Systems Engineering Advancement Research Initiative

Empirical Research on Systems Thinking and Practice in the Engineering Enterprise

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Topics

- Research Motivations
- Research Landscape
- Traits of Systems Leadership
- Three Areas of Research
- Implications for the Practice
- Future Directions

Research Motivations (1)

Shortfalls in the systems engineering workforce

- Increasing demand for systems engineering skills in government and industry
- Erosion of engineering competency particularly in aerospace and defense
- Increased interdisciplinary emphasis as world becomes more connected
- Systems complexity demands more sophisticated systems architecting skills
- Nature of programs necessitates socio-technical rather than pure technical abilities

Research Motivations (2)

Advances in the practice of systems engineering

- Very large systems programs demand a collaborative distributed workforce
- Model-based systems engineering leads to new ways of performing systems work
- Systems engineering applied across many domains – critical infrastructure, energy, transportation, communications, others
- New/evolved practices required for systems of systems engineering

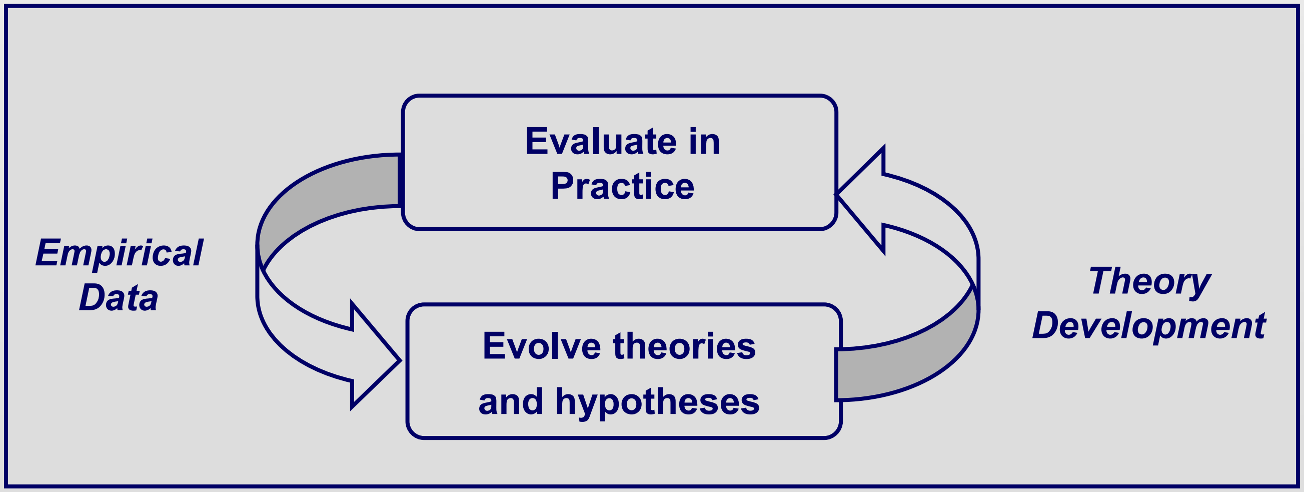
Research Needs

Increasing demand for systems leaders coupled with the growing need to address significant socio-technical challenges motivates research in engineering systems thinking and practice

- Empirical studies and case based research
- Better understanding of systems contexts
- Factors underlying competency in workforce
- Identification of enablers, barriers, precursors
- Systems thinking at multiple levels – individual, team, enterprise

Research Challenges

- Inhibited by traditional structure of academic institutions and funding agencies
- Requires in-depth understanding of engineering but at same time an orientation in the social sciences
- Exploratory nature of research not well suited to typical engineering/science approach -- need to apply grounded theory and other qualitative methods



Research Landscape

A research landscape is the overall mental model under which research is formulated, performed, and transitioned to practice

1. **Provides context for the research agenda, methods, and specific projects**
2. **Determines a community of interest**
3. **Opportunities/constraints on funding sources and sponsors**
4. **Significantly influences research outcomes and broader impact**

Field of Engineering Systems as Research Landscape

Engineering systems is a field of study taking an integrative holistic view of large-scale, complex technologically enabled systems with significant enterprise level interactions and socio-technical interfaces

- *Multi-disciplinary focus via cross-cutting academic unit – engineering, management, social sciences*
- *Draws from both quantitative and qualitative approaches*
- *Deep engagement with real world industry and government projects*

Four Perspectives for Engineering Systems Thinking

1. A very **broad interdisciplinary perspective**, embracing technology, policy, management science, and social science.

2. An **intensified incorporation of system properties** (such as sustainability, safety and flexibility) in the design process.
   - Note that these are lifecycle properties rather than first use properties.
   - These properties, often called "ilities" emphasize important intellectual considerations associated with long term use of engineering systems.

3. **Enterprise perspective**, acknowledging interconnectedness of product system with enterprise system that develops and sustains it.
   - This involves understanding, architecting and developing organizational structures, policy system, processes, knowledgebase, and enabling technologies as part of the overall engineering system.

4. A **complex synthesis of stakeholder perspectives**, of which there may be conflicting and competing needs which must be resolved to serve the highest order system (system-of-system) need.

Traits of Contemporary Systems Leaders

Hall (1962) …

1. An affinity for the systems point of view
2. Faculty of judgment
3. Creativity
4. Facility in human relations
5. A gift of expression

A.D. Hall, A Methodology for Systems Engineering, NJ; Van Nostrand, 1962

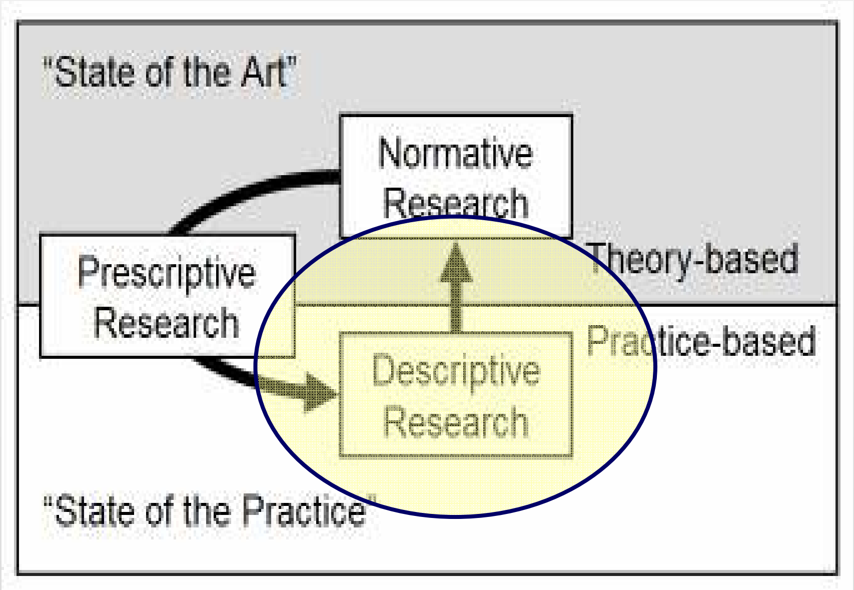
Traits of Contemporary Systems Leaders

1. Powerful integrative leaders focusing on societal needs
2. Utilize approaches beyond traditional engineering
3. Consider context as a design variable rather than a constraint
4. Intellectual skills to deal with many socio-technical dimensions
5. Higher order abilities for analysis and synthesis
6. Be capable of "situational leadership"

Three Areas of Research

1. Engineering Systems Thinking in Individuals
2. Collaborative Distributed Systems Engineering
3. Collaborative Systems Thinking

SEAri Research Structure



Engineering Systems Thinking in Individuals

General systems thinking has been studied empirically, but engineering systems thinking largely unexplored

Frank (2000) characterized engineering systems thinking as unique

Davidz (2006) performed study of 200 engineers in aerospace industry to identify enablers, barriers, precursors

Experiential Learning

Individual Characteristics

Supportive Environment

Rhodes & Adams (2007) find similar indicators in government agency

Studies on Capacity for Engineering Systems Thinking
Moti Frank

Studies to characterize engineering systems thinking as distinct from systems thinking

Examples:

- Understanding whole system and seeing big picture
- Understanding a new system concept immediately on presentation
- Understanding analogies and parallelisms between systems
- Understanding limits to growth

Motivation
Davidz 2006

- Increasing complexity of engineering systems and the corresponding need for systems professionals
- Importance of systems engineering, demonstrated in policy mandates
- Importance of systems engineering workforce issues, also shown in policy documents
- Data needed on systems thinking development in order to know which methods are most effective in developing systems thinking in engineers

Need for DATA on Systems Thinking Development

Enabling Systems Thinking to Accelerate the Development of Senior Systems Engineers

Davidz 2006

Even though systems thinking definitions diverge, there is consensus on primary mechanisms that enable or obstruct systems thinking development in engineers

Consensus on primary mechanisms that enable or obstruct systems thinking development in engineers

- Experiential learning
- Individual characteristics
- Supportive environment

Example Systems Thinking Definitions – Davidz 2006

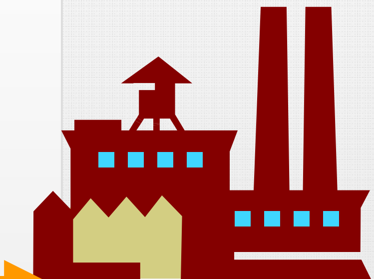
- "Big picture"
- "Interactions"
- "Worrying about everything"
- "System thinking is the ability to think about a system or system architecture holistically, considering the design elements, complexities, the "ilities", the context that product or system will be used in, etc."
- "You have to think extremely broadly. You can't focus on a specific aspect. Think from the application of what a product is. Think from what the customer wants explicitly. Be able to think in all the areas that are related to that device. It's broad and deep thinking. If you can't do both, then you shouldn't do systems stuff. You must be organized. Think without boundaries at the start. If you think that your job is the requirements, then you are a clerk, not a systems engineer."
- "Connecting lots of dissimilar disciplines and weighing trade offs between them…"

Research Methods

Davidz 2006

Literature review

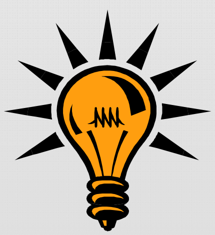
Pilot Interviews (N=12)



Field Study of 10 Companies and 205 Subjects Using Interviews and Surveys

Additional Interviews with "Blue Chip" Proven Experts (N=2)

Data Analysis Using QSR N6, SPSS, MS Excel



Theory Synthesis

Experiential Learning Develops Systems Thinking

Q: What were key steps in your life that developed your systems thinking abilities?

Top Level 1 Key Steps to the Development of Systems Thinking for All Classifications
(Node categories cited by 10% or more of the classification are shaded)

Node Category	All Participants (N=202)			Expert Panelists (N=37)			Senior Systems Engineers (N=61)			Senior Technical Specialists (N=52)			Junior Systems Engineers (N=52)			Chi-Square	Asymptotic Significance
	Rank	Number	Percent	Rank	Number	Percent	Rank	Number	Percent	Rank	Number	Percent	Rank	Number	Percent		
Work Experiences	1	139	69%	1	35	95%	1	36	59%	1	38	73%	1	30	58%	**17.625**	**0.001**
Education	2	80	40%	3	13	35%	3	22	36%	3	17	33%	2	28	54%	6.076	0.108
Individual characteristics	4	64	32%	2	16	43%	4	16	26%	4	11	21%	3	21	40%	7.605	0.055
Life experiences outside work	3	72	36%	4	5	14%	2	27	44%	2	19	37%	3	21	40%	**10.402**	**0.015**
Interpersonal	5	37	18%	4	5	14%	5	13	21%	4	11	21%	5	8	15%	1.515	0.679
Training	6	16	8%	6	4	11%	6	7	11%	6	2	4%	6	3	6%	2.994	0.393

Source: Davidz 2006

"Systems Thinking Mindset"
Davidz 2006

- MUST be decomposed, since understandings can be contradictory
- Before designing an intervention, know what you are trying to produce

Process-Centered SE Traits	System-of-Systems SE Traits
Detail oriented	Not detail focused
Structured	Thinks out-of-the-box
Methodical	Creative
Analytical	Abstract thinking

Define the Goal then Design the Intervention

Determination of Strength of Systems Thinking Davidz 2006

How does your company determine if an employee displays strong systems thinking?

Level

Difficulty

Top Level 1 Coding for Determination of Strong Systems Thinking for All Classifications

(Node categories cited by 10% or more of the classification are shaded)

Node Category	All Participants (N=165)			Senior Systems Engineers (N=62)			Senior Technical Specialists (N=51)			Junior Systems Engineers (N=52)			Chi-Square	Asymptotic Significance
	Rank	Number	Percent	Rank	Number	Percent	Rank	Number	Percent	Rank	Number	Percent		
Difficulty with this	1	100	61%	2	30	48%	1	33	65%	1	37	71%	6.659	0.036
Experience and observation	2	95	58%	1	41	66%	2	29	57%	2	25	48%	3.788	0.150
Look for certain characteristics	3	28	17%	3	9	15%	3	12	24%	3	7	13%	2.277	0.320
Formal methods	4	23	14%	4	7	11%	4	11	22%	4	5	10%	3.648	0.161

Observation & Subjective Measure

Engineering Systems Thinking in Individuals

Empirically Derived Implications for Practice

1. Educate engineers to think more deeply about systems in their context and environment

2. Develop “situational leadership: abilities in engineers – capable of making decisions at component, system, systems of systems level

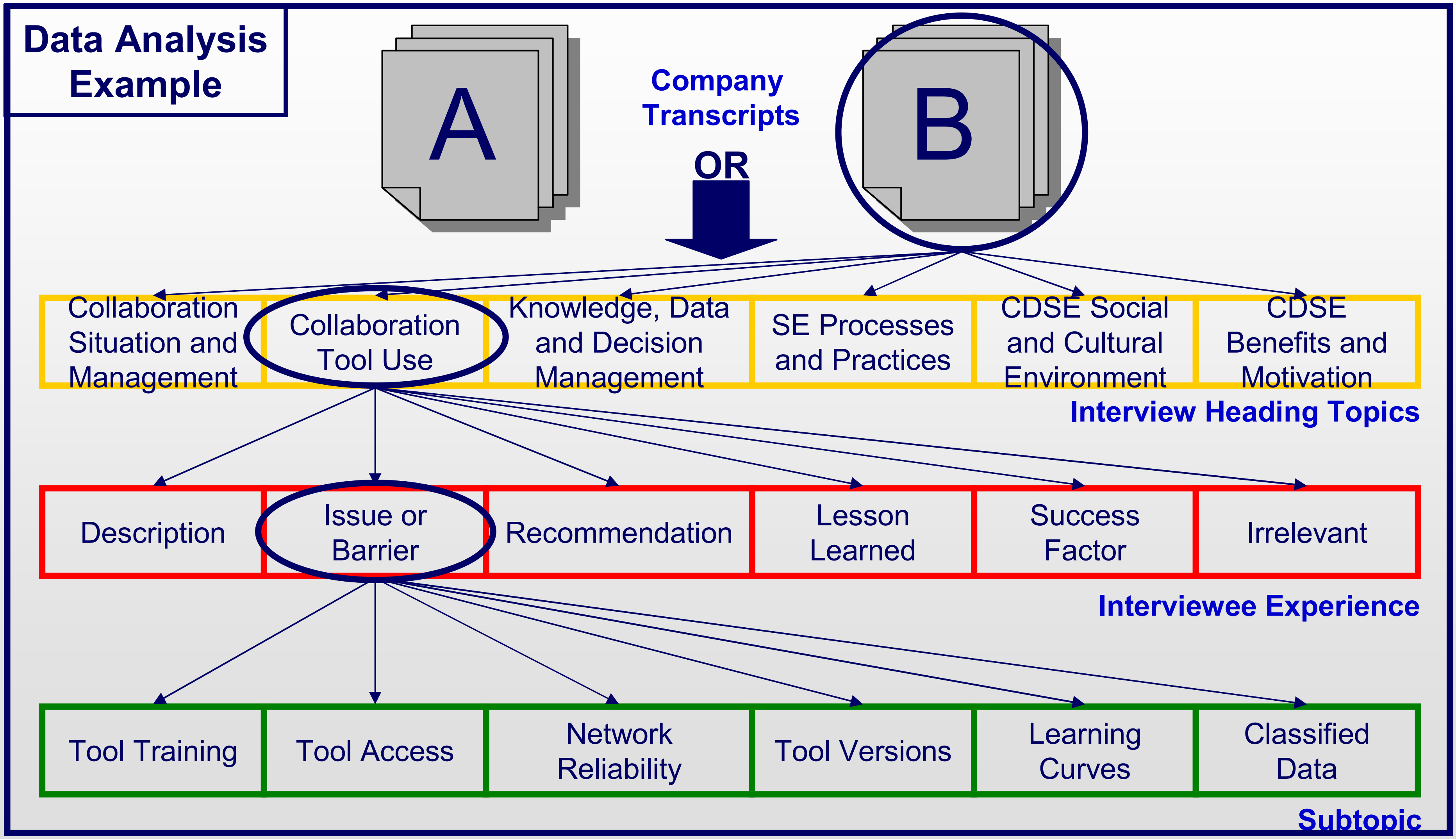
3. Provide classroom and experiential learning opportunities with systems across the life cycle phases – develop ability to make decisions in present for an uncertain future

Collaborative Distributed Systems Engineering (CSDE)

- Utter (2007) performed empirical case studies to identify successful practices and lessons learned
- Social and technical factors studied: collaboration scenarios, tools, knowledge and decision management, culture, motivations, others
- Can not be achieved without first overcoming possible barriers and issues
- Preliminary set of success factors identified

Success Factor: Invest in Up-front Planning Activities
Spending more time on the front- end activities and gaining team consensus shortens the implementation cycle. It avoids pitfalls as related to team mistrust, conflict, and mistakes that surface during implementation.

Empirical Data in Exploratory Study



CDSE Success Factors

Perform Visual Management of Development Process	Visual management of the development process may be useful in **establishing a sense of team**, as well as **keeping the team immediately up-to-date on important programmatic and product related issues**. This visual management may be possible by using the **collaboration tools or environments and/or team room displays**. Imagine an online collaborative environment, and upon logging in, **immediately being informed of a subsystem's current testing or development status** (perhaps in red, yellow, green). Or similarly, entering a CDSE team room to find the color-coded schedule progress of each team. These visual cues provide immediate feedback without having to scour schedules, requirements, or test data and are relatively simple to implement.

Collaborative Distributed Systems Engineering

Empirically Derived Implications for Practice

1. Thirteen socio-technical ‘success themes’ identified that may lead to best practices

2. Exploratory studies uncovered differences in maturity in regard to factors that foster or inhibit – suggesting a “collaboration maturity factor”

3. Desirable future outcome is development of assessment instrument to assist organizations in assessing readiness to undertake collaborative distributed systems engineering

Collaborative Systems Thinking

- It is not enough to understand systems thinking in individuals but also how it emerges in groups and enterprises
- Lamb (2008) performing empirical studies - focus on interaction of process and culture
- Research seeks to identify promising patterns that can lead to larger cross-cutting studies
- Pilot interviews have provided insights to inform the study

Factors in Collaborative Systems Thinking:

These traits are not necessarily of one individual but emerge through interactions of a group of individuals as influenced by culture, team norms, environment, and processes

Collaborative Systems Thinking

Empirically Derived Implications for Systems Engineering Practice

1. Effective communication is necessary condition
2. Need ability to engage in divergent and convergent thinking
3. Product orientation vs single component/function is important
4. Overall team awareness within/across teams is an enabler
5. Hero culture, and associated incentives, is a barrier
6. Team segmentation results in negative behaviors
7. The interplay of culture and process appears to be critical

Limitations of Current Research

- Preliminary and exploratory
- Use of grounded methods to uncover findings and hypotheses
- Access to sensitive data and human subjects
- Organizations reluctant to share “bad” cases
- Difficult to fund this type of research

Future Directions

The understanding of the organizational and technical interactions in our systems, emphatically including the human beings who are a part of them, is the present-day frontier of both engineering education and practice.

Dr. Michael D. Griffin, Administrator, NASA
Boeing Lecture, Purdue University
28 March 2007

- Publication of case studies on social contexts
- Extension of exploratory studies to larger study projects
- Further research into collaboration factors
- New research on methods and infrastructure for virtual enterprises
- Conduct sufficient research and validation to inform enhancements to the practice
- Application of engineering systems thinking to SoS and enterprises

Access to Research
http://seari.mit.edu

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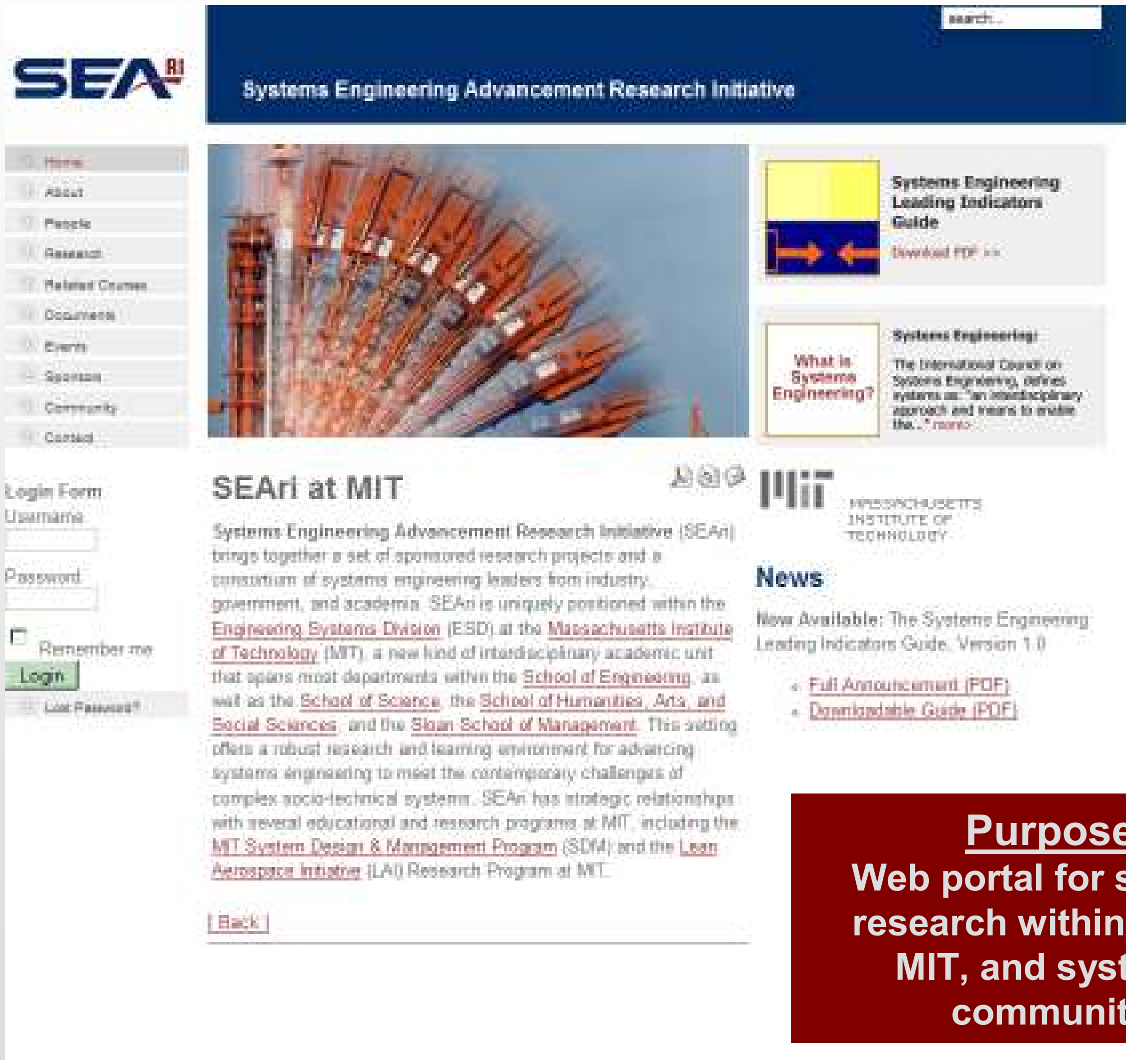

Purpose

Web portal for sharing research within SEAri, MIT, and systems community