Systems Geometry: A Dimensional Approach to T&E Systems of Systems Understanding

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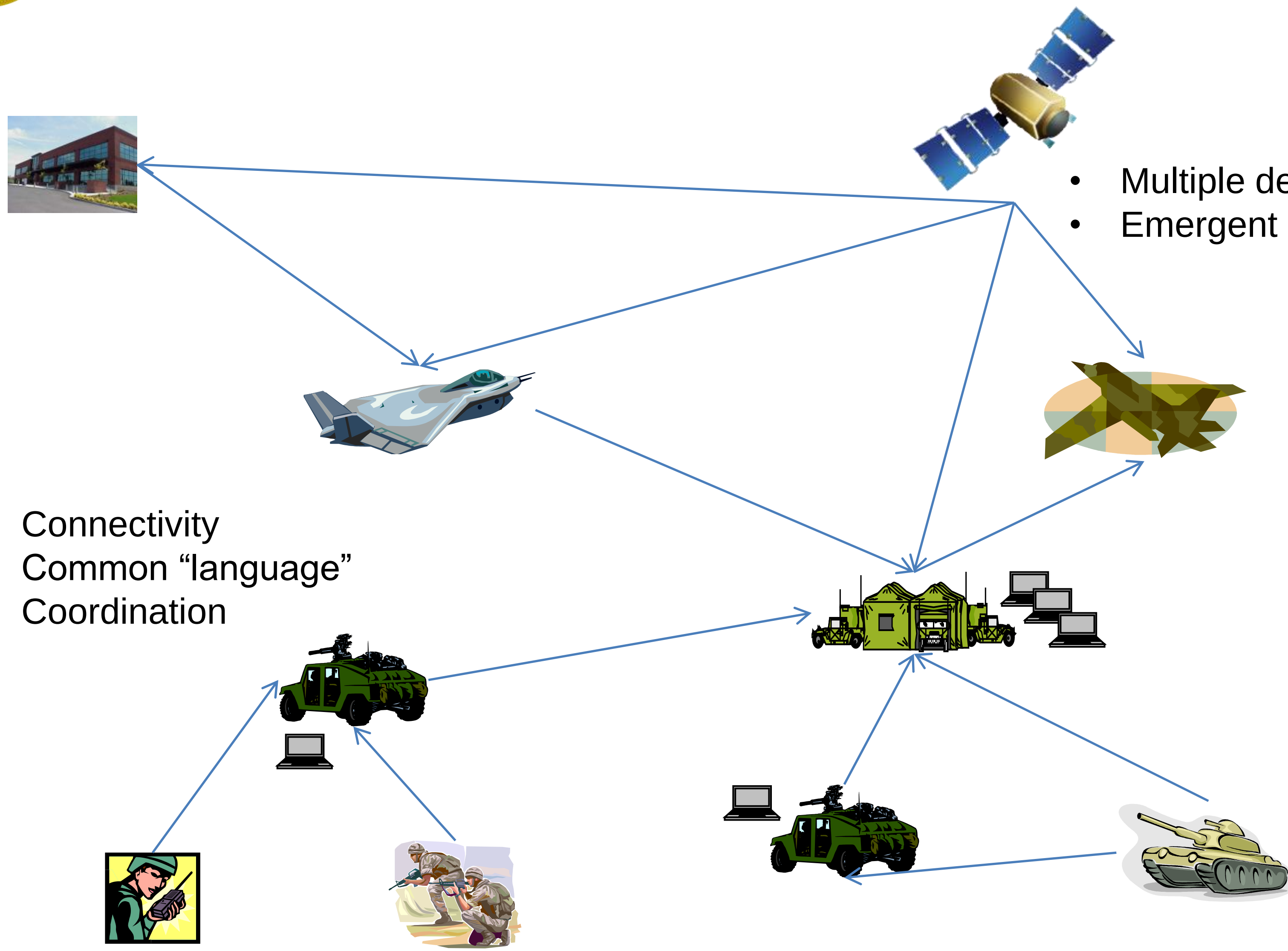
Presentation Overview

- Introduction, Problem and Background
- Systems of Systems
- Test and Evaluation SoS Characteristics
- Systems Geometry
- CAGE II Case Study
- Future Research

Systems of Systems

- What are Systems of 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." (DAG 2004)*
- Five Characteristics (Sage & Cuppan, 2001)
  - Operational Independence of Constituents
  - Managerial Independence of Constituents
  - Geographic Distribution
  - Emergent Behavior
  - Evolutionary Development

The Challenge of Systems of Systems



- Multiple developers
- Emergent behaviors

- Connectivity
- Common “language”
- Coordination

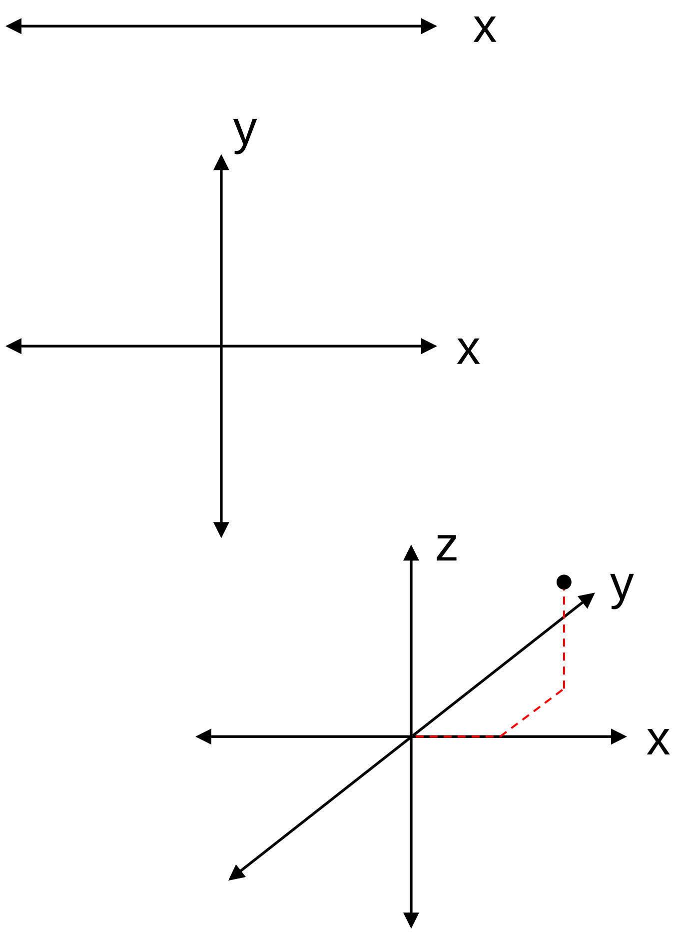
Characteristics of Distributed SoS in T&E (1 of 2)

Characteristic	Explanation	Examples
Geographic location	This is the location of the component system of interest. This could also account for multiple "sites" at a particular location.	Military post, laboratory, city, country
Participants / Stakeholders	There are many "sub" dimensions of stakeholders within an event. It could represent a particular service, command, or division. It could also represent a particular lab, program, or company. It includes funding sources, sponsors, users, developers, etc.	Army, Navy, Air Force, Marines, Canadian Forces, UK Forces, TRADOC, ARL, Contractors, Universities, etc.
Purpose / Mission	Each event or capability has a specific mission or purpose. There is some overlap between capabilities – but not in the resources. There is also overlap in the resources used but not the proposed mission (reuse). This represents the motivation for the desired emergent SoS behaviors.	Training, developmental testing, operational testing, research, network evaluation, etc.
Constituent Systems	Systems can consist of many types. Operational equipment represents constituent systems that are typically used in the field by a warfighter in a real warfare situation. Modeling and simulation is used to explore concepts, augment a SoS environment containing operational equipment, or develop courses of action. A variety of tools are used for operating and monitoring the SoS environment, collection of data for analysis, assessment of the event activities, and so on.	Live, virtual and constructive simulations, command and control equipment, network monitoring tools, test tools, statistical tools, data loggers, etc.
Capabilities – Functional	Functional capabilities highlight the role that an event participant plays in the overall SoS event. These may be tied at a very high level to operational activities but only in overall role. These functional capabilities are more at the event level.	Technical operation and control, blue ground maneuver, engineering support, communication effects, etc.

Characteristics of Distributed SoS in T&E (2 of 2)

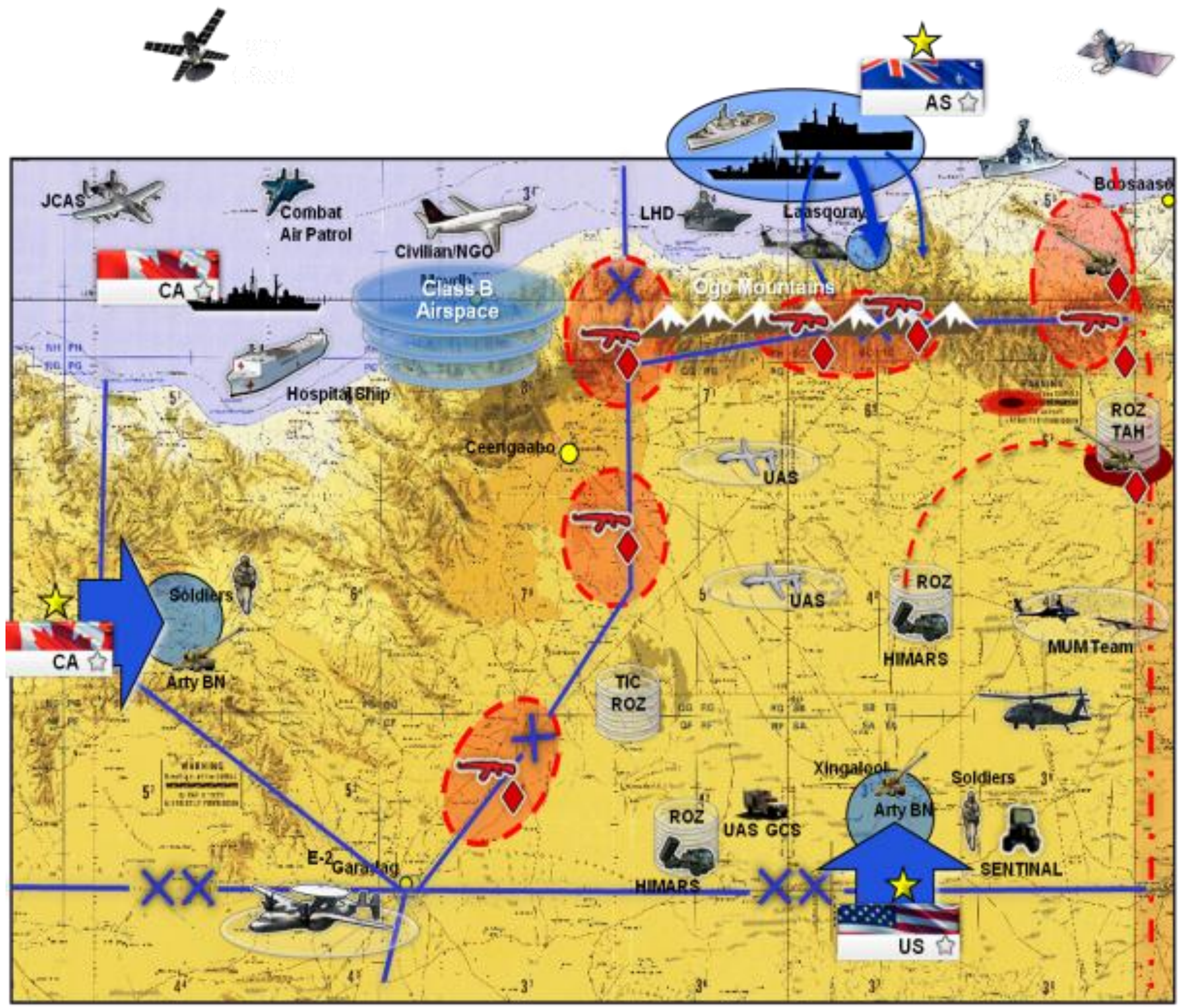
Characteristic	Explanation	Examples
Capabilities – Operational	Operational capabilities directly address the military or operational scenario represented in the event while designating which components of the scenario are represented by which systems.	Air defense, logistics support, blue ground forces, etc.
Network Connectivity	There are several types of networks supporting SoS events – these include: • Physical networks – the actual networking infrastructure (hardware, routers, etc.) used to link the component systems • Operational communications – this represents the operational network that is used for scenario connectivity. • Support / Coordination communications – this network allows the functional teams to coordinate efforts for the system.	Physical: SIPR/NIPRnet, SDREN/DREN, etc. Operational: various tactical networks Support: chat, text, VOIP
Interoperability (layers)	This addresses the ability of the constituent systems to interact in a valid and meaningful way during an event. There are levels of interoperability from simple exchange of raw data to common interpretation of received information. This consists of a number of interoperability architectures and integrating capability (such as gateways) that address interoperability at the various layers.	DIS, HLA, TENA, CTIA, IP, etc.

System Dimensions



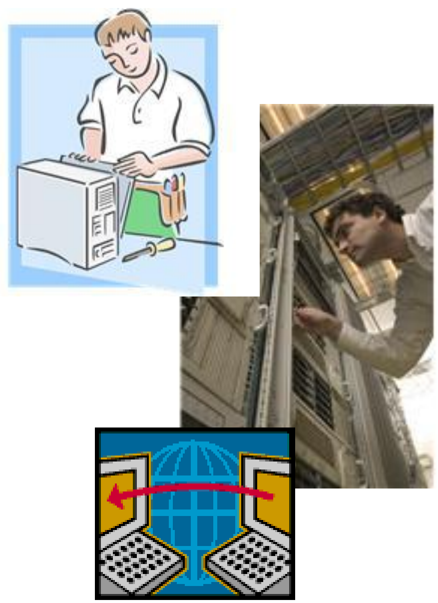
- Geometrically, we understand 1, 2 or 3 dimensions – maybe 4 or more
- Systems, particularly SoS have many dimensions that define them
- SG defines 3: Operational, Functional, and Technical

Operational Dimension



Functional Dimension

Analysts / Experiment Support

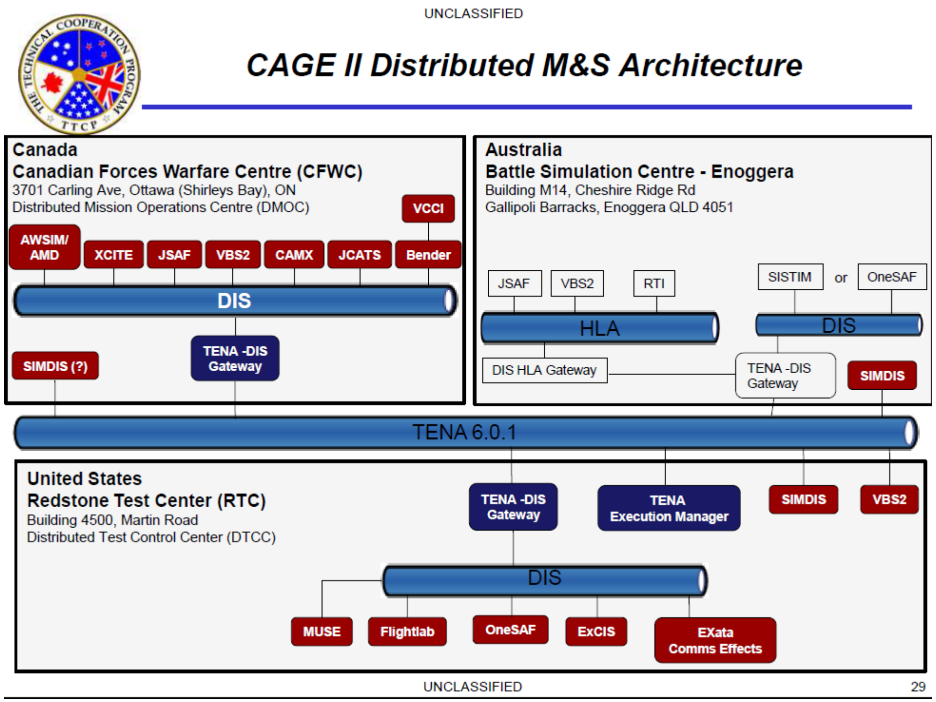


Engineer / Infrastructure Support

Warfighters / Mission Support

Technical Dimension

Exercise Control and Data Tools

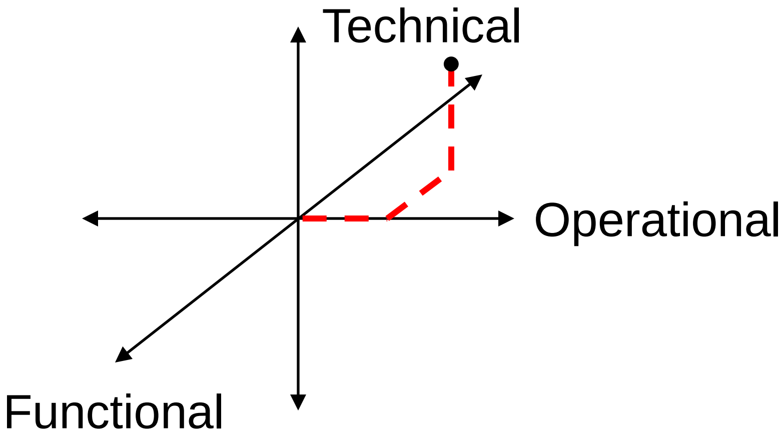


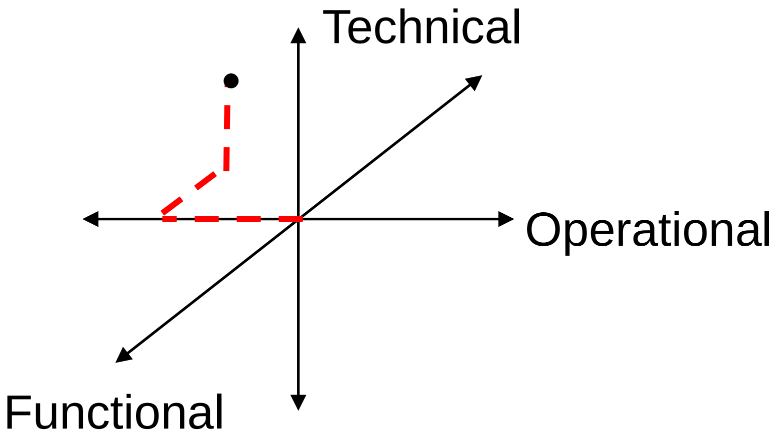
Live Radios

C5ISR

Tactical Apps

Systems Geometry





- Adjusting one or more dimensions changes the geometric definition

Systems Geometry Defined

Systems Geometry is defined as a methodology for exploring emergent system behaviors (planned and unplanned) of multi-dimensional SoS through the capture and analysis of intra- and cross-dimensional characteristics of a targeted SoS.

Purpose of SG:

- Help SoS developers understand and address emergent SoS behaviors
- Support better planning for SoS development
- Assist in proactive mitigation of SoS behaviors that are not intended (risk)

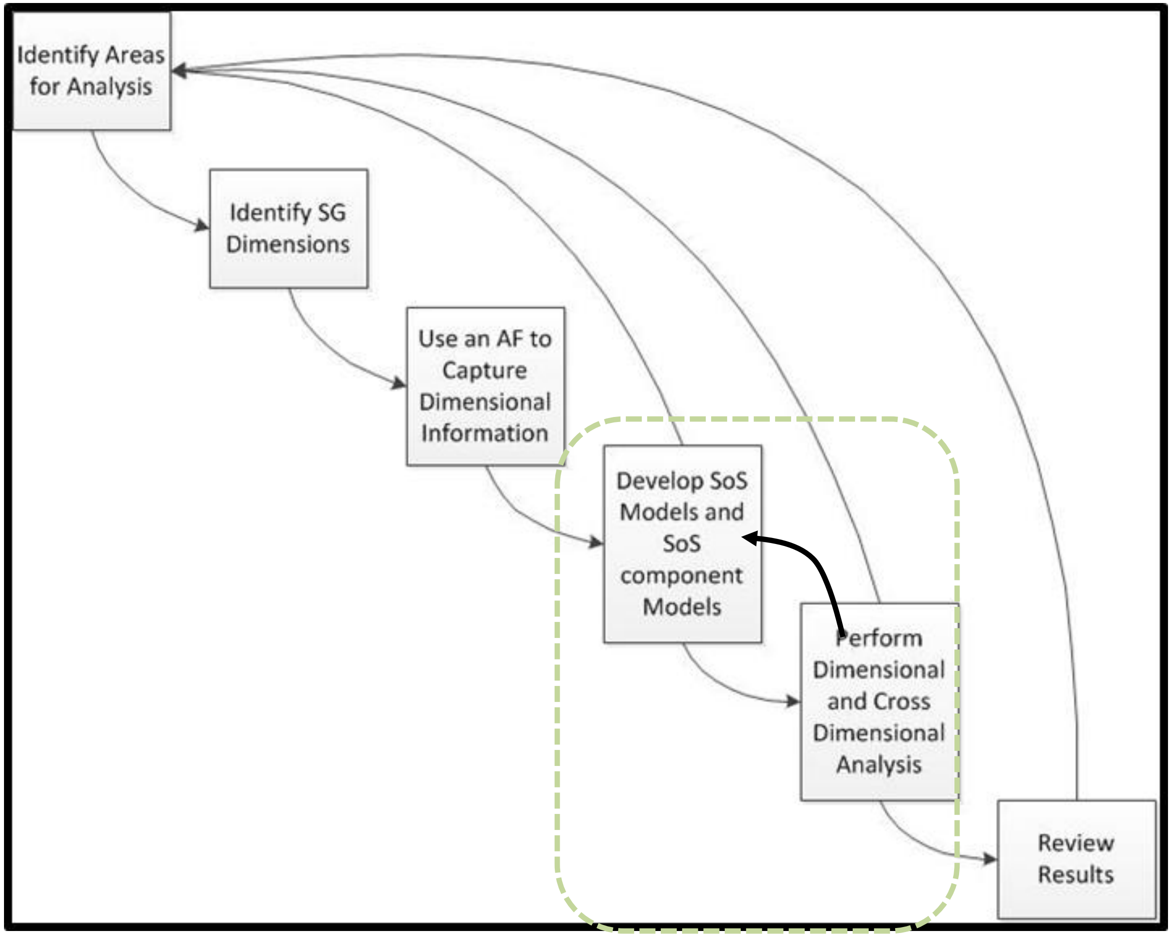
The Problem

- Current system engineering methods fail to address the all the ‘dimensions’ of these complex SoS
  - Particularly the interactions between the dimensions which impact the resulting emergent behavior
- Major issues are uncovered when integrating these SoS – this is much too late in the development cycle
- A methodology is needed to address the emergence of these ‘unintended’ SoS behaviors <u>early</u> in the system development lifecycle to allow for proactive mitigation of these behaviors.

The SG Methodology
SG Architecture Framework

	System Geometry Dimensions			
	Operational	Functional	Technical	Network
Social	Organizations and role players participating in a scenario	Organizations and participants supporting component systems – engineering support	Organizations and engineering staff supporting technical execution of event	Relationships between organizations participating from an operational, functional or technical perspective. Collaboration.
Geographic	Location of functional, technical systems supporting an operational scenario.	Location of technical systems supporting functional activities.	Location of component systems supporting the event. Also location of engineering specific support.	Physical networks connecting virtual and physical component systems.
Business Process	Scenario or mission threads.	Describes how component systems support the operational process. Also includes processes for using the component systems.	Process for conducting the event to include scheduling, system set up, system start up, network connectivity, etc.	Flow of information over the physical network to support operational activities and support activities. Also physical flow of information between sites from both operational and technical view.
Experiment Design / Data Collection	Experiment design and data collection related to the operational scenario activities.	Experiment design and data collection related to the use of component systems and how data is collected with these systems to support operational data collection.	Experiment design and data collection regarding the use of the physical infrastructure and how data is collected to support functional and operational needs.	Flow of data collected to support event experimentation activities. Includes local / site flows as well as inter-site data flows.

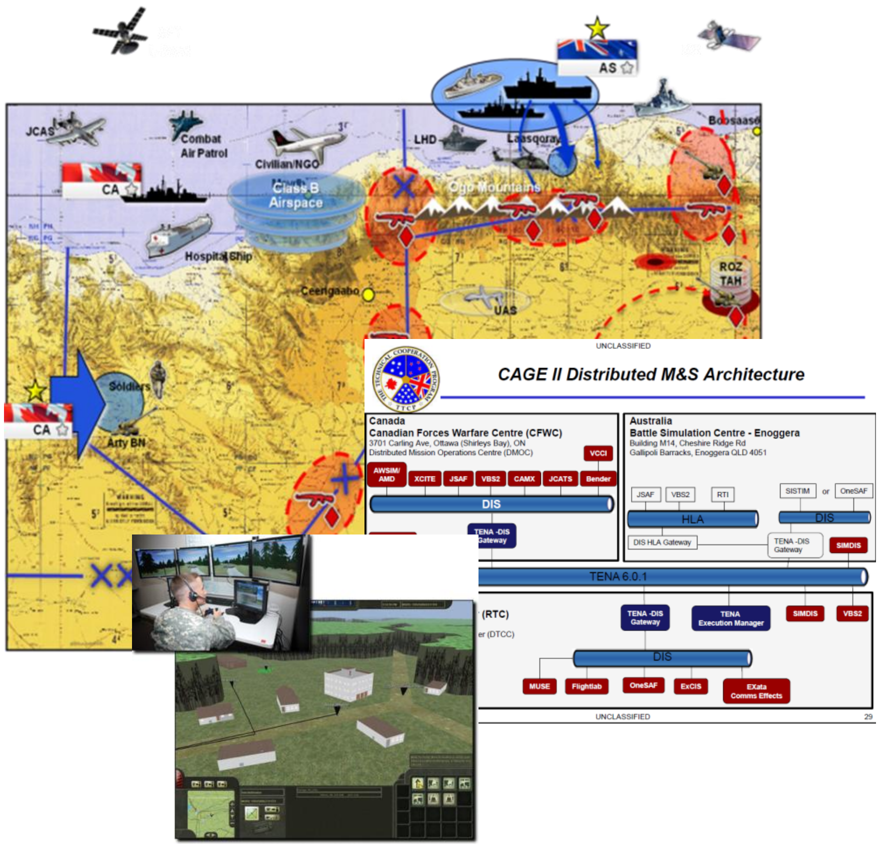
The SG Methodology
SG Process Definition



The SG Methodology
SG Methods Definition (2 of 2)

SysML	• Identification of SoS components, attributes and interactions • Exploration of operational, functional and technical business processes supported by the SoS
Matrix methods	• Interoperability and system interactions • Operational support mapped to specific systems • Identification of redundancies of function and systems • Implementation to analyze experimentation needs: Objectives mapped to Hypothesis mapped to Metrics allowing an exploration of which metrics are most important (mentioned on some of the SE for SoS material)
Network analysis methods	• Bottlenecks in interfaces or networks • Critical systems that interface with many others • Analysis of alternative configurations • Stakeholder analysis

Case Study: Coalition Attack Guidance Experiment



- Series of experiments exploring coalition coordination
- CAGE I served as the “lessons learned” basis for focusing analysis
- CAGE II was the focus of SG implementation
- Exhibited all the characteristics of SoS and the SG dimensions

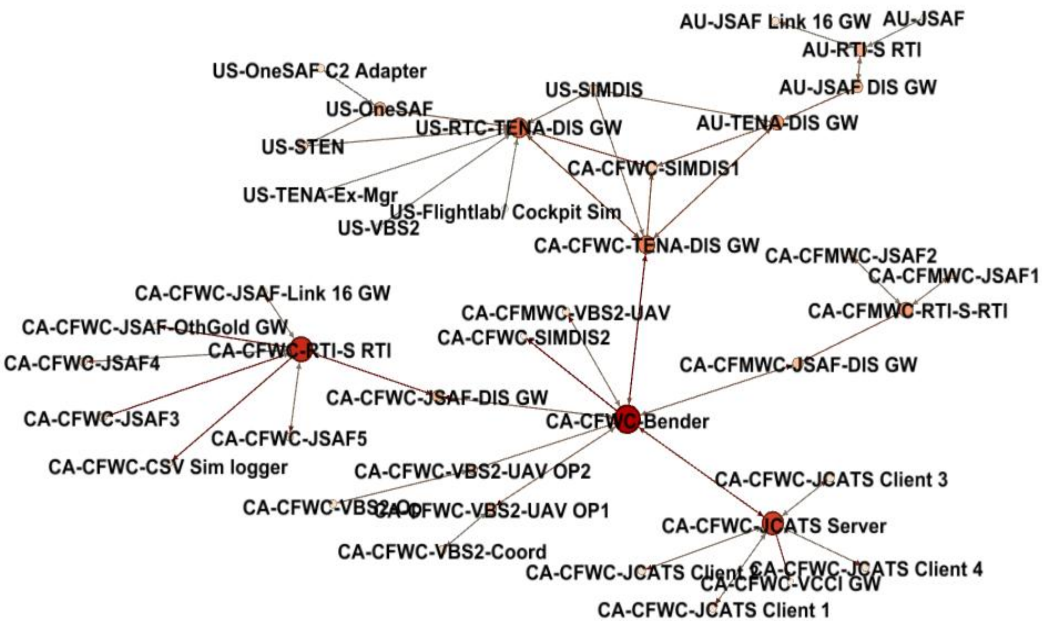
CAGE I Issue Areas To Be Considered

- Constituent System (interface) Maturity
  - Coordination throughout planning critical
  - Pre-event testing is vital
  - Configuration management needs to be maintained
- Integration and Interoperability
  - Clear path for integration needed
  - Consistent use of proper standards well in advance of event
- Experimentation Support
  - Better collaboration of experiment and data collection activities with other event areas

System x System Interaction Matrix

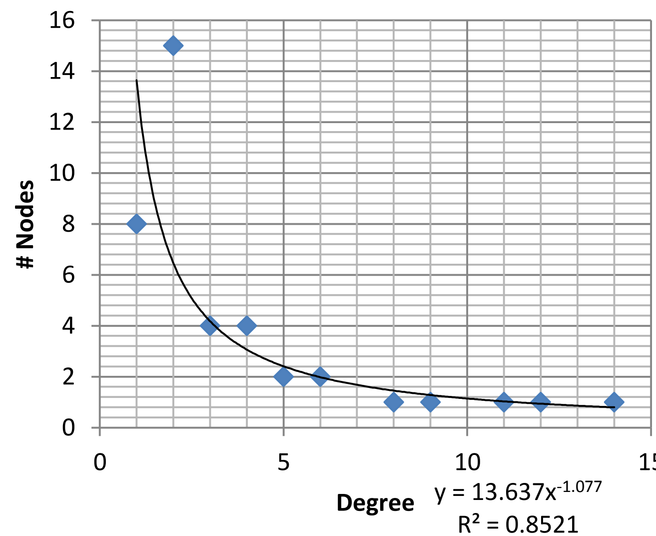
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33
1	AU-JSAF																																	
2	AU-RTI-S RTI	1		1	1																													
3	AU-JSAF Link 16 GW		1																															
4	AU-JSAF DIS GW		1			1																												
5	AU-TENA-DIS GW				1																				1									
6	US-RTC-TENA-DIS GW																								1									
7	CA-CFWC-SIMDIS1					1	1																		1									
8	CA-CFWC-SIMDIS2									1																								
9	CA-CFWC-Bender											1		1					1						1		1			1	1			
10	CA-CFWC-VBS2-Coord											1																						
11	CA-CFWC-VBS2-UAV OP1									1	1																							
12	CA-CFWC-VBS2-Op													1																				
13	CA-CFWC-VBS2-UAV OP2												1																					
14	CA-CFWC-JCATS Client 1																		1															
15	CA-CFWC-JCATS Client 2																		1															
16	CA-CFWC-JCATS Client 3																		1															
17	CA-CFWC-JCATS Client 4																		1															
18	CA-CFWC-JCATS Server									1					1	1	1	1																
19	CA-CFWC-JSAF3																						1											
20	CA-CFWC-JSAF4																						1											
21	CA-CFWC-JSAF5																						1											
22	CA-CFWC-RTI-S RTI																			1	1	1					1		1					
23	CA-CFWC-CSV Sim logger																						1											
24	CA-CFWC-TENA-DIS GW					1	1			1																								
25	CA-CFWC-VCCI GW																		1															
26	CA-CFWC-JSAF-DIS GW									1													1											
27	CA-CFWC-JSAF-OthGold GW																						1											
28	CA-CFWC-JSAF-Link 16 GW																						1											
29	CA-CFMWC-JSAF-DIS GW									1																								1
30	CA-CFMWC-VBS2-UAV									1																								
31	CA-CFMWC-JSAF1																																	1
32	CA-CFMWC-JSAF2																																	1
33	CA-CFMWC-RTI-S-RTI																													1		1	1	

System Analysis – Degree Centrality

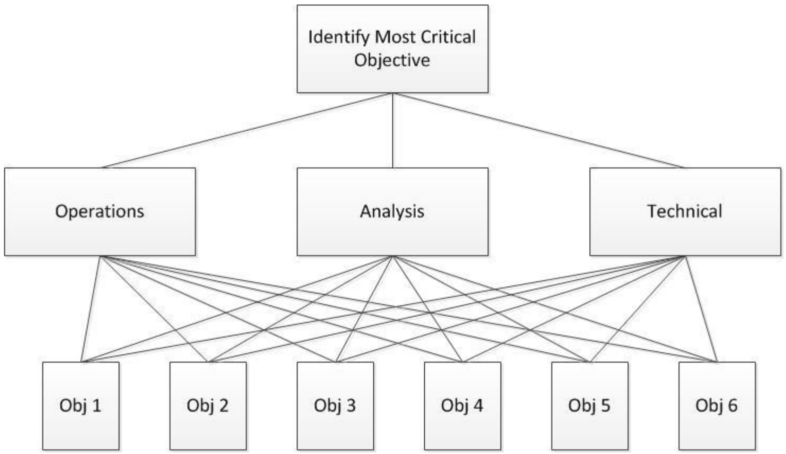


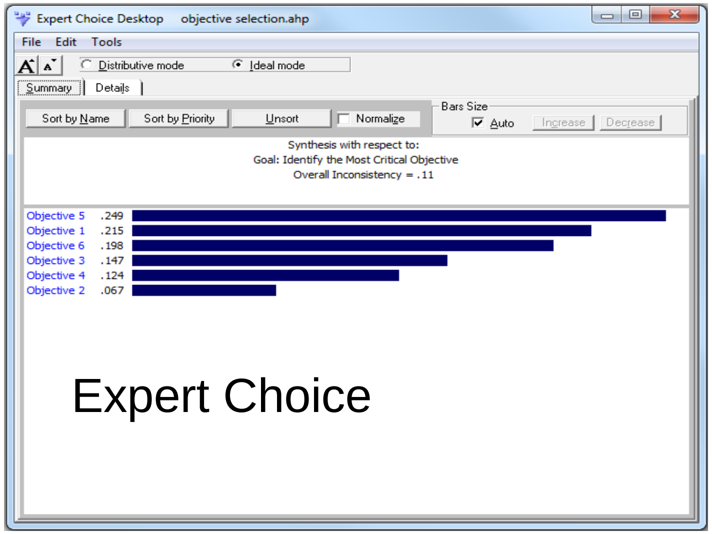
Rank	Id	Degree
1	CA-CFWC-Bender	14
2	CA-CFWC-RTI-S RTI	12
3	CA-CFWC-JCATS Server	11
4	US-RTC-TENA-DIS GW	9
5	CA-CFWC-TENA-DIS GW	8
6	AU-TENA-DIS GW	6
7	CA-CFMWC-RTI-S-RTI	6
8	AU-RTI-S RTI	5
9	US-OneSAF	5
10	CA-CFWC-JSAF-DIS GW	4

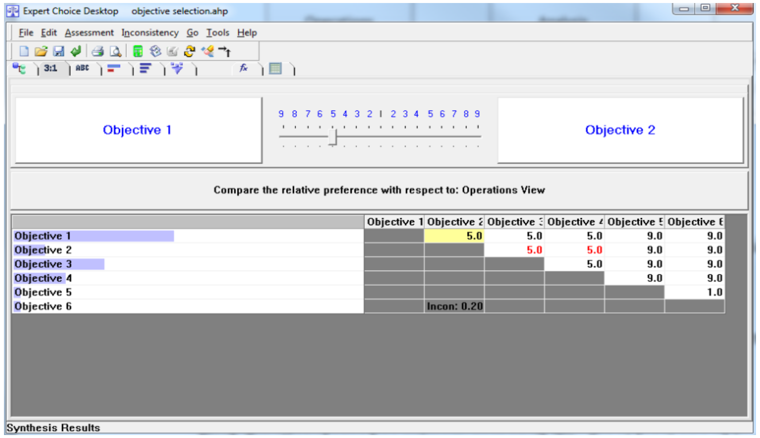
Panel A: Ranking for Degree Centrality

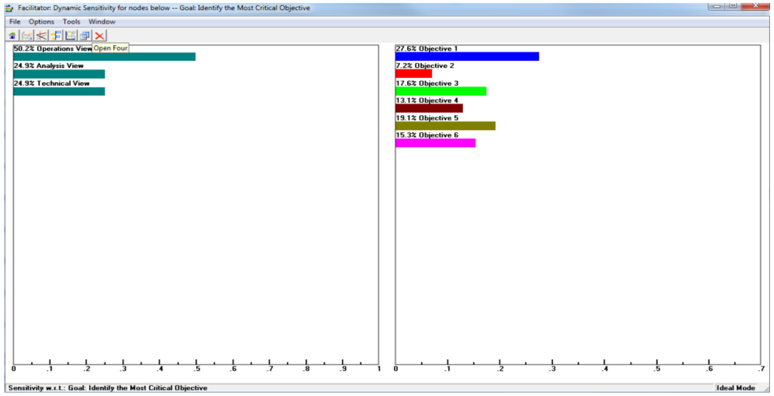


Operational vs Functional Analysis: Importance of Objectives



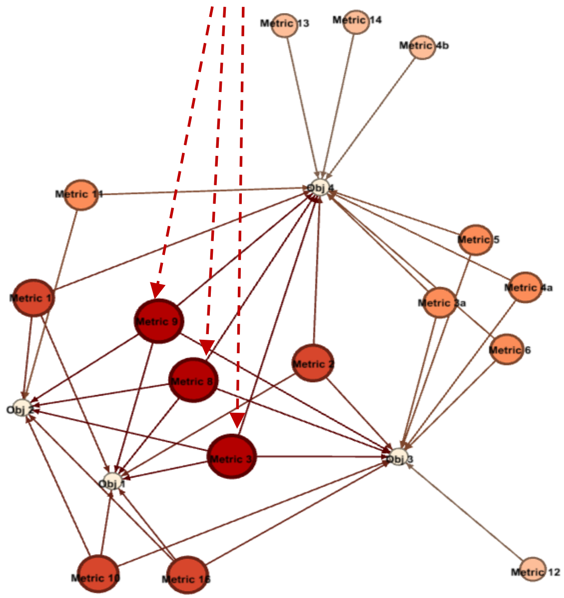


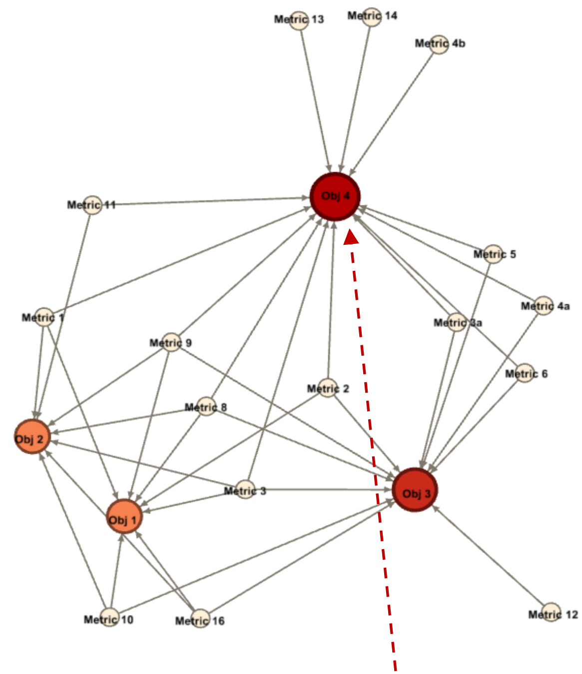




Experimental Design Analysis: Metrics Mapping to Objectives

Significant influence of Metrics 3, 8 and 9





High dependency on many metrics for Objective 4

Case Study Review Results: Issues (1 of 2)

SG Observations & Potential Issues

- **Observation**: System x System network analysis highlighted systems with high centrality measures, indicating significance of proper operation of those nodes
- **Potential Issue**: Major SoS execution problems can occur if system nodes with high centrality measures have problems.
  - There is a need to ensure such nodes are well tested and configuration controlled before an event.

Actual Problems in CAGE II

- During the exercise, the routing tables were changed on one of the network routers causing connectivity issues with conference room calls and malfunction in Sim Radios.
- Incompatibility of one of the TENA gateways with one of the OneSAF simulations caused failure of the simulation and required isolating the simulation on a separate network to allow for its continued its participation in the exercise.
- TENA gateway required five updates during the conduct of the experiment, interfering with the timely conduct of experiment activities.

Case Study Review Results: Issues (2 of 2)

SG Observations & Potential Issues

- **Observation**: Network analysis of experimental design (metrics vs obj) highlighted complexity with metrics use and objective evaluation.
- **Potential Issue**: Overly complex experiment design (too many hypotheses with too many metrics) could make it difficult to evaluate achievement of objectives if certain metrics are unavailable

Actual Problems in CAGE II

- Overlapping hypotheses and metrics where multiple hypotheses had numerous metrics and many metrics were associated with multiple hypotheses led to confusion and also trouble with assigning causality to observed behavior.

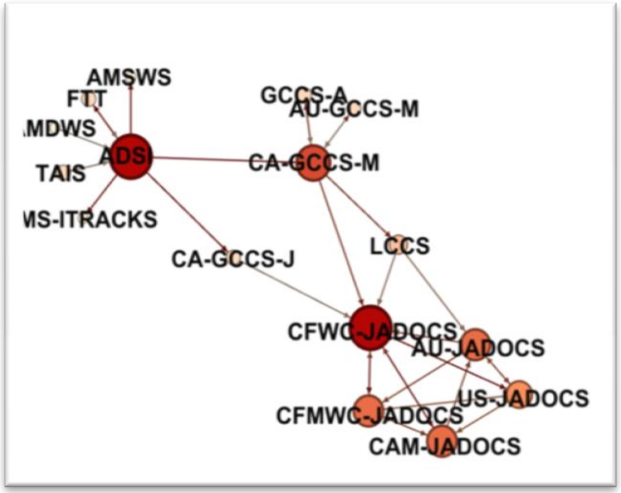
Case Study Review Results: Opportunities

SG Observations & Potential Opportunities

- **Observation**: Operational System x Operational System network analysis highlighted systems with high centrality measures, indicating significance of those nodes
- **Potential Opportunity**: Stable nodes with high centrality measures can contribute to successful execution of the experiment.
  - JADOCS was identified as a highly central C2 node in the network.

Actual Advantages in CAGE II

- JADOCS provided an excellent integration of the tactical air picture from all partners.
- JADOCs operated well across all the objective areas.



Why Should We Care?

- There is great cost associated with the development of complex distributed SoS which grows significantly when issues are not discovered until systems integration.
- Understanding SoS from an emergence standpoint highlights shortcomings of traditional system analysis techniques and opens the door to implementing new approaches.
- New techniques and tools for effective engineering analysis need wider adoption.
  - Engineering education needs to target these tools and techniques to better equip today's systems engineer.

Future Research – Near term

- Implement SG using DoDAF as the architecture framework, fine tuning the methodology with real system development activity
- Perform a multi-dimensional analysis of the relationship between the operational and technical domains – relating scenarios to system configurations or objectives (training, testing, etc.) to system configurations.
- Investigate the use of options analysis for configuration selection in a T&E technical infrastructure (Purdue)
- Conduct a comparative study of SoS modeling methods to determine what types are most appropriate for different dimensional analyses
- Explore network analysis statistics for values that may characterize particular types of configurations of SoS
- Expand the study of emergence and complexity to explore additional analysis methods

BACKUP

The SG Methodology
SG Methods Definition (1 of 2)

SoS Issues	Recommended Methods for T&E
Interoperability & Integration	SysML sequence diagrams along with interface attribute information for all three dimensions will provide important insight into the SoS needs for integration and interoperability.
Constituent System Maturity	Matrix and network methods to show stakeholder relationships with one another and with candidate constituent relationships. Capability analysis (and other SoS configuration alternative techniques) will consider maturity when providing constituent system options to the SoS developer.
Collaboration	Matrix and network methods showing stakeholder relationships along various collaborative areas to include operational collaboration, functional and technical.
Training	Matrix methods mapping processes, systems and stakeholders can determine what kind of training is needed and who needs to be trained. Traditional project management methods of planning and tasking can ensure that proper training takes place.
Resource Assessment / Utilization	Matrix methods help to identify system resources required to support operational and functional activities. Network methods could be used to examine which resources are most critical to the success of the event.
Analysis & Experimentation Support	SysML use case and sequence diagrams can be used to show the business process for analysis and experimentation activities, ensuring that they are supported. Matrix methods will relate the needed capabilities with specific systems for implementation. Network analysis methods can reveal the importance of certain metrics or hypotheses for performing capability analysis.
Implementing Architectural Views	Utilize DoDAF which is recommended for use in the DoD T&E environment and can capture the information required for other analysis techniques.

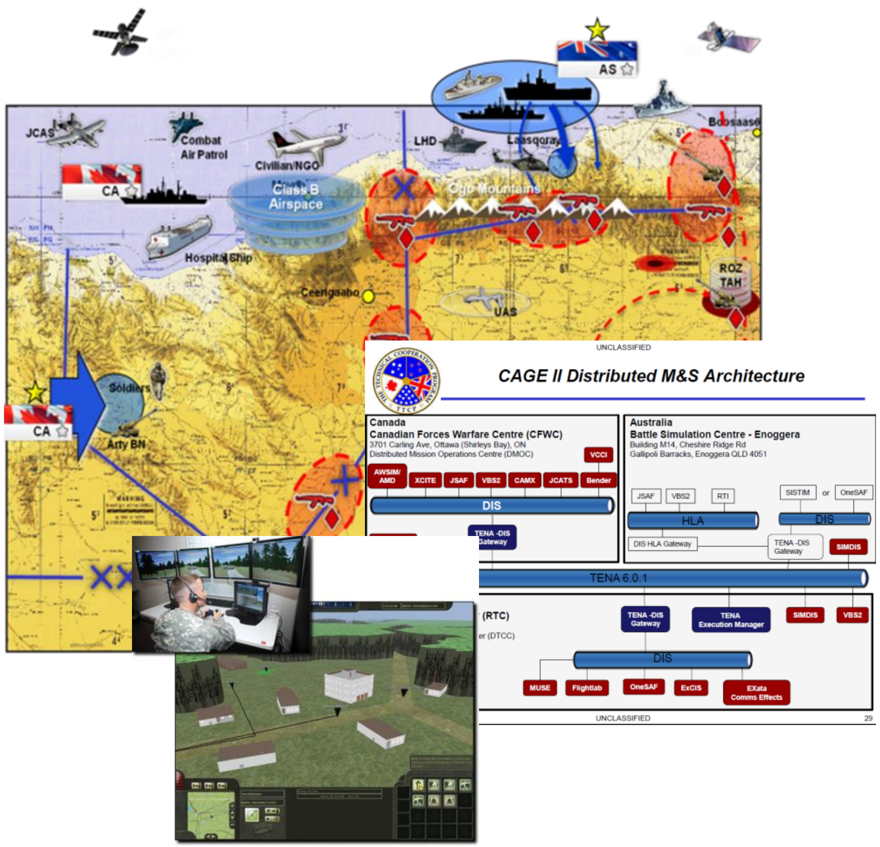
The SG Methodology
SG Tools Definition (1 of 2)

SG Process Step	SG Analysis Methods	Tool Features	Examples
Identify Areas for Analysis	Review lessons learned and capability requirements through stakeholder meetings	Brainstorming tools, office products for documentation, desktop sharing, whiteboard applications, audio and video teleconferencing	MindManager, Text 2 Mindmap, Skype, WebEx, Adobe Connect, Sharepoint
Identify SG Dimensions	Discussion with stakeholders, review of analysis areas, previous experience	Brainstorming tools, office products for documentation, desktop sharing, whiteboard applications, audio and video teleconferencing	MindManager, Text 2 Mindmap, Skype, WebEx, Adobe Connect, Sharepoint
Use an Arch Framework to Capture Dimensional Information	Use DoDAF and/or ESM to capture key dimensional information.	Office products for documentation, tools for developing architecture views	Office products (MS Excel, MS Word), Innoslate, Genesys, IBM Rational Tools, MagicDraw, Open System Engineering Environment

The SG Methodology
SG Tools Definition (2 of 2)

SG Process Step	SG Analysis Methods	Tool Features	Examples
Develop SoS Models and Functional Models	Use SysML, AB and SD to model SoS and key SoS functional areas	System level models development supporting model-based systems engineering to include UML, SysML, discrete event simulation, system dynamic and agent based models	IBM Rational Tools, MagicDraw, Arena, AnyLogic, NetLogo, Expert Choice
Perform Dimensional and Cross Dimensional Analysis	Use previous experience and network analysis methods to explore cross dimensional relationships	Functional block diagrams, data flow diagrams, N2 Charts, IDEF Diagrams, UML diagrams, SysML diagrams Tools for generating network graphs and calculating node and network statistics MS Excel, Gephi, ORA (CASOS tool), Statistical tools	Office products (MS Excel, MS Word, etc.), Innoslate, Genesys, IBM Rational Tools, MagicDraw, Open System Engineering Environment Gephi, Ora, Pajek, NetLogo, NodeXL, UCInet, R
Review Results	Meet with stakeholders to review results and update dimensional information and methods as needed	Brainstorming tools, office products for documentation, desktop sharing, whiteboard applications, audio and video teleconferencing	MindManager, Text 2 Mindmap, Skype, WebEx, Adobe Connect

The Case Study: Coalition Attack Guidance Experiment



- **Operational Independence:** Standalone simulations and operational systems
- **Managerial Independence:** Developed in different countries and by different groups in each country.
- **Geographic Distribution:** US, Canada and Australia locations
- **Emergent Behavior:** Coalition operations only possible using combination of systems.
- **Evolutionary Development:** Evolving constituent participation over time as the SoS event was developed

Case Study Review Results: Issues

SG Observations & Potential Issues

- **Observation**: Analysis of interactions between functional groups highlights dependencies and constraints that can cause decisions by one group to impact other groups.
- **Potential Issue**: Lack of collaboration between functional groups working on a SoS could lead to systems not integrating in a timely manner because they were selected for use late in the development process.

Actual Problems in CAGE II

- Not enough time or resources were devoted to the integration spirals to properly checkout and debug the entire simulation environment and its interoperability with the C2 systems.
- Significant technical issues were encountered due to lack of attention to critical integration spirals which were used as “dress rehearsals” for the event.
- Collaboration issues led to conflicting goals regarding the overall purpose of the event: training vs testing. The main focus of a training event runs counter to the focus of a testing event. This led to major disagreements between stakeholders.