Systems Engineering for Systems of Systems

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SoS SE Challenge

- US DoD builds and fields large systems employed to support Joint and Coalition operations
  - Conceived and developed independent by Military Services
  - Acquisition (and SE) on a system by system basis
- Focus of DoD investment shifting to broad user capabilities implemented in a networked environment
  - Mix of material and non-material assets which must work together to meet capability objectives
  - Individual systems are no longer considered as individual bounded entities and are evolved based on extant capabilities
  - Components in larger, more variable, ensembles of interdependent systems which interact based on end-to-end business processes and networked information exchange
- Increasingly SoS of various types proliferate despite continued focus on individual systems

What are the implications for SE?

DoD System of Systems SE Guide

SoS Guide Version .9

- Effort led by the Office of the Secretary of Defense
- Collaborative Approach with DoD, Industry, Academia
- Purpose
  - 6 month effort addressing areas of agreement across the community
  - Focus on technical aspects of SE applicable across SoS management constructs
  - Vehicle to ***capture*** and ***debate*** current SoS experience
- Audience
  - SoS and Program Managers and Lead/Chief Engineers

Version 1.0

- Develop 'Boots on the Ground' basis for Version 1.0
  - Structured reviews with practitioners
  - Refine early draft guide content, identify areas for future study
- Update findings and release Version 1.0
  - Draft released for comment December 2007
  - ~600 comments received in February 2008 (Industry, FFRDCs, Gov't)
  - Revision reviewed by Senior SE leadership in July 2008
  - Final release in August 2008

What does SoS Look Like in the DoD Today?

- Typically an overlay to ensemble of individual systems brought together to satisfy user capability needs
- Are not new acquisitions per se
  - Cases like FCS are extremely rare and, in practice, still must integrate with legacy systems
- SoS 'manager' does not control the requirements or funding for the individual systems
  - May be in a role of influencing rather than directing, impacts SE approach
- Focus of SoS is on evolution of capability over time
- A functioning SoS takes start-up time but, in steady state, seems well-suited to routine incremental updates

Most military systems are part of an SoS operationally
Only by exception do we manage and engineer at SoS level

Definitions

SoS: *A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities* [DoD, 2004(1)].

Accepted Taxonomy of SoS [Maier, M. 1998]

- Directed
  - SoS objectives, management, funding and authority; systems are subordinated to SoS
- Collaborative
  - No objectives, management, authority, responsibility, or funding at the SoS level; Systems voluntarily work together to address shared or common interest
- Virtual
  - Like collaborative, but systems don't know about each other

US DoD Pilots identify a new SoS type:

- Acknowledged
  - SoS objectives, management, funding and authority; however systems retain their own management, funding and authority in parallel with the SoS

SoS SE Guidebook focuses on 'Acknowledged' SoS

Characteristics of Acknowledged SoS

- Top-down direction for an SoS capability concurrent with independent direction and autonomy in system operation and development
  - Multiple levels of objectives
  - Multiple management authorities with independent priorities, funding and development plans
  - Multiple technical authorities
- Much of SoS functionality is in extant capabilities of the systems
- SoS manager and SE do not have control over all the parts of the SoS
  - In fact, they may not be aware of all the systems which may impact their objectives and both the systems and the objectives may change over time.

Management of Acknowledged SoS

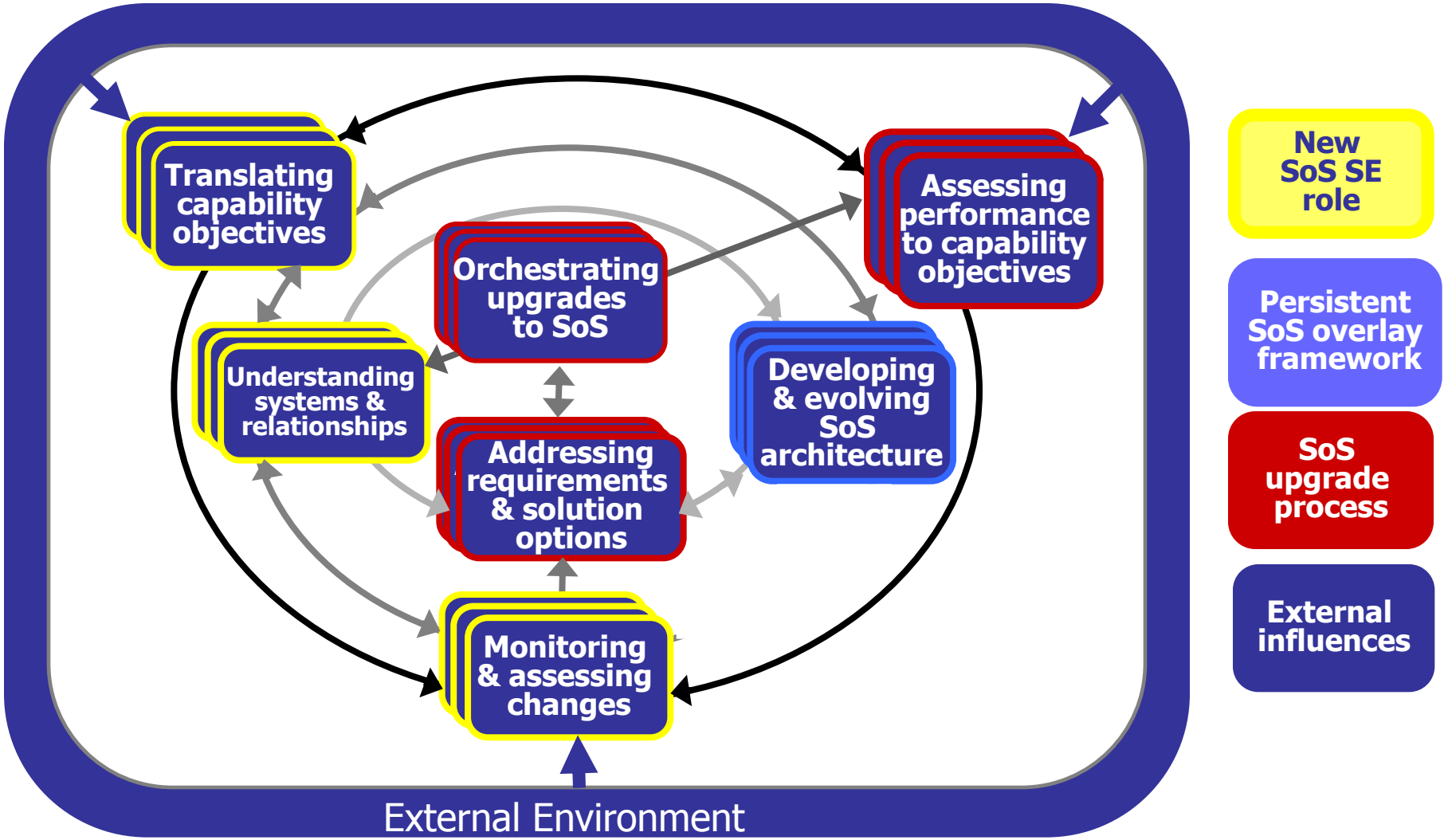
- Independent, concurrent management and funding authority pose management issues
- In defense, a solid governance & management approach is seen as key for SoS
  - Independent authorities are unlikely to accept direction from a systems engineer they do not control
  - Argue to make 'acknowledged' into 'directed' made difficult by 'multi-mission' systems which are important to multiple SoS
- Beyond defense 'acknowledged' SoS exist and evolve without top down management
  - Systems or services are designed to be broadly useful and have as their business objective to support numerous user applications
  - They naturally retain authority over decisions regarding their development and are not likely to agree to limit themselves to one specific customer

Management issues have technical implications for SE

A Comparison

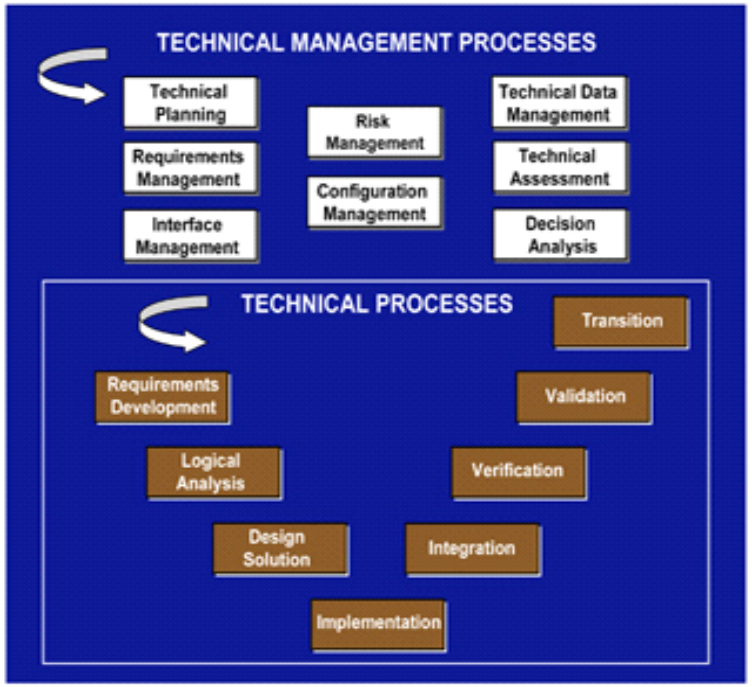
	System	System of Systems
Management & Oversight		
Stakeholder Involvement	Clearer set of stakeholders	Two levels of stakeholders with mixed possibly competing interests
Governance	Aligned PM and funding	Added levels of complexity due to management and funding for both SoS and systems; No SoS does over all systems
Operational Environment		
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet operational objectives using systems whose objectives may or may not align with the SoS system's objectives
Implementation		
Acquisition	Aligned to established acquisition processes	Cross multiple system lifecycles across acquisition programs, involving legacy systems, developmental systems, and technology insertion; Capability objectives but may not have formal requirements
Test & Evaluation	Test and evaluation the system is possible	Testing more challenging due systems' asynchronous life cycles and given the complexity of all the moving parts
Engineering & Design Considerations		
Boundaries & Interfaces	Focuses on boundaries and interfaces	Focus on identifying systems contributing to SoS objectives and enabling the flow of data, control and functionality across the SoS while balancing needs of the systems
Performance & Behavior	Performance of the system to meet performance objectives	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the systems

SE Model for SoS Based on 7 Core Elements of SoS SE



SE Processes Support Core Elements

- DoD Defense Acquisition Guide presents 16 basic SE processes
- In an SoS, SE team adapts these processes to execute core SE elements
- Focus for SoS SE is on technical management since implementation is in systems



SoS SE Core Elements	Technical Processes								Technical Management Processes							
	Rqts Devel	Logical Analysis	Design Solution	Implement	Integrate	Verify	Validate	Transition	Decision Analysis	Tech Planning	Tech Assess	Rqts Mgt	Risk Mgt	Config Mgt	Data Mgt	Interface Mgt
Translating capability objectives	X											X		X	X	
Understanding systems & relationships		X							X				X		X	X
Assessing performance To capability objectives		X					X		X		X		X		X	
Developing & evolving SoS architecture	X	X	X						X	X		X	X	X	X	X
Monitoring & assessing changes									X				X		X	X
Addressing requirements and solution options	X		X						X	X		X	X	X	X	X
Orchestrating upgrades to SoS				X	X	X	X	X	X	X	X	X	X	X	X	X

Core Elements of SoS SE (1 of 3)

- Translating SoS capability objectives into high level requirements over time
  - SoS objectives based on broad capability objectives
  - SE team plays strong role in establishing requirements and understanding dynamics of the environment

- Identifying and understanding the systems that impact SoS objectives
  - Focus on components and dynamics vs boundaries
  - Extends beyond technical to broader context of management, organizational, development plans, funding, etc.

- Anticipating and assessing impacts of potential changes on SoS performance
  - Given scope of SoS authority, key to SoS SE is identifying and addressing changes in systems and other areas (e.g. threat) which may impact the SoS

Core Elements of SoS SE (2 of 3)

- Developing and evolving SoS architecture
  - This includes
    - Concept of operations
    - Systems, functions and relationships and dependencies, both internal and external
    - End-to-end functionality, data flow and communications within the SoS.
  - Provides the technical framework for assessing options and implications for meeting requirements over time
    - Persistence, tolerance for change

- An **architecture** is the structure of components, their relationships, and the principles and guidelines governing their design evolution over time (IEEE Std 610.12 and DoDAF).
- The architecture of an SoS is a persistent technical framework for governing the evolution of an SoS over time.

Core Elements of SoS SE (3 of 3)

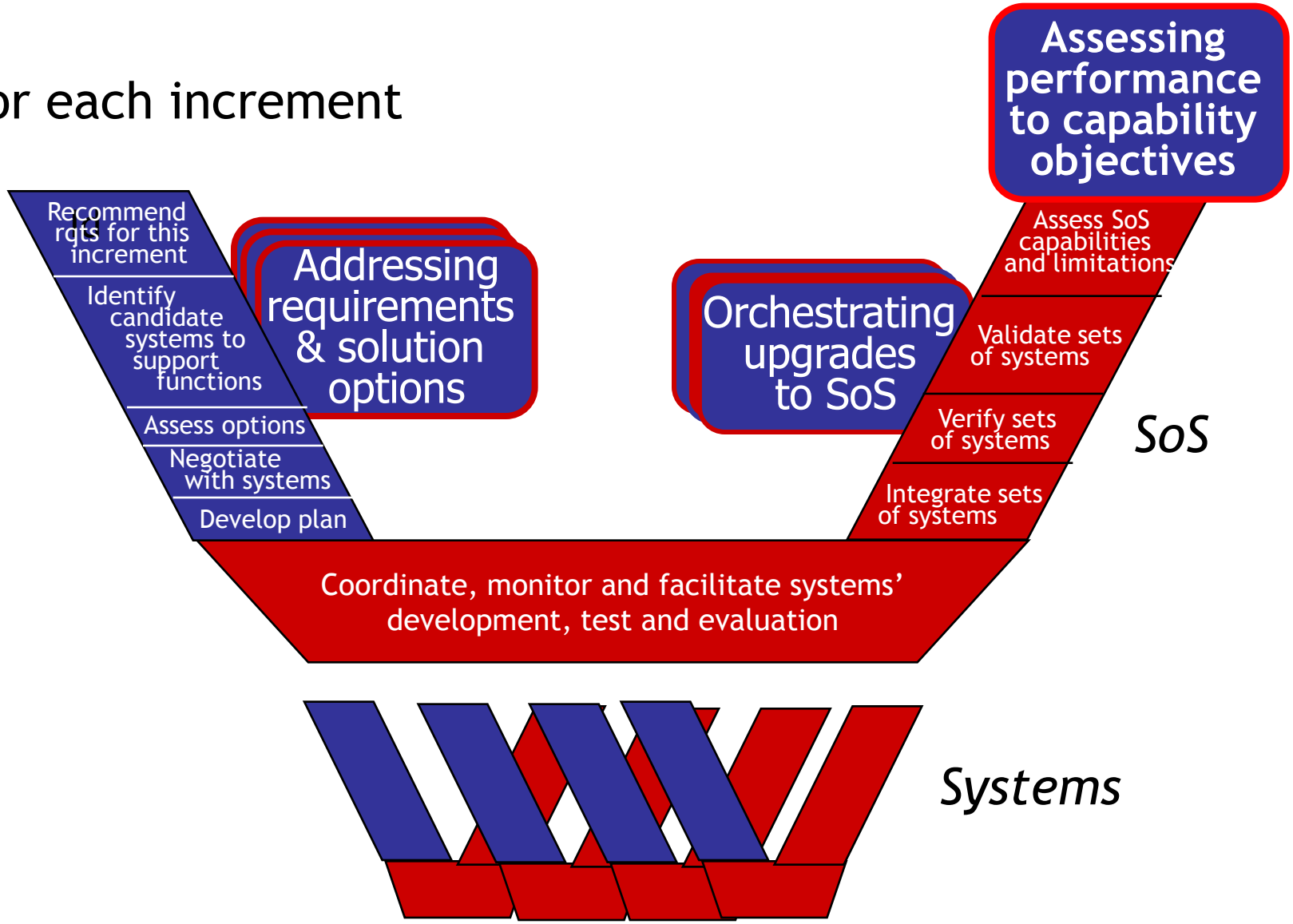
- SoS requirements and solution options
  - Requirements addressed at both SoS & systems
  - Recommend SoS requirements based on both priority and practicality
  - SoS and system SE teams identify and assess options
  - Result is plan for development for next increment

- Orchestrating SoS Upgrades
  - Upgrades implemented by systems under system SE teams
  - SoS SE team plans, facilitates, integrates and tests upgrades to the SoS
  - Development based on incremental approaches (bus stop, wave) which accommodate asynchronous system developments

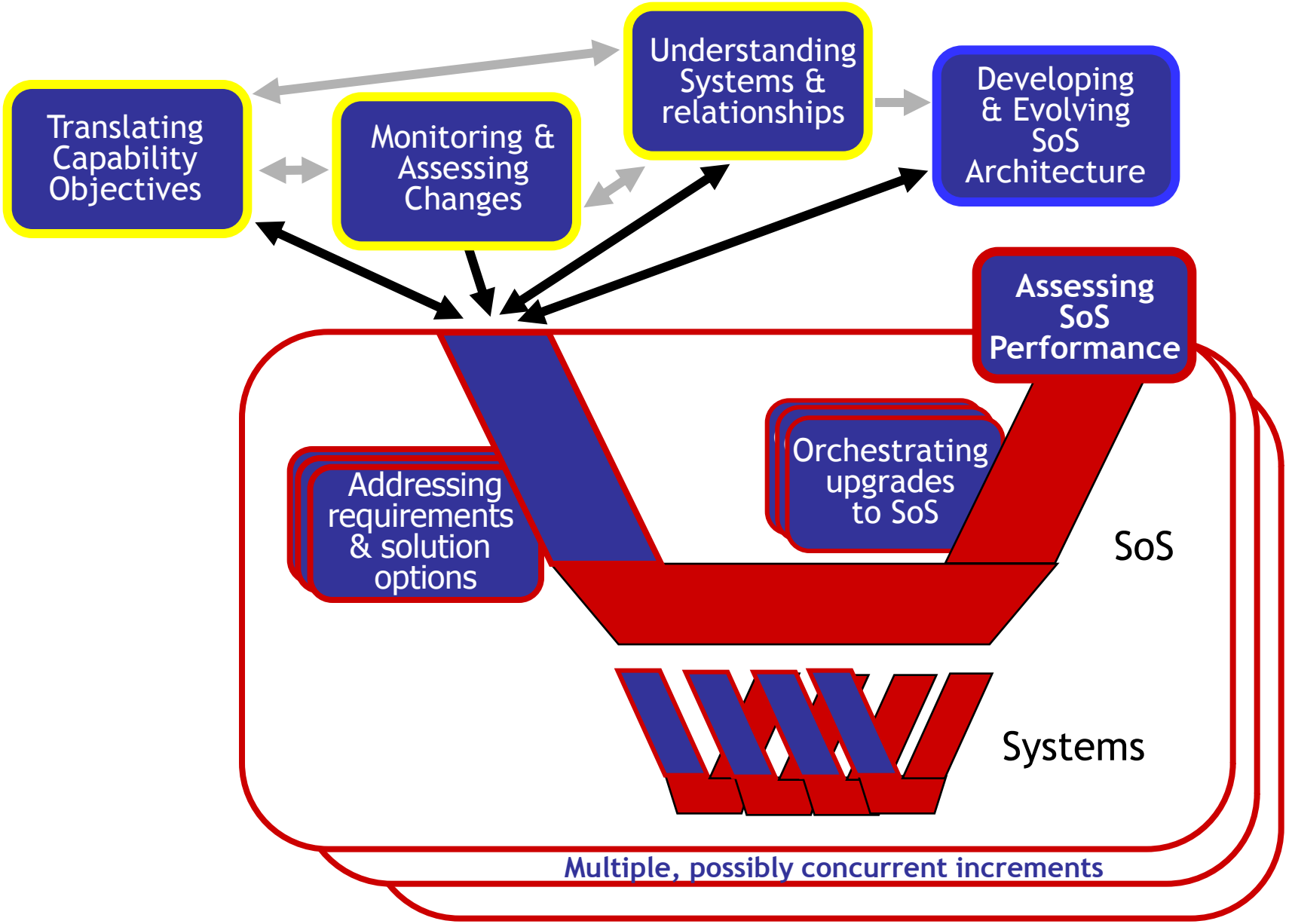
- Assessing SoS Performance
  - Based on measures of SoS user results applied in different settings (test, exercises, M&S, operations)
  - Opportunity to identify changes and emergent behavior

View of SoS Upgrade (1 of 2)

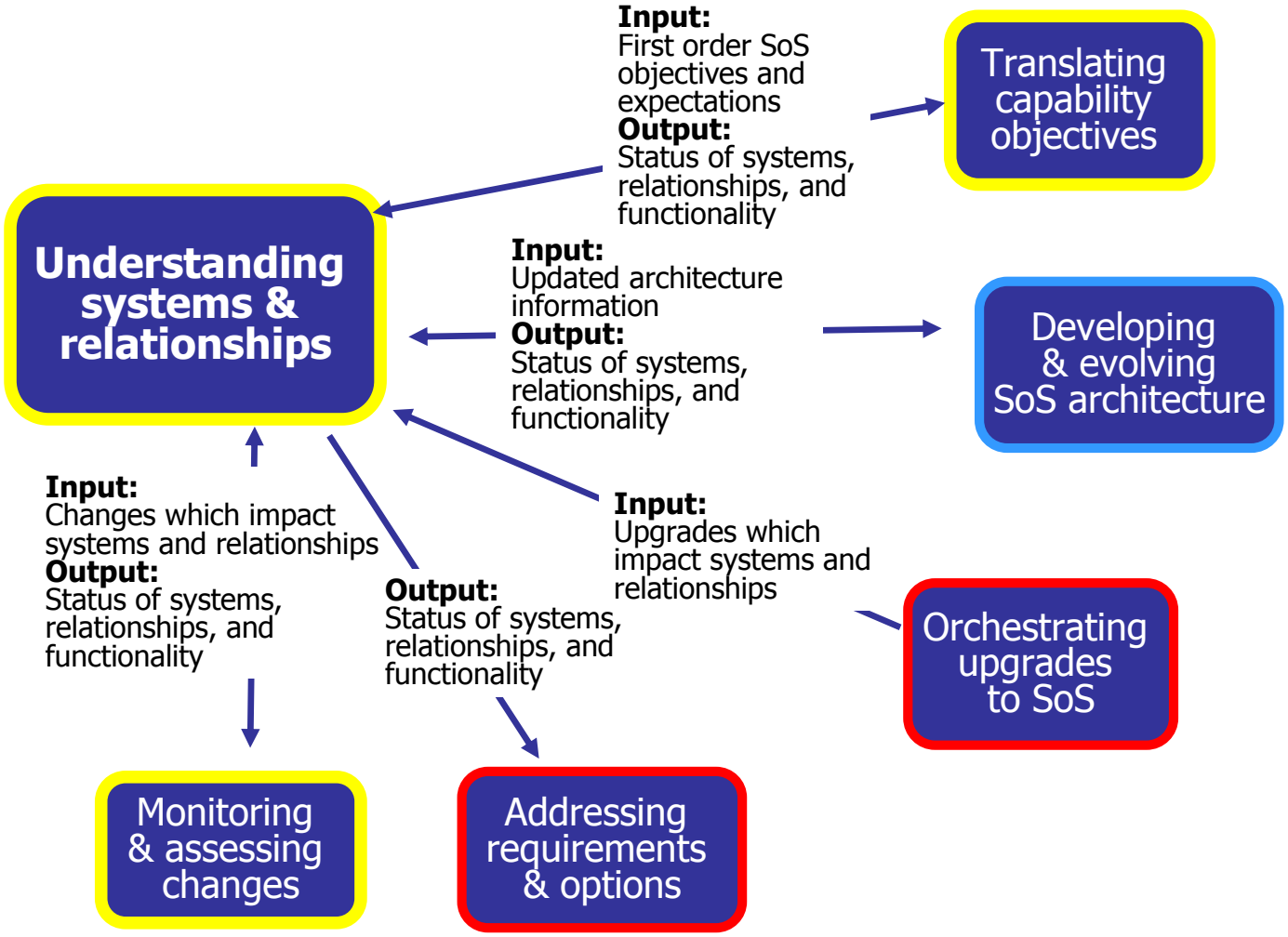
For each increment



View of SoS Upgrade (2 of 2)



Guide Extract
Relationships Among the Core Elements



Guide Extract: SE Processes Supporting Each SoS SE Element

Technical or Technical Management Process	Relationship to SoS SE Core Element
Logical Analysis is the process of obtaining sets of logical solutions to improve understanding of the defined requirements and the relationships among the requirements (e.g., functional, behavioral, temporal).	Logical Analysis is a key part of **Understanding Systems and Relationships**. Basic to engineering an SoS is understanding how systems support SoS functionality. In developing a new system, the systems engineer allocates functionality to system components based on a set of technical considerations. In an SoS, the systems engineer develops an understanding of the functionality extant in the systems and how that functionality supports SoS objectives, as a starting point for SoS architecture and evolution. …
Risk Management … helps ensure program cost, schedule, and performance objectives are achieved at every stage in the life cycle and to communicate to all stakeholders the process for uncovering, determining the scope of, and managing program uncertainties.	Risk management is a core function of SE at all levels. In **Understanding Systems and Relationships**, the systems engineer assesses the current distribution of functionality across the systems and identifies risks associated with either retaining the status quo or identifying areas where changes may need to be considered. The systems engineer also considers approaches to monitor, mitigate, or address risks. Such risks might include …
Configuration Management is the application of sound business practices to establish and maintain consistency of a product's attributes with its requirements and product configuration information.	**Understanding Systems and Relationships** is where the CM process for the "as is" SoS resides and is maintained as the SoS product baseline. In a system the CM process addresses all of the 'product's' features where the system itself is the product. In an SoS, the ensemble of systems and their functionality is the product; the SoS CM depends on the CM of the systems to maintain much of the product information, since the system owner, PM, and system systems engineer normally retain responsibility for their systems. The SoS CM focuses on the linkage to the system CM and crosscutting attributes which pertain to the SoS not addressed by the CM of the systems….

What is Working? SoS SE Principles

- Address organizational as well as technical perspectives
  - Factor in broader set of consideration into trade space and technical planning
- Focus on areas critical to the SoS
  - Leave the rest to the systems engineers of the systems
- Technical management approach reflects need for transparency and trust with focused active participation
- SoS designs are best when open and loosely coupled
  - Impinge on the existing systems as little as possible
  - Are extensible, flexible, and persistent overtime
- Continuous ('up front') analysis which anticipates change
  - Design strategy and trades performed upfront and throughout
  - Based on robust understanding of internal and external sources of change

Way Ahead

- Guide is out and in use, offers a first step
  - Highlights the issues of SoS in DoD today
  - Provides some support for SE teams operating in SoS today
  - Plan for outreach and educational materials
  - Assess added guidance for areas such as Systems Engineering Plans
- Efforts are underway to support update to the guide
  - A follow-up data collection to get an understanding of ‘how to’ level of information from ongoing SoS SE efforts
  - Cooperative effort with NDIA M&S Committee to examine promise and experience with M&S to support SoS SE
  - Series of industry exchanges on SoS topics of common interest
  - International cooperative efforts are being initiated
  - Expansion into broader areas
    - SE for Capability Portfolio Management
    - Net Centric Enterprise Systems/Services

Backup

Active SoS SE Practitioners

Name	Acronym	Owner	Approach
Army Battle Command System	**ABCS**	Army	Acquisition Program
Air Operations Center	**AOC**	Air Force	Acquisition Program
Ballistic Missile Defense System	**BMDS**	Joint	Acquisition Program
USCG Command & Control Convergence	**C2 Convergence**	Coast Guard	Strategy
Common Aviation Command & Control System	**CAC2S**	Marine Corps	Acquisition Program
Distributed Common Ground Station	**DCGS-AF**	Air Force	Program Office
DoD Intelligence Information System	**DoDIIS**	Intel	DIA CIO Initiative
Future Combat Systems	**FCS**	Army	Program Office
Ground Combat Systems	**GCS**	Army	Program Executive Office PEO
Military Satellite Communications	**MILSATCOM**	Joint	AF Wing
Naval Integrated Fire Control – Counter Air	**NIFC-CA**	Navy	SE Integrator in PEO
National Security Agency	**NSA**	Intel	Agency
Naval Surface Warfare Center Dahlgren	**NSWC**	Navy	Warfare Center
Single Integrated Air Picture	**SIAP**	Joint	Acquisition Program
Space and Missile Systems Center	**SMC**	Air Force	SE Authority
Space Radar	**SR**	Joint	Acquisition Program
Theater Joint Tactical Networks	**TJTN**	Joint	PEO
Theater Medical Information Systems – Joint	**TMIP**	Joint	Acquisition Program

Provided a basis for understanding SoS in DoD Today