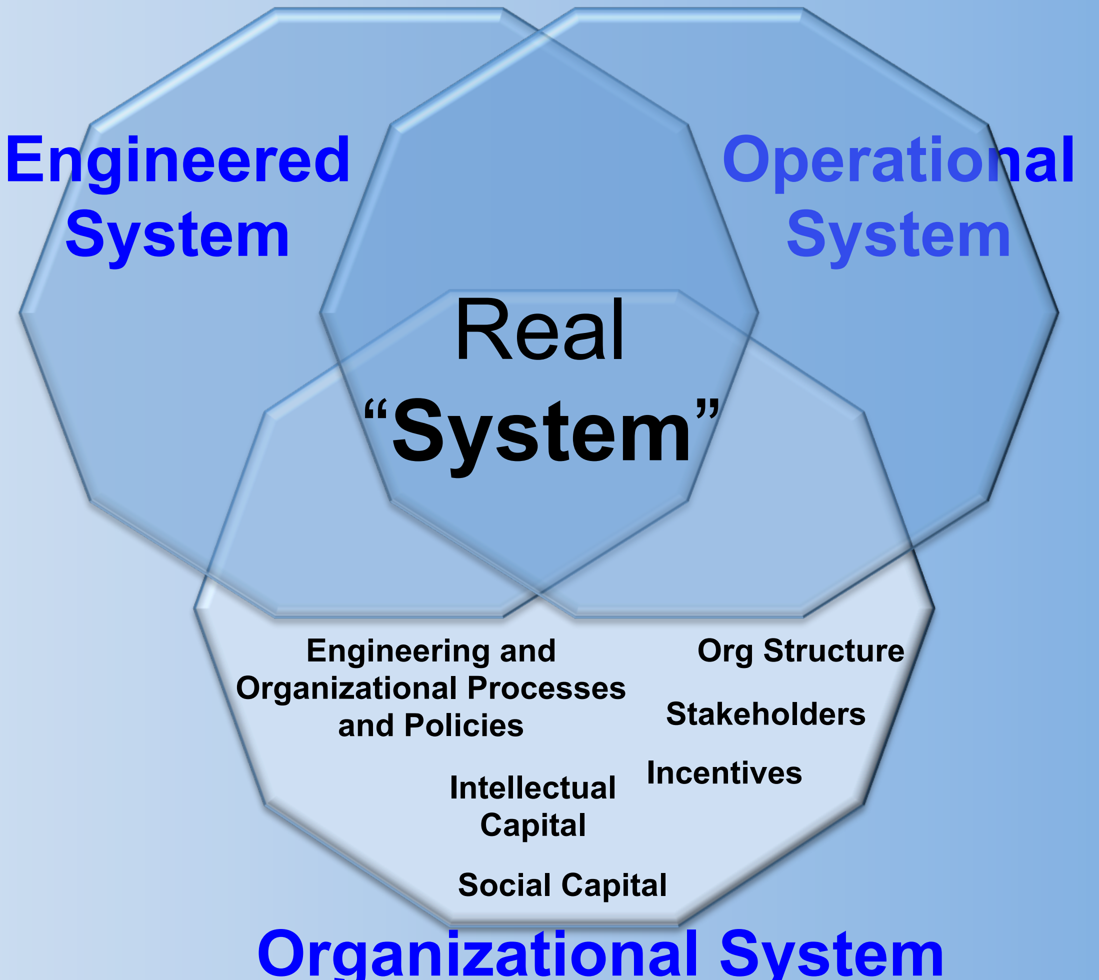
What's Coming?



Courtesy NIST

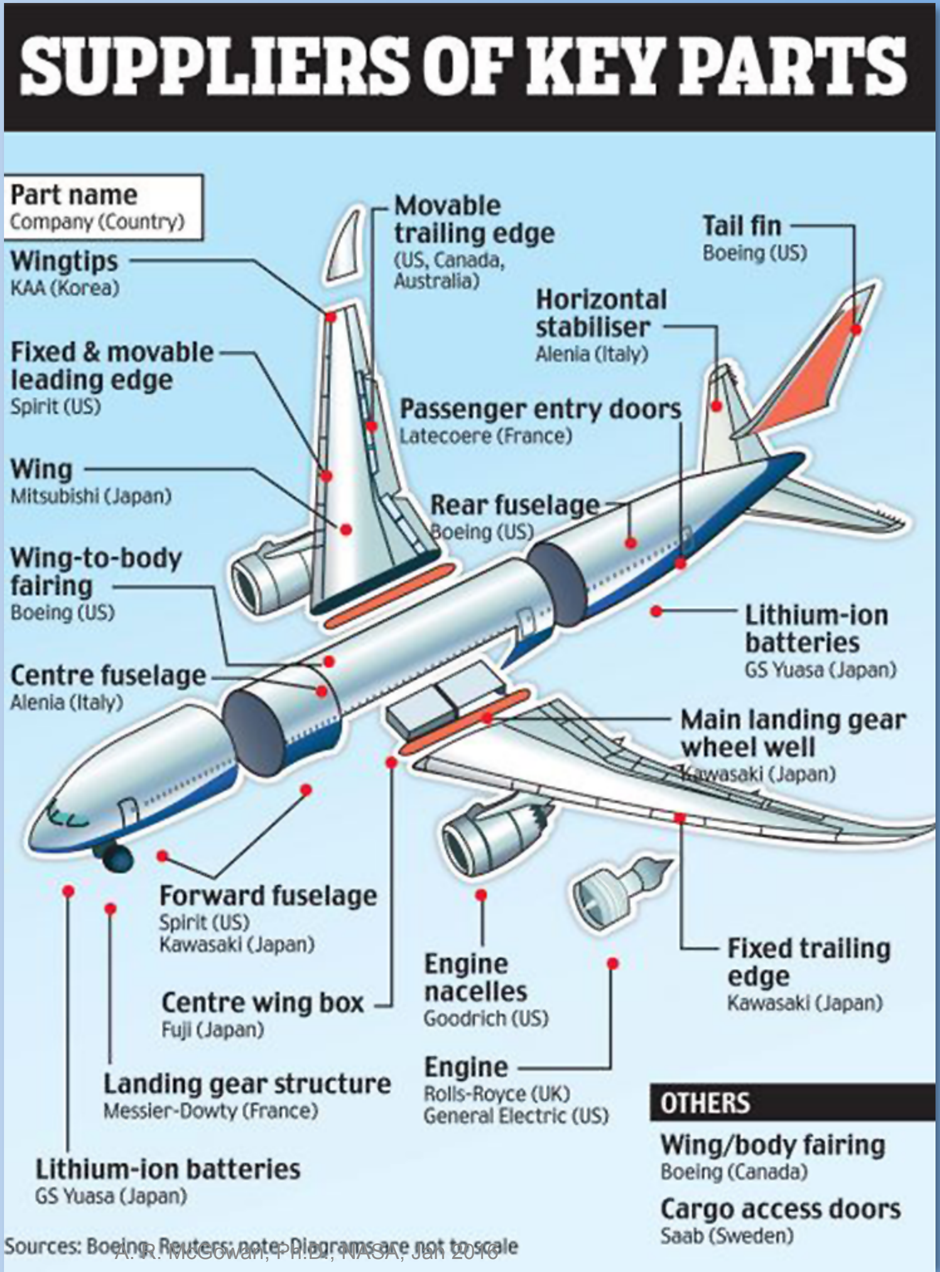


Some Aspects of the **Organizational Context**



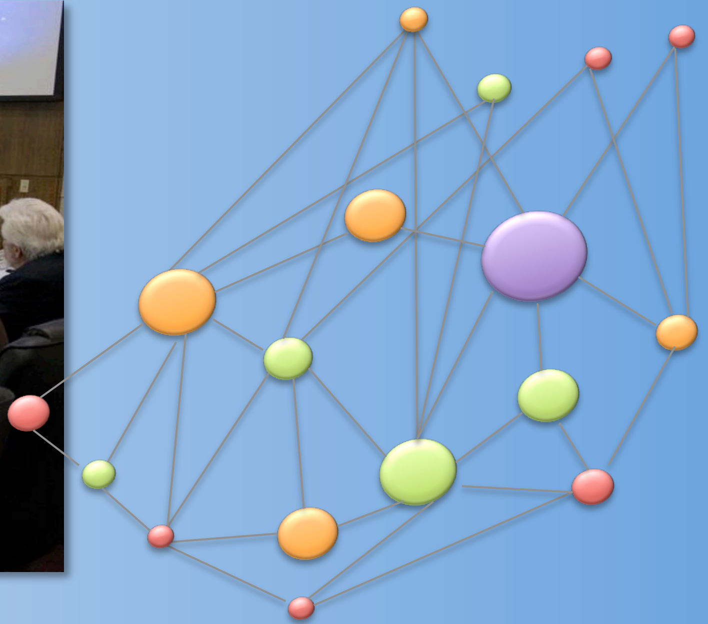
Large-Scale Complex Engineered Systems

Large number of people and organizations involved



Who Has *All* of the Information for a Large-Scale Complex Engineered System?

Who Has *All* of the Information for a Large-Scale Complex Engineered System?

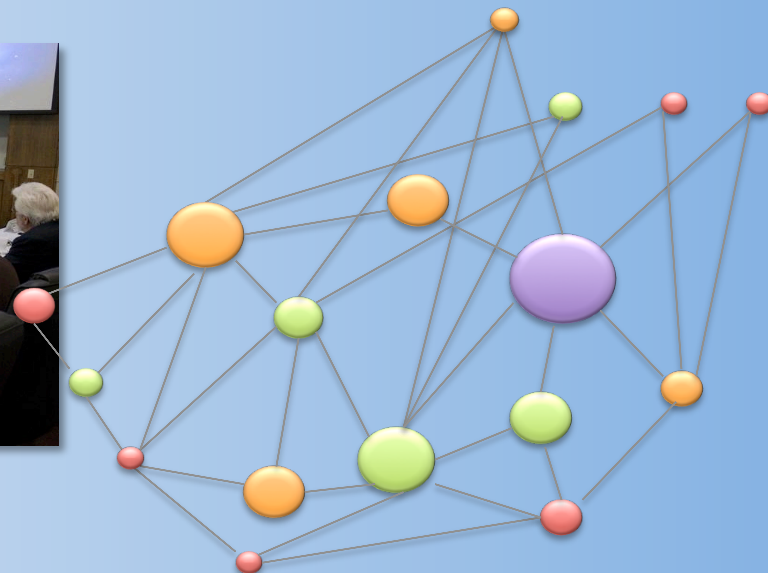


<u>"Meeting Room?"</u>
Unable Get All Team Members in a Room to Work Collectively on the System

<u>Bridging:</u>
Language
Assumptions
Culture
Engineering methods
Organizational processes

<u>Multiplicity</u>
Multiple People (>1000)
Multiple Interfaces (>500,000)
Multiple Organizations
Multiple Disciplines

Who Has *All* of the Information for a Large-Scale Complex Engineered System (LaCES)?



No Real Meeting Room

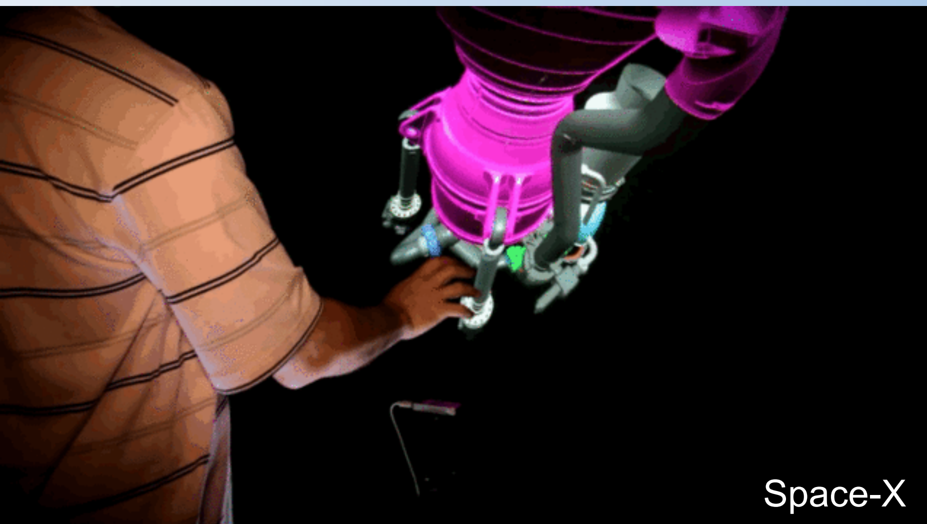
Multiple People, Interfaces, Organizations, and Disciplines

Bridging Many Organizational and Social Constructs

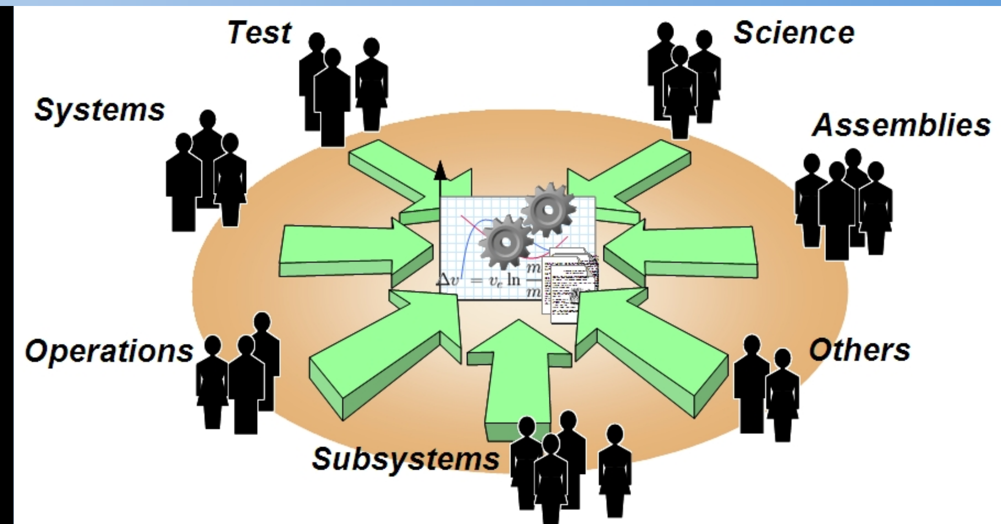
Dispersed
System Knowledge

No Single Entity Has *All* of the "System" Knowledge
System Knowledge is Held Collectively by the Organization

Working with a System in “No One’s Head” And in No Singular Computer



https://www.youtube.com/watch?v=xNqs_S-zEBY



B. Muirhead, JPL

“Portions of the envisaged system are known to all, but all of it is known to none.”

(Weick, 1993)

Area of Study: Organizational Sensemaking & High Reliability Organizations

Next Steps: Transforming how we work, communicate, and share knowledge and data blending advancements in
Cognitive, Computer, Decision, Information, and Organizational Sciences


DEVELOPMENT FLIGHT TEST
ARES I-X
NASA
Ares I-X
National Aeronautics &
Space Administration
GO ARES I-X!
USA


ORION
ORION | LAS
ORION Launch Abort System


PA-1
ORION
FLIGHT TEST
ORION
PA-1
Pad Abort-1


ORION EFT-1
OR1ON
EXPLORATION FLIGHT TEST
ORION
EFT-1 LAS
Exploration Flight Test-1
Launch Abort System
ULA

Interdependencies

Interconnectivities

Interactions

Interoperability

Dynamics

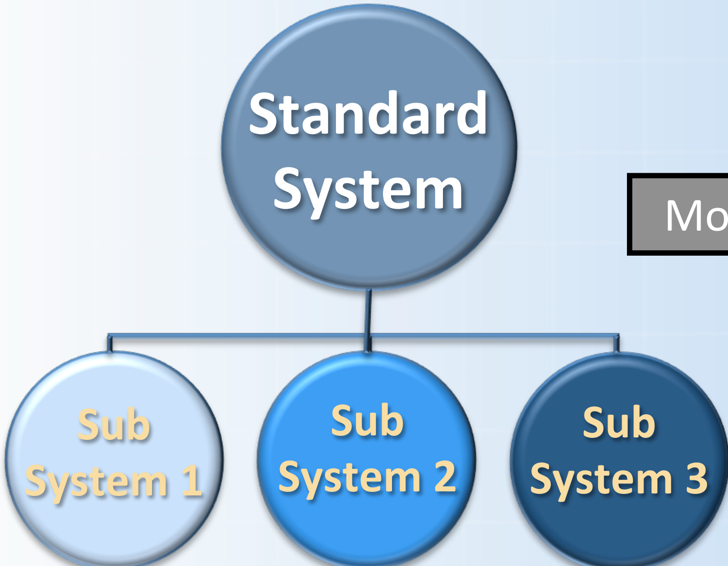
Nonlinear, Adaptive, & Emergent

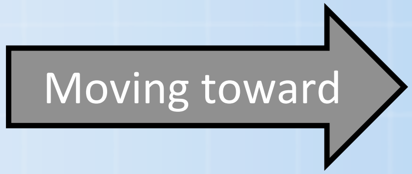
Large Number of People

In Development and In Use

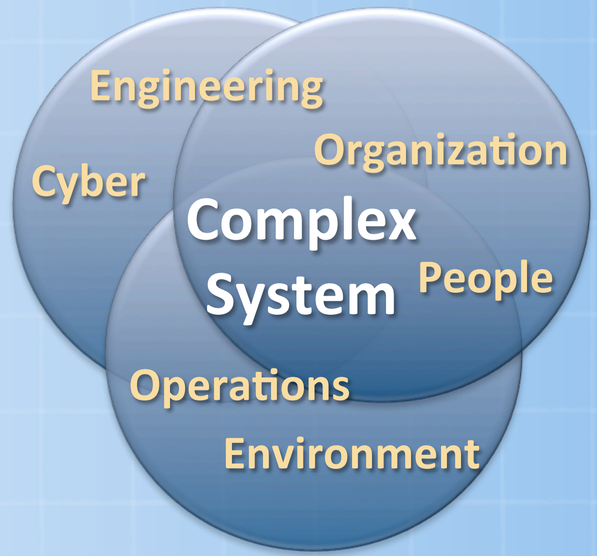
A Different View of “Systems Thinking”?

Conventional View of a System





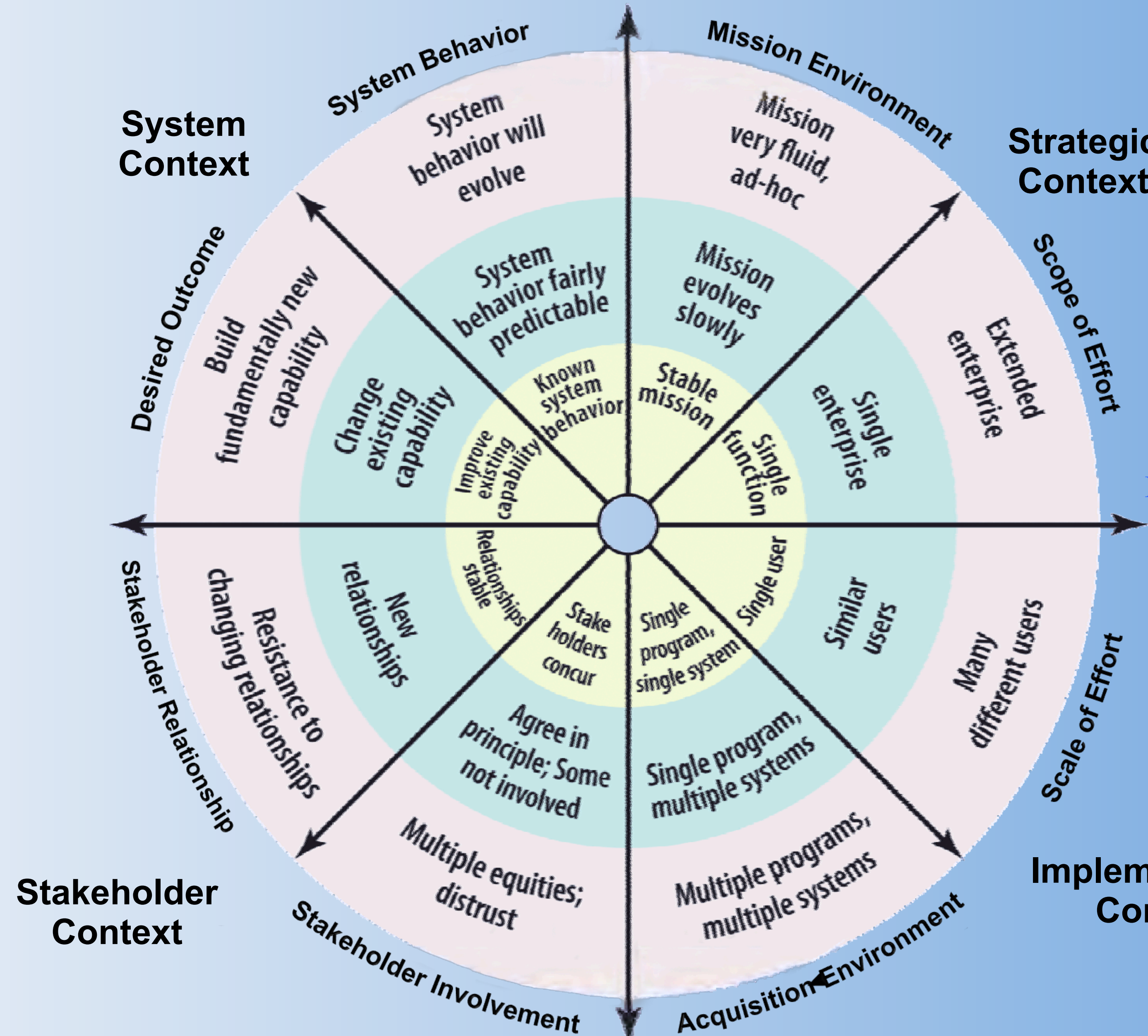
An Interdisciplinary View of a Complex System



Reductionist Approach

System Approach

A Complex System is often more a function of the *interactions of the components* than the components themselves

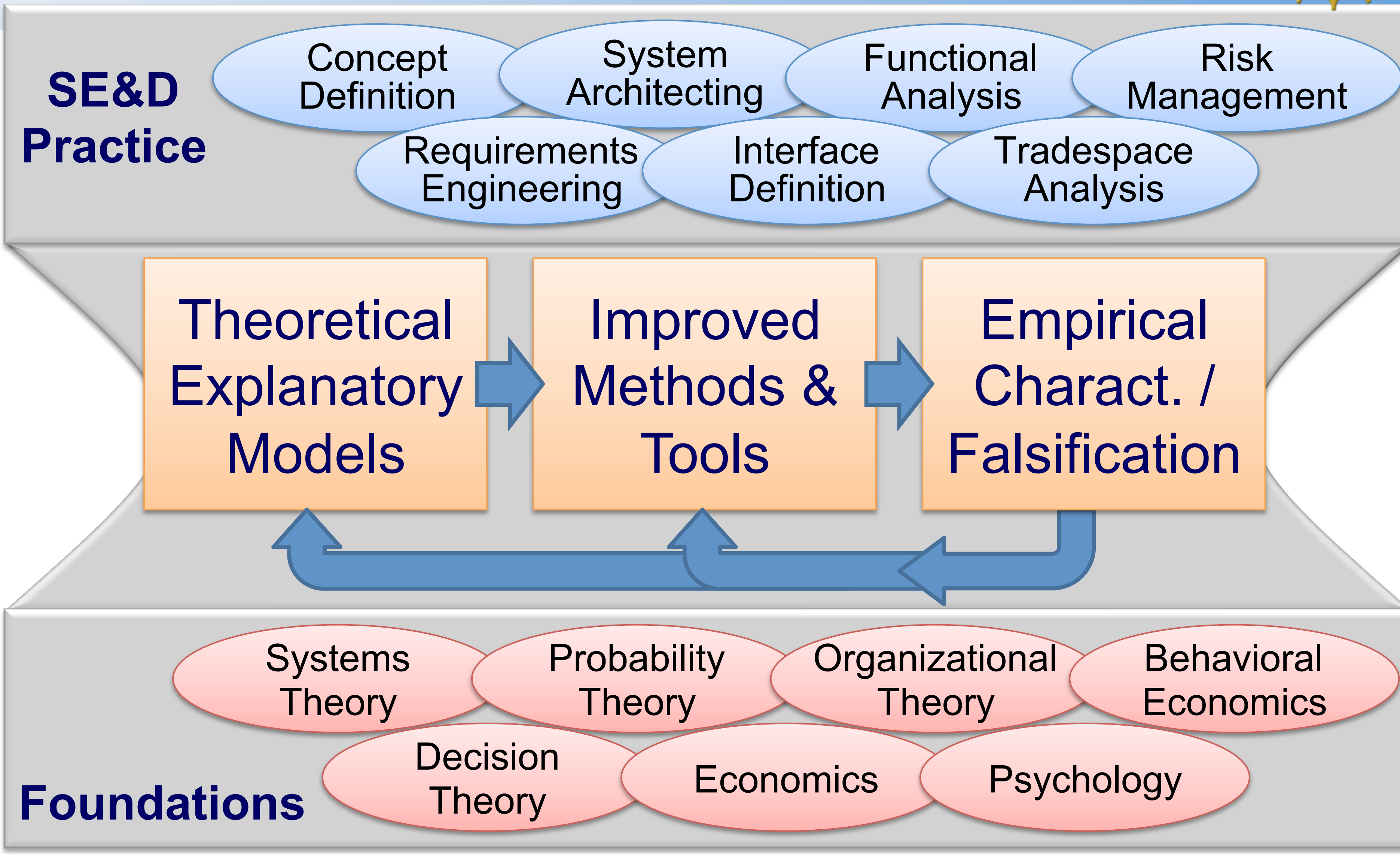


Profiling Complex Systems
Dr. Renee Stevens, 2006
The MITRE Corporation

The Enterprise Systems Engineering Profiler

Theoretical Framework for SE & Design

Explanatory Models Supported by Empirical Evidence



Courtesy Dr. Chris Paredis, NSF

Engineered Resilient Systems Major Investment Areas

Mission-Relevant Tradespace Analysis

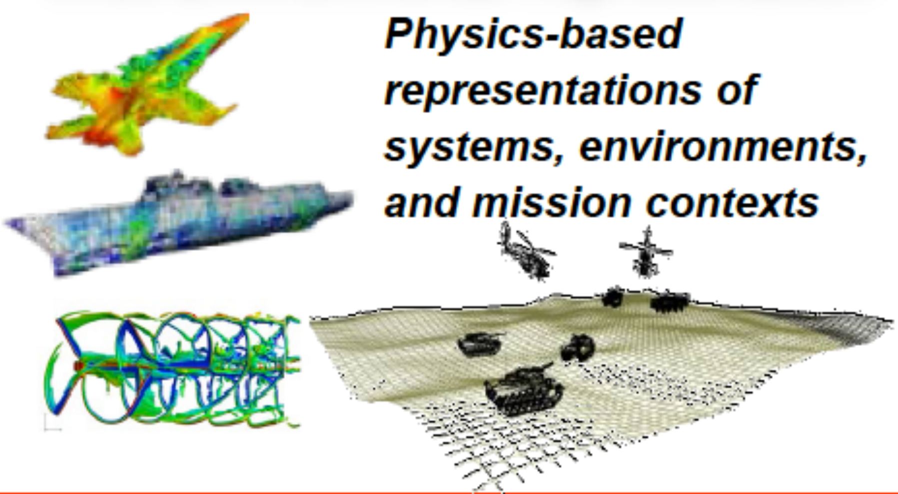
Cross-domain Tradespace Analytics, Cost/Lifecycle Analysis, Integration of Manufacturability, Producibility, and other "-ilities"

Collaborative Analysis and Decision-Making

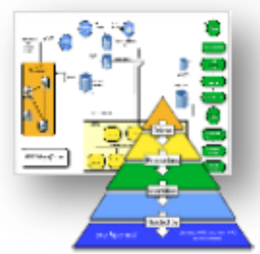
Knowledge management and decision support across communities

Conceptual, Computational, and World-Wide Environmental Representation

Physics-based representations of systems, environments, and mission contexts



ERS Capability Integration and Demonstration



Open, extensible architectural framework that integrates representations, tradespace, and analysis tools

Continual technology insertion -- Continual demonstration

Interdisciplinary Research

The Good:

Innovation and opportunity often occurs between disciplines

- **Sharing ideas and iterating toward new solutions**
- **Enabling design solutions impossible from a single or a few perspective(s)**

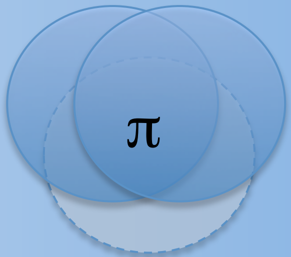
The Difficulties:

Errors and inefficiencies often occur between disciplines

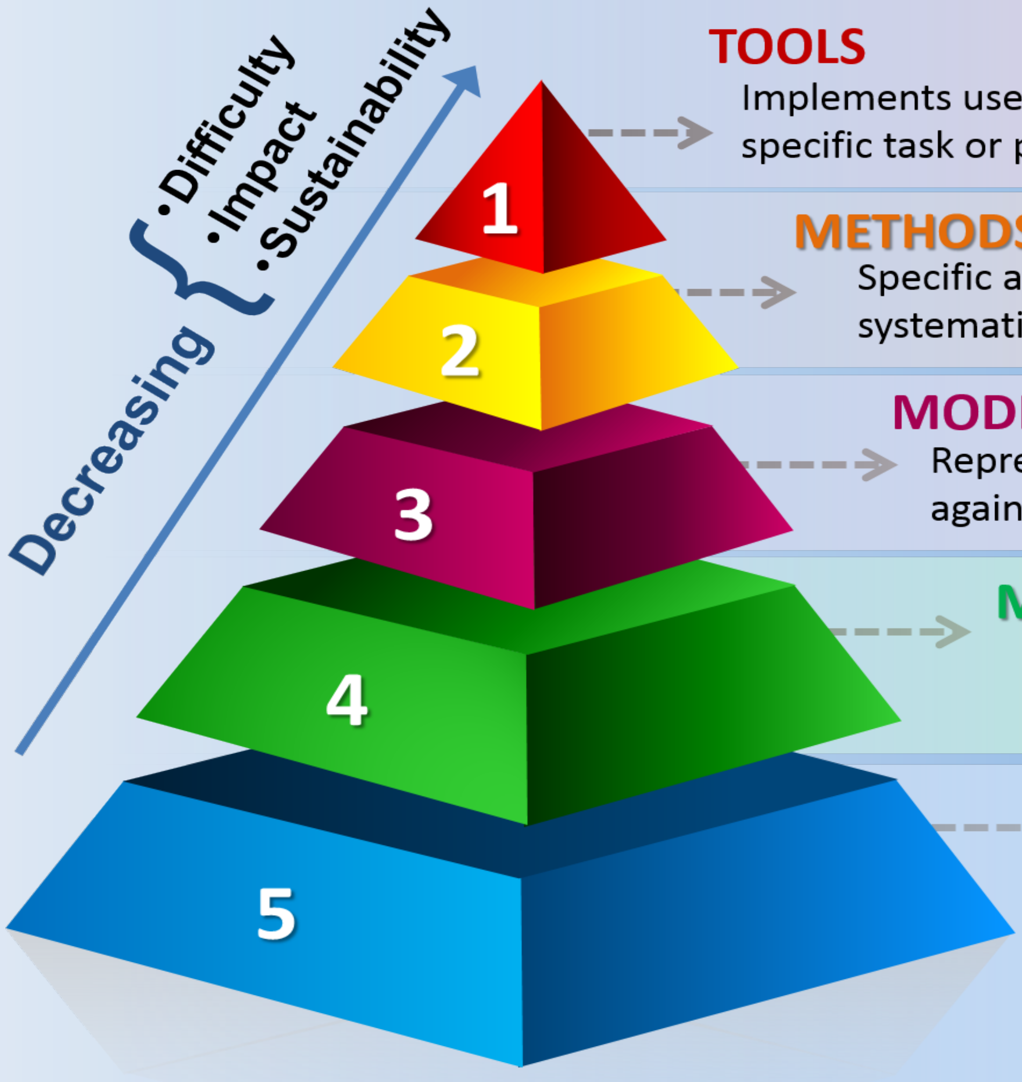
- **Confusion, misunderstanding, miscommunication**
- **Considerable variability and equivocality**
  - Terminology, styles, leadership, culture, risk, networking, creativity, expectations

Rethinking Roles & Creating More Interdisciplinary Approaches

- **Specialists & Generalists**
  - Traditional Fields
  - Nontraditional Fields
- **T-Shaped**
- **Connectors (Social skills are important)**
- **π-shaped (Interdisciplinary Engineers and Scientists)**



Interdisciplinary Rigor



TOOLS
Implements used to support accomplishment of a specific task or purpose

METHODS
Specific approaches that are performed in a systematic manner to accomplish something

MODELS
Representations that capture attributes against which comparisons can be made

METHODOLOGIES
Generalized frameworks that guide applications for the field

CONCEPTUAL FOUNDATIONS
The fundamental underlying philosophical, theoretical, and axiomatic (principles) basis for the field

Source: adapted with permission from Dr. Keating, ODU

Interdisciplinary Rigor

Knowledge:

- **Greater Knowledge: You must understand the theoretical foundations of both (or all) parts of the interdependency**
  - Clearly understand the limits of the theories used and delineate the statistical or theoretical generalizability or transferability of the results and findings of the different disciplines or fields of research

- **Creating New Knowledge: Understanding the parts is necessary but insufficient for understanding the interdependency**
  - Some of the assumptions used to understand the separate parts **do not make sense** at the intersection (i.e., static, linear)
  - New theoretical explanations usually have to be derived that differ from those used to describe the separate parts

Interdisciplinary Rigor

Some Things are Irreducibly Entwined

- **Oversimplification can be dangerous (or illogical)**
  - The interdependent behavior (i.e., combustion) cannot be derived from a simple summation of the behavior of the parts of the interdependency
  - ~~“Interface”~~ loses meaning as boundaries between disciplines blur (i.e., aeroacoustics)
  - New properties emerge and change in the interaction (i.e., aeroelasticity)

- **Theoretically rigorous simplifications** are usually derived after extensive research of the interdependency

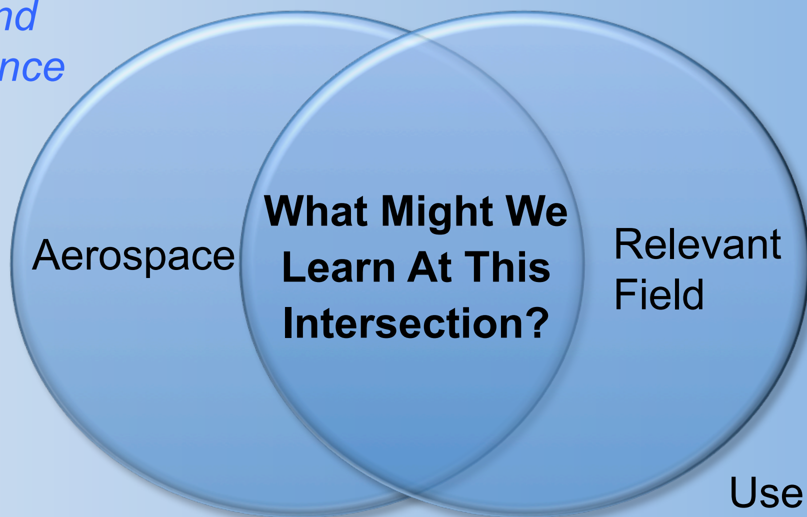
Examples of Other Relevant Fields

Understanding and Exploiting the Connections

Making decisions in the presence of many, often conflicting, factors and decision makers
Decision Science and Organizational Science

Architecting, Innovation, Problem Formulation, Creating Engineering Solutions
Design Science

Designing experiments and analyses to best evaluate the system
Statistical Science



Designing Teams, Org Structures, Incentivizes; Improving Sensemaking and Collaboration
Organization Science

Use of NASA technologies and data by the general public
Sociology

Handling diverse and copious amounts of information with a large dispersed team
Information Science and Cognitive Science

Ultimately: Create or Design an Interdisciplinary Methodology

a strategy or framework for solving the complex problem in a specific context

Interdisciplinary Methodology:

Includes the collection, plan, organization, and integration of different methods and disciplines that will be used to solve the problem

Theoretical Perspectives on Interdisciplinarity from an Engineering Practice Lens:

Integration is Technical and (very) Human

- **Knowledge is Enacted and Co-Constructed Through Ongoing Interaction**
- **Argument and Ignorance are Inherent <u>and Useful</u>**
- **Examples from the literature:**
  - "To share and assess each others domain-specific knowledge… is a **political process**. (Carlile, 2004)
  - "Integration is **a human action** … negotiated, situationally dependent, and **contingent on the participants**." (Klein, 2008)
  - "**Negotiation** of practices and co-evolution of practices and technology. …**co-construction of meaning**" (Haythornthwaite, et al., 2006)
  - **Socially constructed** (Weick, 1993, 1995, 2005)
  - **Knowing** vs Knowledge (Orlikowski, 2002)

Embrace Interdisciplinarity

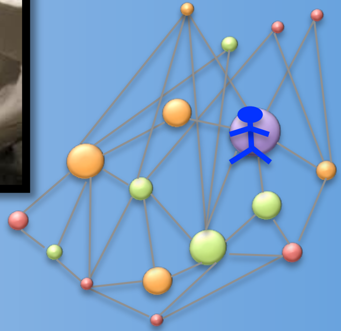
Many of the Challenges ***and Opportunities*** for Solving Complex Challenges are at the **Intersections** of Disciplines Including Non-Engineering Disciplines

Interdependencies
Interactions
Interconnectivities
Interoperability

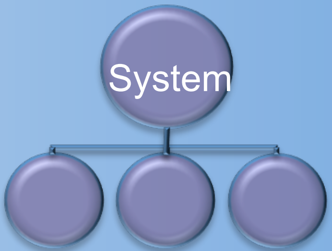
Rigorously Integrate Non-Engineering Influences

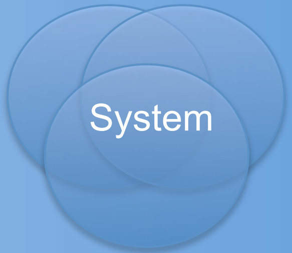
Human-Centered Design Approaches

Qualitative and Quantitative Methods



Balance "Reductionist System Thinking" With Strategic "Complex System Thinking"





Acknowledgements

Design Science

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Shana Daly, Univ. of Michigan

Pete Parker, NASA

Christina Bloebaum, Univ. of Iowa

Paul Collopy, Univ. of Alabama

Chris Paredis, Georgia Tech

Scott Lucero, Pentagon, DASD

Al Jones, NIST

National Aeronautics and Space Administration

Thank You

Discussion and Questions

REACH NEW HEIGHTS

BENEFIT ALL HUMANKIND

REVEAL THE UNKNOWN

NASA.gov

Representative Positive Example

Senior Researcher with Over 35 Years Experience:

"They [discipline A] run into [this problem]; in order to have [their sub-system] perform, you have to have some [work from our discipline]. …They feel like you're an important part of [the discipline A sub-system] development. There's a <u>mutual understanding</u> that they need us…

… We work together. That's how we do one and one and make it more than two, us working together.

It's not like, here is a [discipline A] model; go do the [discipline B] work. We're working together. We're defining the requirements together. …it's a collaborative effort. Everybody is seen as a so-called <u>equal partner</u>. Every contribution is valued."

Representative Negative Example

Senior Researcher with Over 25 Years Experience:

"The [discipline A] folks basically said just give us [this interface]. We don't care what you [do in your discipline]. We don't care how much [you do this]. Just make it so it [meets the interface requirements we have].

So, based on that interchange, my general feeling was they felt like they didn't need us. They were dictating the [the interface] and as long as I [created the interface they wanted] they didn't care about what I did in my discipline.

… So the reality is that …I can [meet their interface demands perfectly], no kidding, … but you're never going to get it [the overall system to work].

Terminology

- **Cross-Disciplinary = all forms of working across disciplines**
- **Multidisciplinary**
  - Non-interactive inclusion and juxtaposition of disciplines
  - Discipline methods, assumptions, theories are updated but not significantly modified
- **Interdisciplinary**
  - Interactive integration of disciplinary knowledge
  - Co-construction of new knowledge
  - Disciplinary methods, assumptions, theories are often challenged, then changed
  - Disciplinary methods become interdependent
- **Trans-disciplinary**
  - Transcending the constructs of existing disciplines, methods, conventions