Systems Engineering for Systems of Systems: Update

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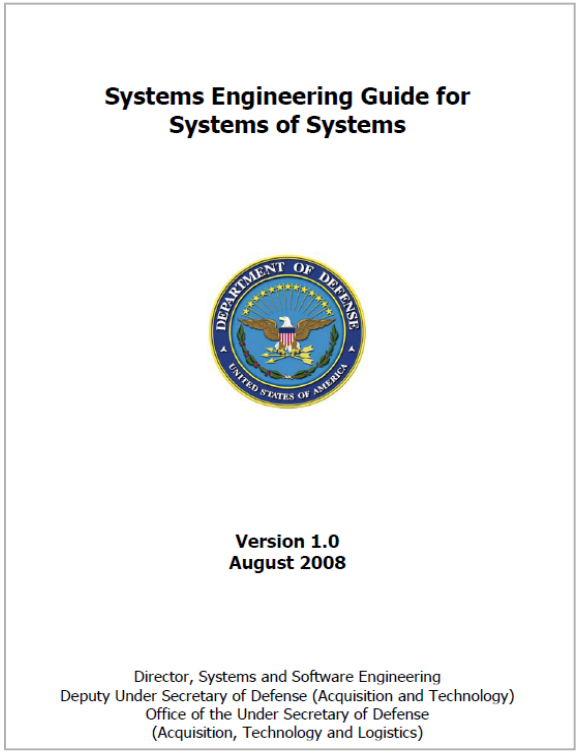
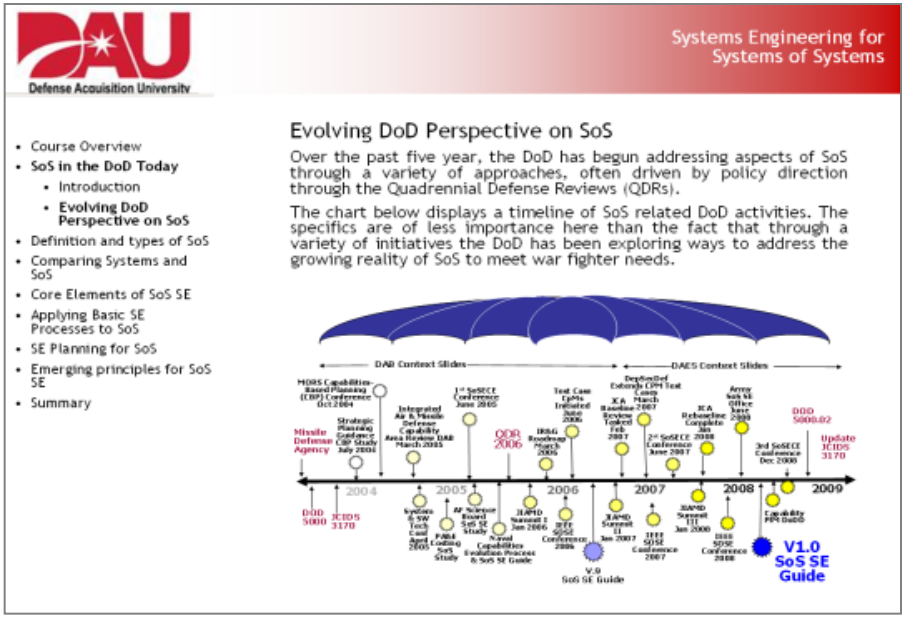
Background

- **DoD SoS SE Guide was published in late 2008 and is now being applied in a variety of settings across the DoD**
- **Current DDR&E SoS emphasis is on implementation, with major activities focus on**
  - Outreach
    - DAU Continuous Learning Module
    - NDIA SoS SE Committee, SharePoint and Webinars
  - Collaboration – TTCP and DoD SoS Initiatives
  - Initiatives to support SoS SE Implementation
    - SoS and T&E
    - SoS and Development Planning
    - SoS Artifacts
    - SoS 'Wave' Model
- **Next Steps**

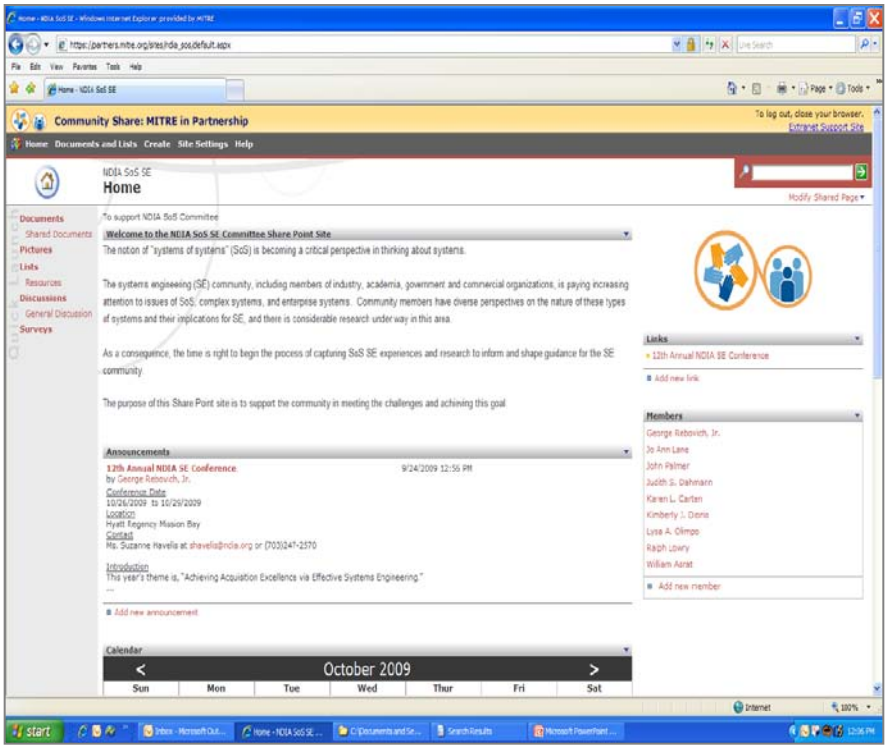


Outreach
SoS SE Continuous Learning Module



- Defense Acquisition University (DAU) provides education and training to US DoD workforce
- SoS SE Continuous Learning Module (CLM) is in development
  - Presents critical information from the SoS SE Guide
  - Online offering, 3-4 hour course
  - Expected to be available ~December 2010

Outreach
NDIA SoS SE Committee



- National Defense Industrial Association (NDIA) Systems Engineering Division (SED)
  - Forum for industry, government and academic collaboration
- SoS SE Committee created in Feb 2009
  - Meet every 2 months (20-50 participants)
  - Identify areas of common interest; current focus
    - SoS and T&E
    - Approaches to SoS Assessment
  - Sponsor track at Annual NDIA SE Conference
    - Webinar Series

Outreach
SoS SE Webinar Series

Systems of Systems Engineering Collaborators Information Exchange (SoSECIE)

Co-Sponsored by the
Director, Systems Analysis
DDRE Systems Engineering
And
National Defense Industrial Association (NDIA)
Systems Engineering Division
Systems of Systems Committee
Judith Dahmann,Mitre and John Palmer, Boeing Co-Chairs

- Twice monthly webinar on topics of interest to SoS SE Community
- Began with selected presentations from initial NDIA SE Conference SoS SE Track with added presentations from other venues
- Presentations are available on DDR&E Website and NDIA SoS SE Share Point Site

Outreach
SoS SE Webinar Series

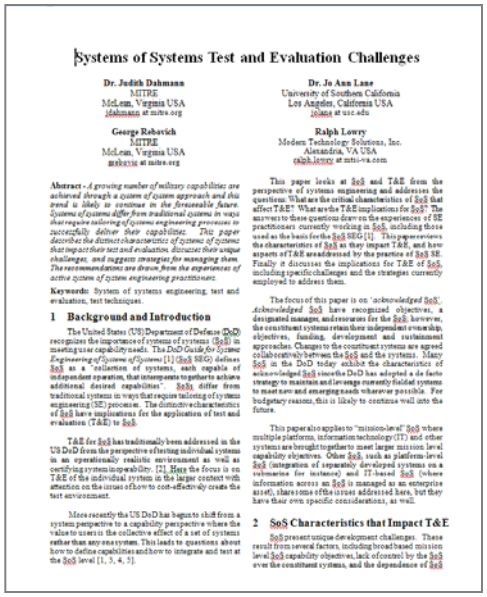
- **An Introduction to Influence Maps: Foundations, Construction, and Use**
  February 23, 2010**,** Jim Smith, SEI
- **On Modeling and Simulation Methods for Capturing Emergent Behaviors for Systems of Systems**
  March 9, 1010, J. M. Zentner, T. R. Ender, S. Balestrini-Robinson, Georgia Tech
- **A Distillation of Lessons Learned from Complex System of Systems Acquisitions**
  March 23, 2010, Richard Turner and Dinesh Verma, Stevens, Mark R. Weitekamp, ANSER, Ann Tedford, Federal Aviation Administration
- **Dynamic Modeling of Programmatic and Systematic Interdependence for System of Systems**
  April 13, 2010, Dan DeLaurentis, Purdue and Brian Sauser, Stevens
- **SysML Strategies to Characterize and Analyze Systems of Systems**
  April 27, 2010, Dr. Jo Ann Lane, USC and Tim Bohn, IBM
- **System of Systems Interoperability Challenges and Potential Approaches: Reports from the Field**
  May 25, 2010, Dr. Carol Sledge, SEI
- **Assurance Cases for Analysis of Complex System of Systems Software**
  June 8, 2010, Stephen Blanchette, Jr., SEI
- **System of Systems Artifacts**
  July 13, 2010, Dr. Judith Dahmann, Mitre
- **Accelerating System of Systems Engineering Understanding and Optimization through Lean Enterprise Principles**
  July 27, 2010, Dr. Jo Ann Lane, USC and Dr. Ricardo Valerdi, MIT

Collaboration
US DoD and International

- The Technical Cooperation Program
  - Joint Systems Analysis Technical Panel 4: SE and Modernization SoS SE focus area with active interest by US, UK, Canada, and Australia
    - Focus on SoS SE Artifacts
    - Shared lessons learned from nations
- DoD Components and Agencies have been instituting SoS SE efforts or applying SE to SoS areas
  - DDR&E SE collaboration with these activities to
    - Share experiences
    - Identify areas of common interest
    - Understand experience with application of DoD SoS SE Guidance
    - Assist in developing component specific guidance

Initiatives
SoS and T&E

- Topic of 2009 in NDIA SoS SE Committee
- IEEE SoSE Conference 2010 Paper : SoS and T&E Challenges
  - Distinct characteristics of systems of systems that impact their test and evaluation
  - Unique challenges and strategies
  - Recommendations drawn from experiences of active SoS SE practitioners
- Foundation for August 2010 SoS and T&E Workshop



Systems of Systems Test and Evaluation Challenges

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Abstract - *A growing number of military capabilities are achieved through a system of system approach and this trend is likely to continue in the foreseeable future. Systems of systems differ from traditional systems in ways that require tailoring of systems engineering processes to successfully deliver their capabilities. This paper describes the distinct characteristics of systems of systems that impact their test and evaluation, discusses their unique challenges, and suggests strategies for managing them. The recommendations are drawn from the experiences of active system of system engineering practitioners.*

Keywords: System of systems engineering, test and evaluation, test techniques.

1 Background and Introduction

The United States (US) Department of Defense (DoD) recognizes the importance of systems of systems (SoS) in meeting user capability needs. The *DoD Guide for Systems Engineering of Systems of Systems* [1] (SoS SEG) defines SoS as a "collection of systems, each capable of independent operation, that interoperate together to achieve additional desired capabilities". SoSs differ from traditional systems in ways that require tailoring of system engineering (SE) processes. The distinctive characteristics of SoS have implications for the application of test and evaluation (T&E) to SoS.

T&E for SoS has traditionally been addressed in the US DoD from the perspective of testing individual systems in an operationally realistic environment as well as certifying system interability. [2]. Here the focus is on T&E of the individual system in the larger context with attention on the issues of how to cost-effectively create the test environment.

More recently the US DoD has begun to shift from a system perspective to a capability perspective where the value to users is the collective effect of a set of systems rather than any one system. This leads to questions about how to define capabilities and how to integrate and test at the SoS level [1, 3, 4, 5].

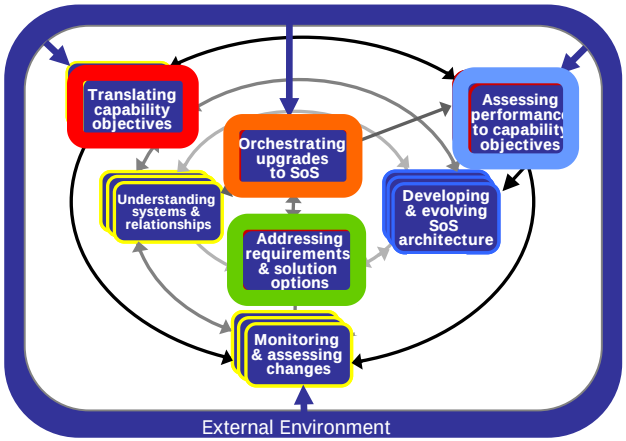
This paper looks at SoS and T&E from the perspective of systems engineering and addresses the questions: What are the critical characteristics of SoS that affect T&E? What are the T&E implications for SoS? The answers to these questions draw on the experiences of SE practitioner currently working in SoS, including those used as the basis for the SoS SEG [1]. This paper reviews the characteristics of SoS as they impact T&E, and how aspects of T&E are addressed by the practice of SoS SE. Finally it discusses the implications for T&E of SoS, including specific challenges and the strategies currently employed to address them.

The focus of this paper is on '*acknowledged* SoS'. *Acknowledged* SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, development and sustainment approaches. Changes to the constituent systems are agreed collaboratively between the SoS and the systems. Many SoS in the DoD today exhibit the characteristics of acknowledged SoS since the DoD has adopted a de facto strategy to maintain and leverage currently fielded systems to meet new and emerging needs wherever possible. For budgetary reasons, this is likely to continue well into the future.

This paper also applies to "mission-level" SoS where multiple platforms, information technology (IT) and other systems are brought together to meet large mission level capability objectives. Other SoS, such as platform-level SoS (integration of separately developed systems on a vehicle or platform for instance) and IT-based SoS (where information across an SoS is managed as an enterprise asset), share some of the issues addressed here, but they have their own specific considerations, as well.

2 SoS Characteristics that Impact T&E

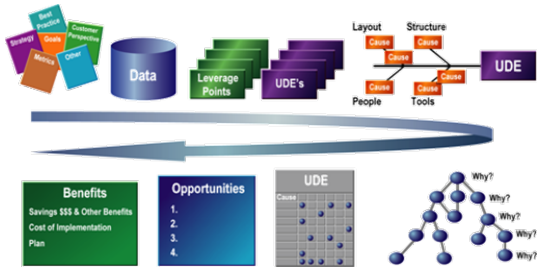
SoS present unique development challenges. These result from several factors, including broad based mission level SoS capability objectives, lack of control by the SoS over the constituent systems, and the dependence of SoS



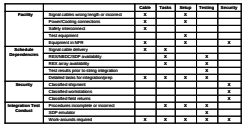
Initiatives
SoS and T&E Workshop (1 of 2)

- Sponsored by NDIA SoS SE and DT Committees
- ~25+ participants from T&E and SoS Communities
- Facilitated by Martin Leek, Raytheon
- Developed insights into 5 issues identified prior to the workshop
- Identified 8 potential areas for action
- Selected 3 for follow up

Data Collection:
SoS White Paper
SE Conference Papers



Improvement Areas:
Strategic Initiatives
Collaborative Go-Do



Potential Problem Areas
1. *Future T&E for Systems brought together as SoS*
2. *Requirements*
3. *Metrics*
4. *Systems Changes*
5. *End to End Testing with systems not yet available*

Potential Causes
If we could only fix one thing, it would be _____

Leverage Matrix
Map Causes to problem areas

T&E in SE Track
10604 – T&E Issues for SoS
Wednesday 8AM
Palm II

NDIA
SoS SE Committee
DT&E Collaboration
August Workshop

August 2010

9/24/2010 1

Initiatives
SoS and T&E Workshop (2 of 2)

Strategic Initiatives

- **Best Practices Model for SoS T&E**
  - Develop and validate T&E model for SoS as a
    - Continuous improvement process
    - Provides information on 'capabilities and limitations' of SoS to end users and feedback to SoS SE on areas for attention
    - Leverages various non-traditional methods for generating 'test type' data
  - Identify use cases and investigate as basis for assessing model
  - Objective is to publish a validated model as an SoS T&E community best practice

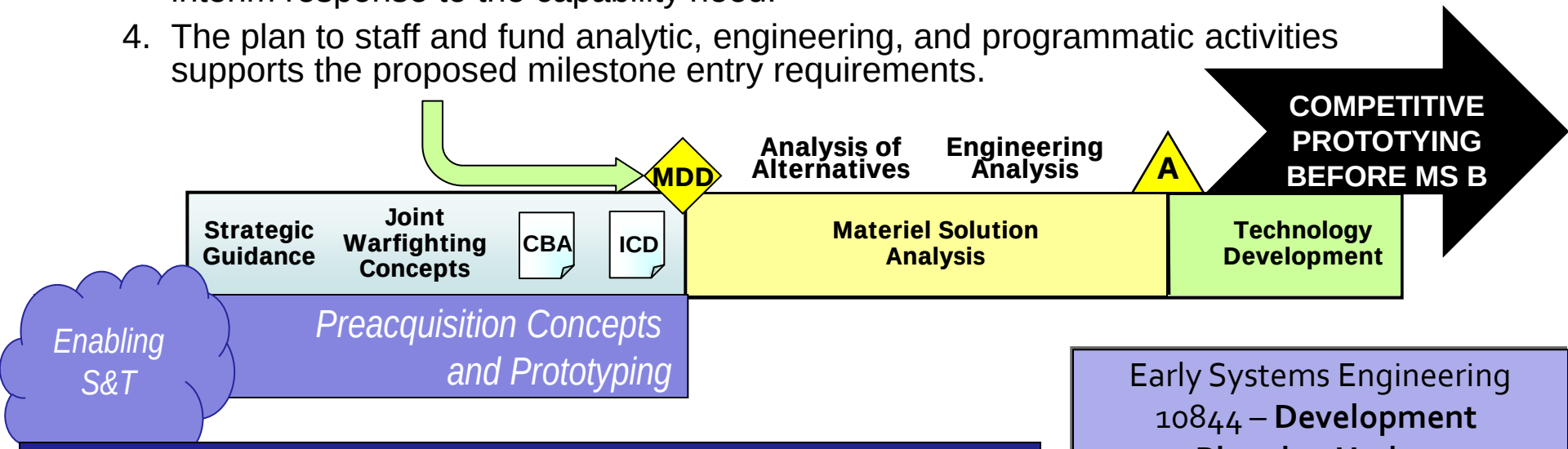
Focus for 2011 NDIA SoS SE

- **Radical Approach to SoS T&E**
  - Investigate the concept of replacing DT, OT, NR-KPPs, etc. with an overall SoS capability test.
- **SoS Governance**
  - Minimum set of characteristics that are required to govern SoS T&E efforts

Initiatives
New Development Planning Policy

Development Planning Policy Memo (DTM 10-017) establishes new MDD Entrance Criteria

1. The candidate materiel solution approaches have the potential to effectively address the capability gap(s), operational attributes and **associated dependencies**.
2. There exists a range of technically feasible solutions generated from across the entire solution space, as demonstrated through early prototypes, models, or data.
3. Consideration has been given to near term opportunities to provide a more rapid interim response to the capability need.
4. The plan to staff and fund analytic, engineering, and programmatic activities supports the proposed milestone entry requirements.



MDD is the lever to provide greater technical and engineering foundation for initiating an acquisition

Early Systems Engineering 10844 – **Development Planning Update**
Wednesday 8AM
Mission 1

Initiatives
SoS in Development Planning

- Development planning activities span the lifecycle, including:

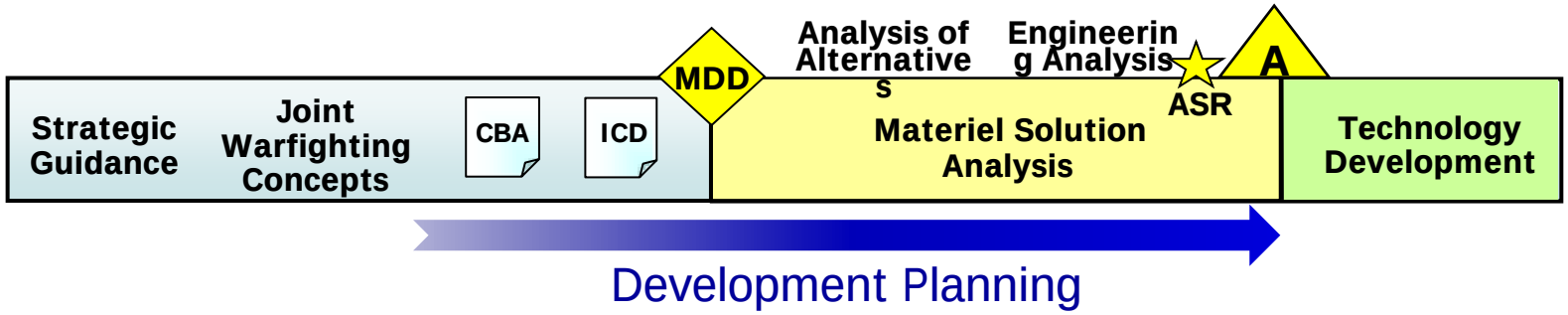
Analysis of future user needs and engineering of new system concepts in a System of Systems (SoS) operational environment

Multiple sufficiently robust, material options to address gap

Defined costs and benefits of the options including technical risk

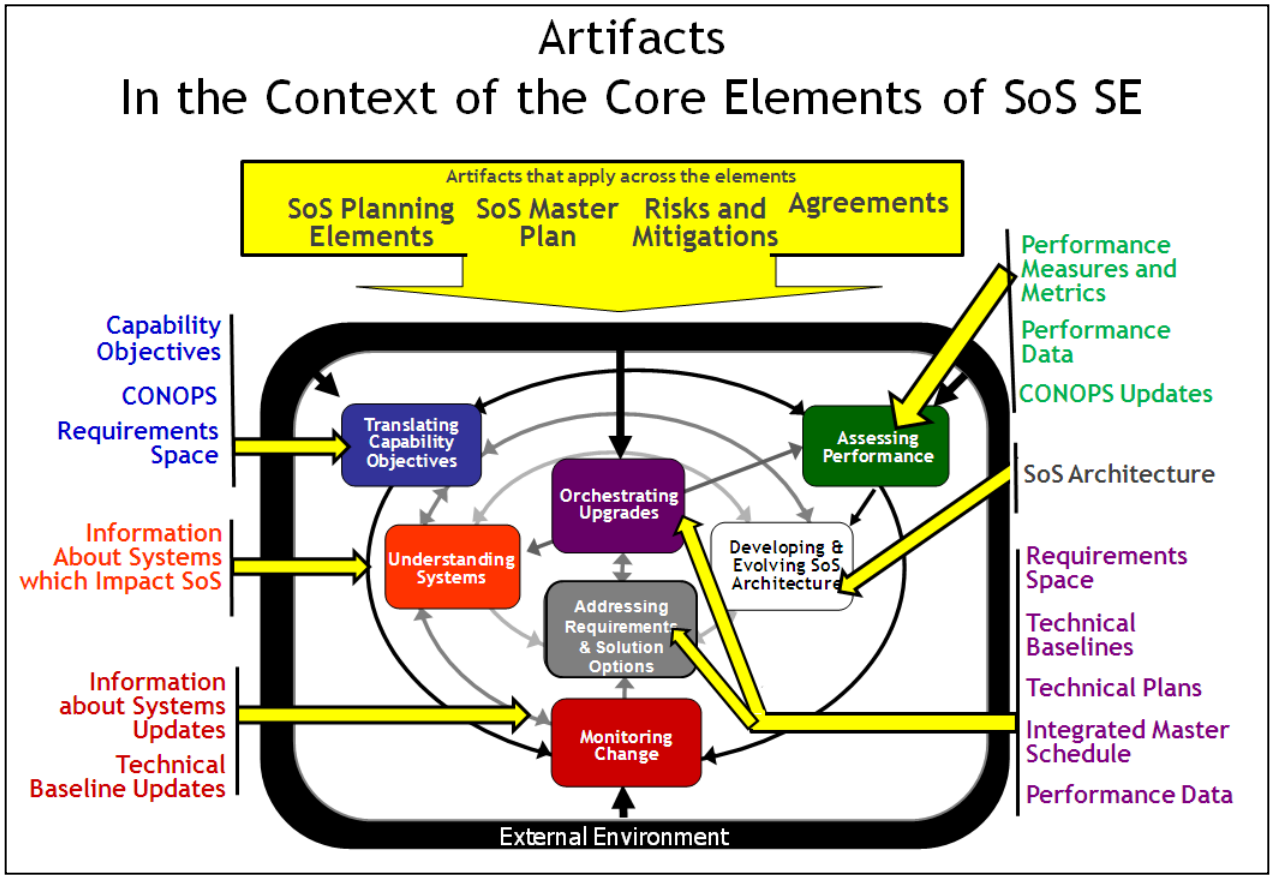
Preferred solution with clear evidence & under-standing of risk

Sufficiently robust, material solution and a risk-based TD Plan



Development Planning is the upfront technical preparation to ensure successful selection and development of a materiel solution

Initiatives
SoS SE Artifacts



System Engineering Artifacts for SoS

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Abstract— This paper describes system of systems (SoS) systems engineering (SE) artifacts, compares and contrasts them with similar sets developed and used for individual systems, and explains how they are used to guide SoS engineering processes. The paper concludes with next steps for using SoS artifacts to continue maturing the understanding of SoS SE in an international cooperative effort with the United Kingdom, Australia, and Canada.

Keywords-component; system of systems, system of systems engineering, engineering artifacts

I. BACKGROUND AND MOTIVATION

The system of systems (SoS) systems engineering (SE) community is evolving SE processes to better apply SE to broadly defined SoS capabilities which span multiple systems. The knowledge from these efforts includes a greater awareness of SoS characteristics which create SE challenges, a recognition that some activities are unique to SoS SE, and ways to better employ fundamental SE processes in an SoS environment. Building on this knowledge, a United States (US) team is identifying key SoS SE artifacts (work products) and applying them to SE of SoS. The focus is on the critical information included in the artifacts rather than the documents. The objective is to develop a common set of concrete approaches to applying SE to SoS by understanding SE artifacts developed and used in SoS SE today.

II. SYSTEMS ENGINEERING FOR SYSTEMS OF SYSTEMS

With the increased emphasis on capabilities and networking, the US Department of Defense (DoD) is recognizing the criticality of effective end to end performance of SoSs to meet user needs. While acquisition processes continue to focus on systems, system requirements are increasingly based on assessment of gaps in user capabilities that require integration across systems. Thus, the role of systems engineering is expanding to the engineering of SoS that provide user capabilities. This dynamic is occurring in other arenas as well and in many beyond defense to include civilian and commercial enterprises.

Applying SE to SoS requires an understanding of the characteristics of SoS and their impact on basic SE processes which have traditionally been applied to the development of new, individual systems. An SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [1]. A primary interest in SoS SE concerns "acknowledged" SoS [2]. This type of SoS leverages existing system capabilities to address new needs while recognizing the programmatic and operational autonomy of the systems. Acknowledged SoS have top level objectives and governance and have SE teams working at the SoS level. These operate in concert with SE teams for the constituent systems. Acknowledged SoS are common in the DoD. Examples include the Single Integrated Air Picture, Ballistic Missile Defense System and Naval Integrated Fire Control Counter Air [3]. This paper is based on interviews with practitioners working in this environment conducted as part of the development of the DoD guide for SE of SoS [3] and the artifacts described here apply to acknowledged SoS. Future work will investigate their applicability other types of SoS.

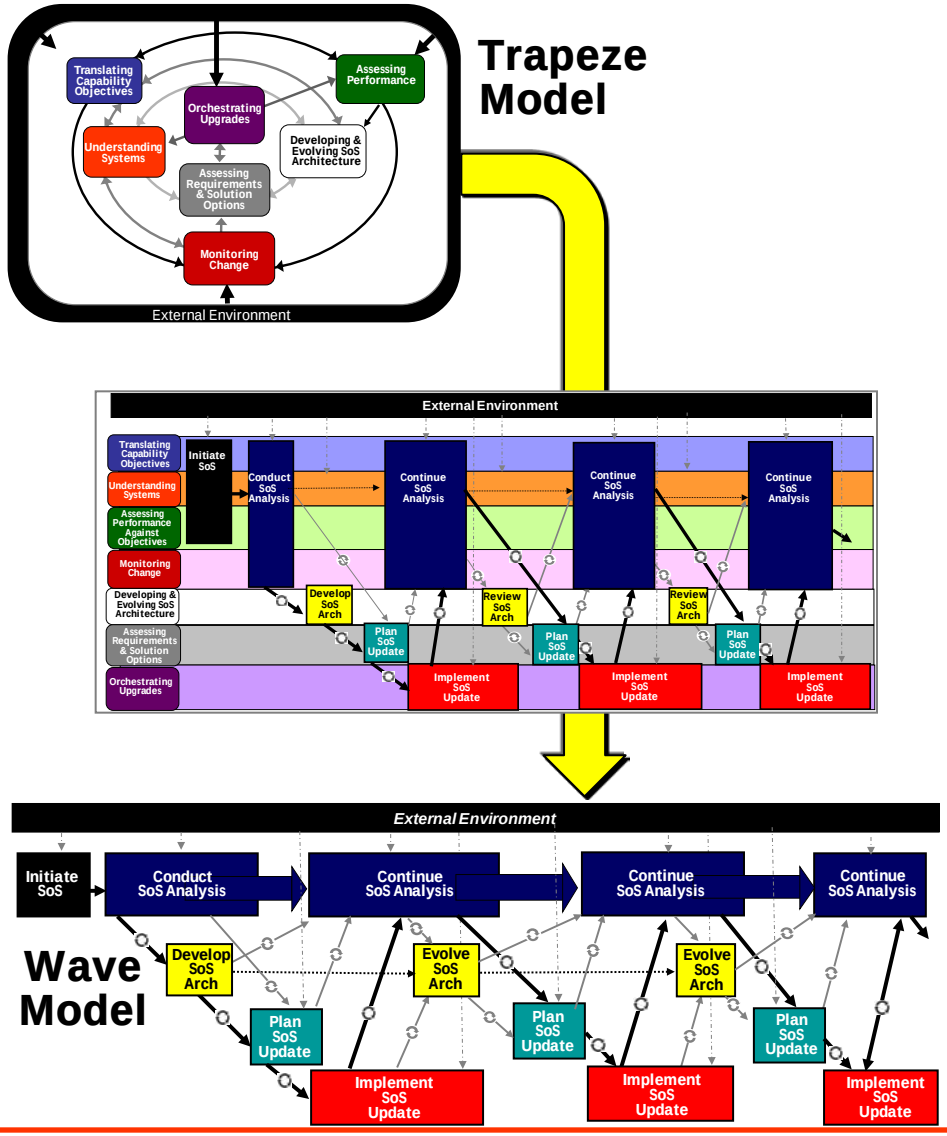
The analysis of SoS SE efforts in DoD today has identified a set of core elements of SE in an SoS environment. SoS systems engineers focus attention on the core elements as they evolve an ensemble of multiple existing and new systems to meet user capability objectives:

"In SoS SE, systems engineers are key players in the core elements of: (1) translating SoS capability objectives into SoS requirements, (2) assessing the extent to which these capability objectives are being addressed, and (3) monitoring and assessing the impact of external changes on the SoS. Central to SoS SE is: (4) understanding the systems that contribute to the SoS and their relationships, (5) developing an architecture for the SoS that acts as a persistent framework for (6) addressing SoS requirements and solution options. Finally, the SoS systems engineer (7) orchestrates enhancements to the SoS, while monitoring and integrating changes made in the systems to improve the performance of the SoS." [3]

Described in 2010 IEEE Systems Conference Paper

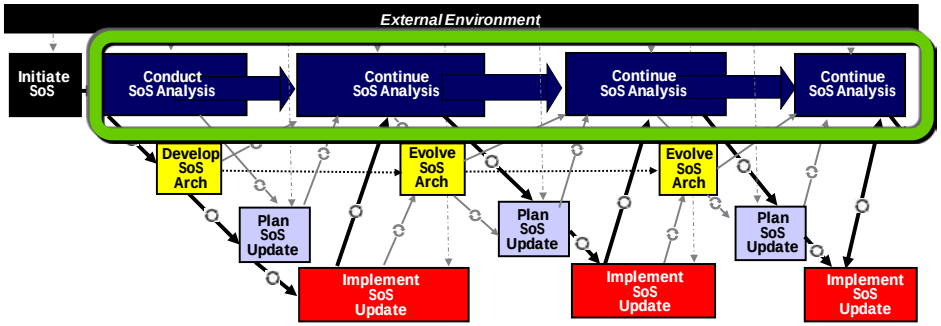
SoS SE Artifacts Developed as Part of an International SoS SE project under The Technical Cooperation Program (TTCP)

Initiatives
Implementers View of SoS SE

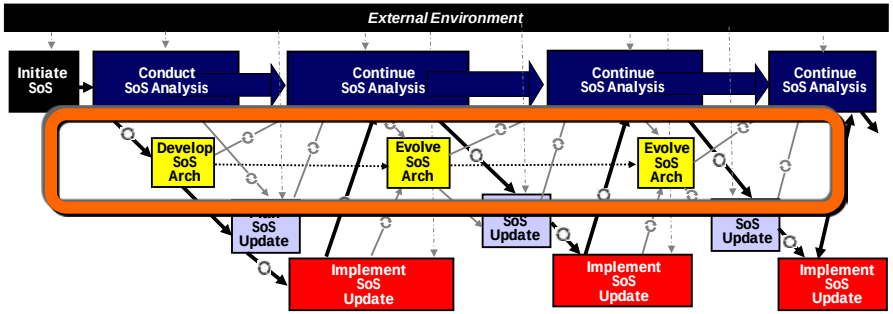


- Trapeze Model
  - Presents the core elements of SoS SE and relationships
  - Provides a good 'conceptual' view of SoS SE
  - Not very useful to practitioner to help chart an implementation approach
- Wave Model
  - 'Unwinds' the trapeze model
  - Provide a view of SoS SE in terms of series of major steps in implementing an SoS SE process
  - More intuitive for an implementer

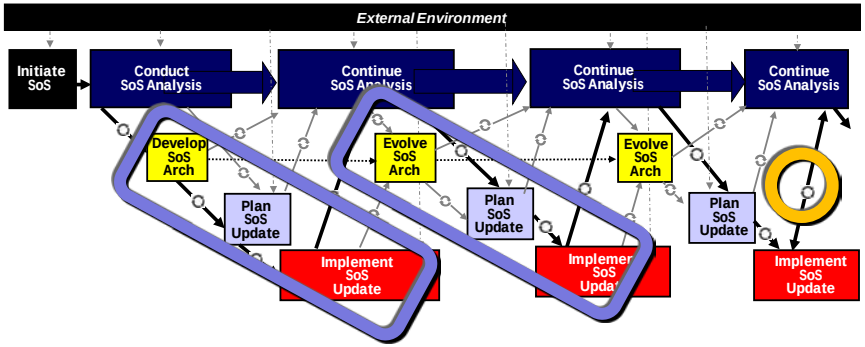
Implementer View – Key Features



Backbone of ongoing analysis



Architecture Evolution



Multiple overlapping iterations of SoS evolution

Forward movement with possible iterations

SoS SE Activities At Each Step

Initiate SoS

Establish the foundation for the SoS SE including an understanding of objectives, key users, user roles and expectations, and core systems supporting capabilities

Conduct SoS Analysis

Establish initial 'SoS Baseline' based on the CONOPs including
- Measures of SoS performance
- Data on current performance
- Understanding how systems currently support SoS
- Risks and mitigations

Develop *initial* plans for the SoS engineering including
- Key planning element (Battle rhythm, organization, decision processes, roles and responsibilities)
- Agreements with critical players (users, constituent systems)
- SoS Master Plan

Continue SoS Analysis

Update 'SoS Baseline' based on
- Changes in objectives, CONOPs or external factors
- Results of the last SoS update
- Data on SoS performance
- Data on unanticipated factors
- Changes in systems
- Risks and mitigations

Update plans including
- Key planning element (Battle rhythm, organization, decision processes, roles and responsibilities)
- Agreements with critical players (users, constituent systems)
- SoS Master Plan

Develop SoS Arch

Develop the persistent technical framework for addressing SoS evolution and a migration plan identifying risks and mitigations

Evolve SoS Arch

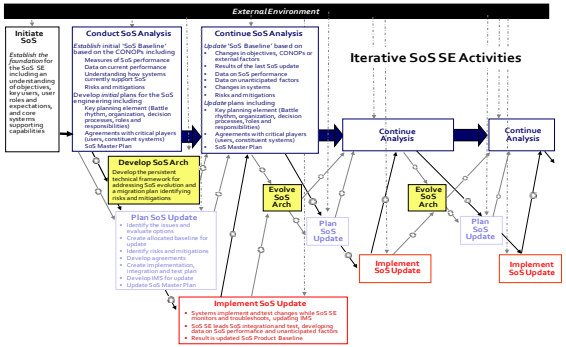
Plan SoS Update

- Identify the issues and evaluate options
- Create allocated baseline for update
- Identify risks and mitigations
- Develop agreements
- Create implementation, integration and test plan
- Develop IMS for update
- Update SoS Master Plan

Plan SoS Update

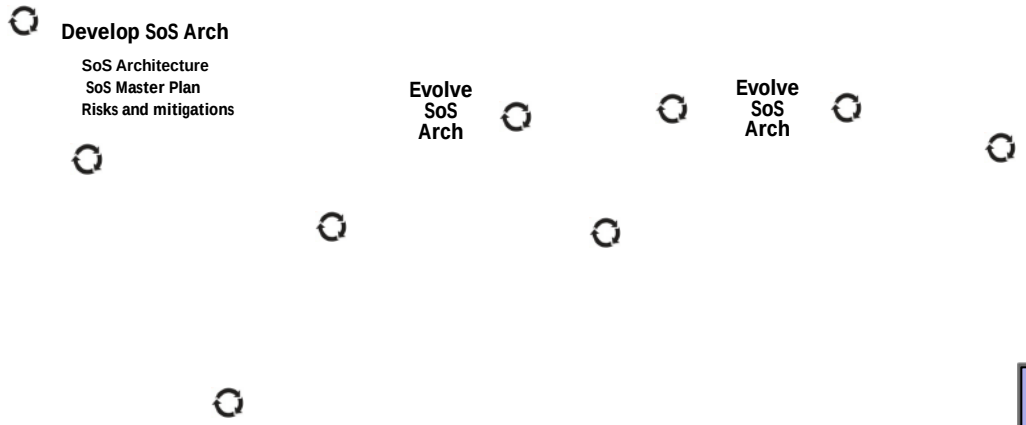
Implement SoS Update

- Systems implement and test changes while SoS SE monitors and troubleshoots, updating IMS
- SoS SE leads SoS integration and test, developing data on SoS performance and unanticipated factors
- Result is updated SoS Product Baseline



- Understanding activities at each step provides a vehicle for implementation level guidance and support

Initiatives
SoS SE Artifacts



- Artifacts can be usefully understood from a implementer perspective in terms of the role they play in each step in the SoS SE process

Systems of Systems
10806 – **Key SoS SE Artifacts To Guide Engineering Activities**
Wednesday 8:35 AM
Palm II

Ongoing Initiative

Key SoS Acquisition Questions (1 of 3)

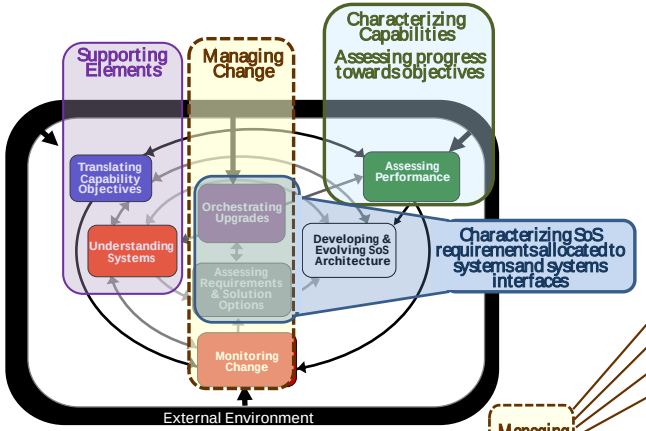
- Work in progress with NDIA SoS SE Committee to address a set of SoS questions posed by DDR&E Director, SE
- Two parallel actions
  - Examine how current guidance addresses questions
  - Set of presentations to committee on SoS analysis approaches
- Review and assessment now underway

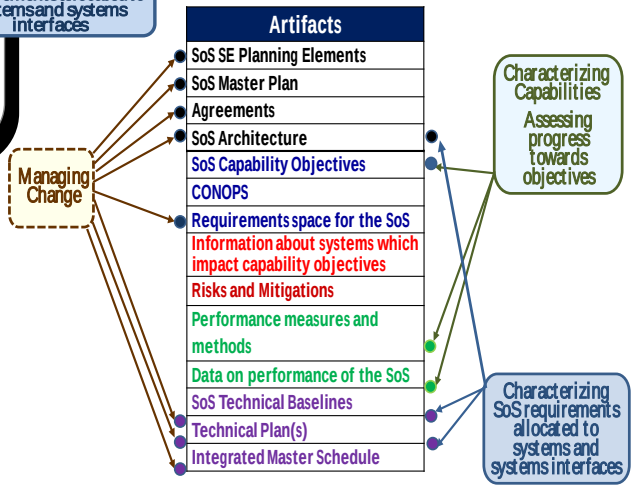
The acquisition community needs the ability to assess risk and review progress on programs where the significant capability is provided by investment in SoS, not by any one of the individual systems

- How do we capture a coherent picture of the capabilities provided by a SoS?
- How do we characterize and capture the sub-allocated requirements, risks and interfaces visible at the individual program level that contribute to SoS level capabilities?
- How do we assess progress and risk associated with building toward these SoS capabilities?
- How do we manage change in a SoS environment, etc.?

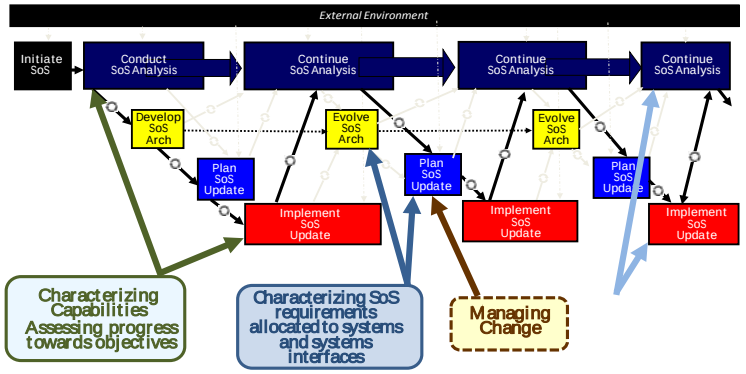
Ongoing Initiative
Key SoS Acquisition Questions (2 of 3)

- Mapped questions to current SoS SE guidance and research results
  - SoS SE Core Elements
  - SoS SE Artifacts
  - Wave Model



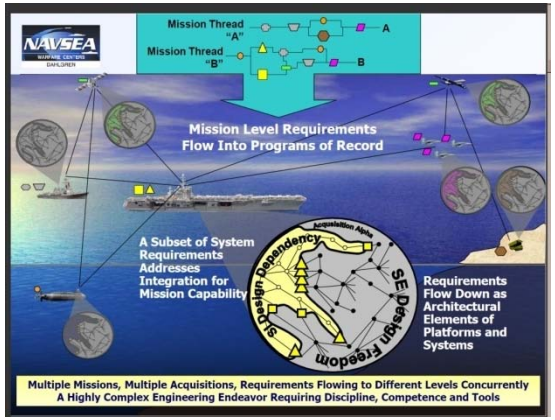


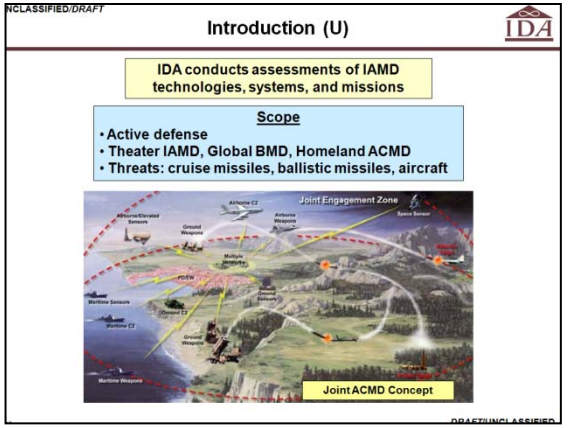
Original Welby Question	Elements of Questions	Direct Core SoS SE Elements	SoS SE Artifacts	Steps in the SoS SE Wave Model
How do we capture a coherent picture of the capabilities provided by a SoS?	**Characterizing Capabilities**	• Assessing Performance vs. Objectives	• Capability Objectives • Performance Metrics • Performance Data	• SoS Analysis • Implementing Upgrades
How do we assess progress and risk associated with building toward these SoS capabilities?	**Assess progress towards objectives**	• Assessing performance	• Capability Objectives • Technical Baselines • Master Plan	• SoS Analysis
How do we characterize and capture the sub-allocated requirements, risks and interfaces visible at the individual program level that contribute to SoS level capabilities?	**Characterizing** • **SoS rqts allocated to systems** • **Interfaces among systems**	• Developing and evolving arch • Addressing rqts and solution options • Orchestrating upgrades	•Architecture •Technical Baselines •Technical Plans	• Developing and Planning SoS Architecture • Planning Updates
How do we manage change in a SoS environment, etc.?	**Planned change**	• Addressing requirements and solution options • Orchestrating upgrades	•SoS SE Planning Elements •Agreements •Architectures •Requirements space •Information about systems which impacts the SoS •Master Plan •Technical Baselines •Technical Plans •Master integrated schedule •Risks and Mitigations	• Planning SoS Updates • Implementing Upgrades
	Uncontrolled change	• Monitoring and addressing change	• Risks and Mitigations	• SoS Analysis • Implementing Upgrades

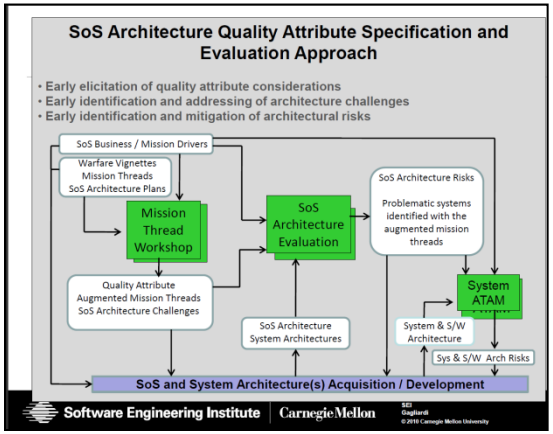


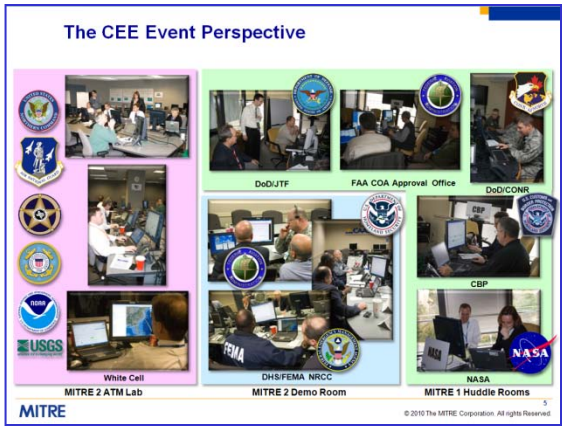
Ongoing Initiative
Key SoS Acquisition Questions (3 of 3)

- **NDIA Architecture Task Force Report**
  Joe Kuncel
- **Engineering Systems of Systems: An Integration Perspective**
  Emmet Maddry (NSWC Dahlgren)
- **SoS Quality Attribute Specification and Architecture Evaluation**
  Michael Galiardi (SEI)
- **Integrated Air and Missile Defense (IAMD) Studies**
  Dr. Joseph T. Buontempo (IDA)
- **Enabling Engineering of Complex Systems Through Simulation-Based Experimentation**
  Zach Furness (MITRE)









Next Steps

- Continuing to work with the broader community through NDIA and TTCP to address growing interest and understanding of SoS and SE
- Continued technical work
  - To support DoD acquisition initiatives which call for a SoS perspective
    - SoS Acquisition Programs
    - Development Planning
  - To apply current understanding and learn from experiences with Component initiatives
  - To build guidance which supports the SoS SE practitioner
    - Wave model
    - Artifacts
    - Relationship to DoD acquisition
  - To address Director, SE questions