



Systems of Systems Where's the Beef?

As presented to:

INCOSE San Francisco Bay Area Chapter

1/13/09

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Topics

- Systems of Systems: 4 Characteristics
- Complexity
- Distinct SoS Engineering Processes
- Special Training Needs
- Distinctive Tools & Techniques
 - Distinctive Architectural Patterns used in SoS
 - Special Integration Patterns used in SoS
 - Special Collaborative Engineering Processes
 - Special Testing & Evaluation Processes
 - Strategies for Managing Complexity
- A Key Example: Why does the Internet work?
(And what can we learn from it?)

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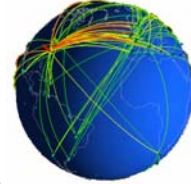
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Systems of Systems

Technical Leadership in a Networked World

- Technical leadership → An SE's role
- Networked World → Major challenges for our profession
- Purpose of Course → Prepare SE's for the challenges
- Primary Audience: Senior Architects / SEs



SoS Course Offering by: Honourcode www.hcode.com

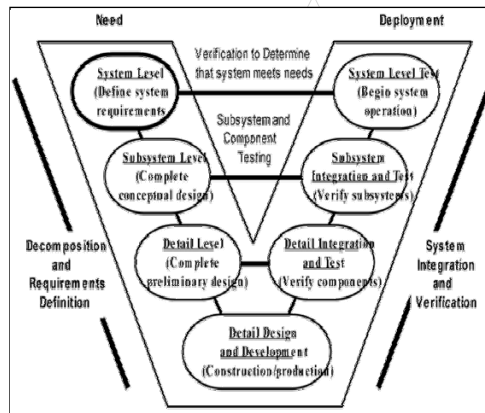
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Classical View:

The V Model



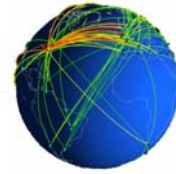
- One Person's System → Another Person's Component
- Why do we need another term?
- Answer: It's pragmatic

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Definition: Systems of Systems



A System of Systems – 4 Characteristics:

- 1) Operational Independence: Component systems achieve well-substantiated purposes even if detached
- 2) Managerial Independence: Component systems are managed for their own purposes
- 3) Emergent Behavior: Exhibits emergent behavior not achievable by the component systems acting independently
- 4) Evolutionary Development: Component systems, functions, and behaviors may be added or removed during its use.

Assertion:

- Levis, Maier, Sage and USAF report SAB TR-05-04

- ❑ Networked Computing has created a new paradigm
- ❑ The New Paradigm includes “Systems of Systems”

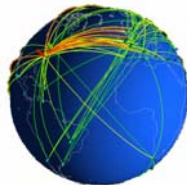
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Examples of Systems of Systems

- ❑ A Supply Chain
- ❑ A Military Force
- ❑ A Modern Airport
- ❑ The iPod Music Delivery System
- ❑ The Internet



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Classical View:

Paradigms



Thomas Kuhn

- What is to be observed
- The kind of questions that can be asked
- How these questions are structured
- How results of scientific investigations should be interpreted
- How an experiment is to be conducted

- Key role for exemplars (Solved Problems)

The Structure of Scientific Revolutions – Thomas Kuhn, 1962.

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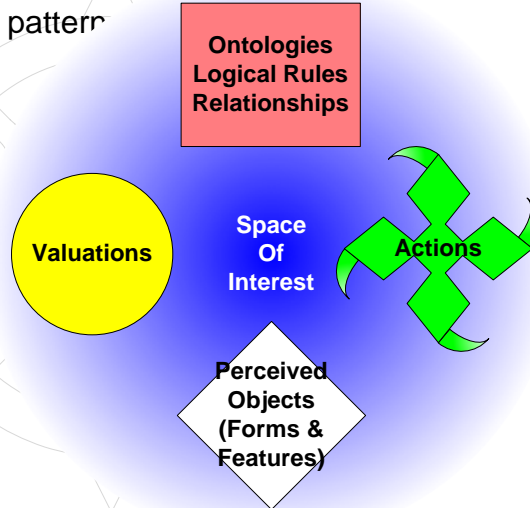
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Another View of Paradigms:

Conceptual Frameworks

- Paradigm: A large pattern
- Framework for
 - Analysis
 - Design
 - Theories
 - Laws
 - Generalizations
 - Experiments
- Consists of
 - Ontology
 - Valuations
 - Perceived objects
 - Actions



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Context:

Applying Paradigm to Process

- General engineering process
- Draw from the paradigm
 - Tools
 - Solutions

System of Systems Paradigm

"In the knowledge is the power." - Feigenbaum

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Education in the New SoS Paradigm

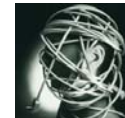
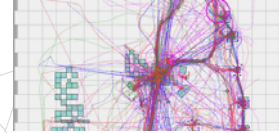
- **Space**
 - Defining
 - Viewing
 - Scoping
- **Assessment**
 - Structure
 - Behavior
 - Valuation
- **The Objects**
 - Systems of Systems
 - Interfaces & Protocols
- **Modeling and Architecture**
 - Complexity
 - Logical Relationships
 - Architectural Patterns
- **Methods**
 - Analysis
 - Architecture
 - Capability Engineering
 - Dynamic Optimization
 - Mixed Initiative Arch.
 - Integration
 - Collaboration
 - Testing & Evaluation
 - Leadership

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Definitions of “Complex System”

- 1) A system having so many interacting components that behavioral phenomena are inexplicable by any conventional analysis.
- 2) A system whose overall behavior is difficult to describe, even when given almost complete information about its atomic components and their relationships.
- 3) A system with many strongly-coupled degrees of freedom.
- 3) As system with emergent and self-adaptive behavior.
- 5) A system studied by complexity theorists.



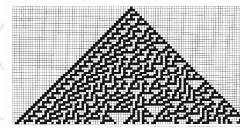
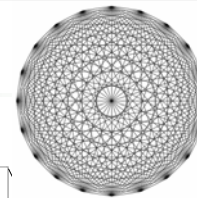
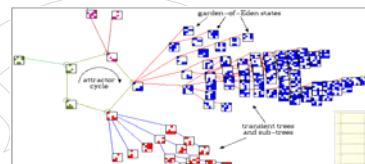
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Complexity Effects

- Network Effect
- Small Worlds
- Nonlinear Dynamics
- Dynamic Patterns
- Emergent Behavior
- Self Organization

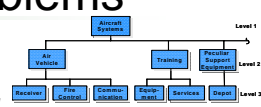


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A Sampling:
Systems of Systems → Problems


- **Model Problems**
 - Most Mathematics is specialized. (“Stove piped”)
 - Computable forms of models don’t predict many types of emergence & other behavioral complexities.
 - Affordances for manipulating large models are difficult to create.
 - Architecture is still mostly art.
- **View Problems**
 - Viewing very large systems
 - Shared awareness
 - Seeing emergent properties
 - Supporting shared view, meaning, awareness, and collaborative effort for large, non co-located teams.
- **Process Problems**
 - Most SE Methodology is Top-Down
 - Misses emergent behavior
 - Suppresses opportunities
 - Little understanding of large-scale collaboration without central leadership
 - Emphasis on control at the expense of influence



Is this an effective way to model an SoS?



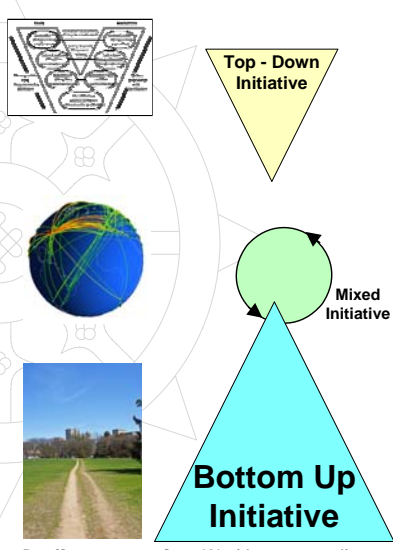
Milky Way (Detail)



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Architecture & Integration:
Three SoS Engineering Processes

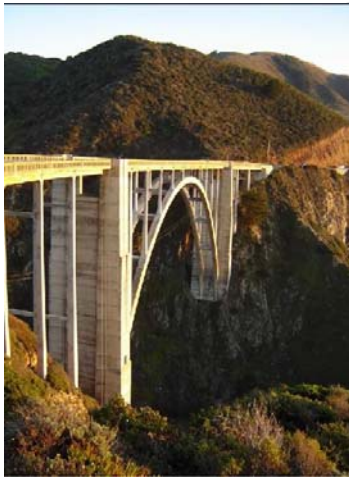
- **Top Down:**
 - Capability engineering
 - Techniques:
 - Architecture based
 - Function based
- **Mixed Initiative:**
 - Designing for emergence
- **Bottom Up:**
 - Paving the worn path
 - Organic integration



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Architectural Patterns



“...a solid and reliable invariant which relates **context**, **problem**, and **solution** in an unchanging way.”

- Christopher Alexander

When a design works, the essence of the concept, that which makes it work, is its architectural pattern.

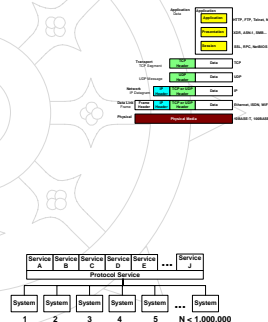
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A Sampling of SoS Patterns

- ❑ Networked Computation
- ❑ The System of Systems
- ❑ Interface Patterns
 - Layered Interface Pattern
 - Interface Constitution
- ❑ Stateless Server
- ❑ Integrated Operations Space
- ❑ Open System
- ❑ COTS
- ❑ Reachback



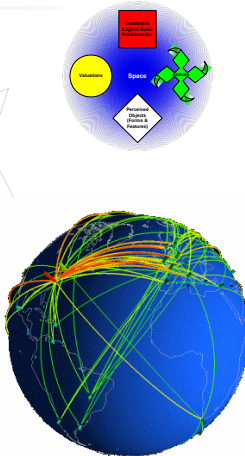
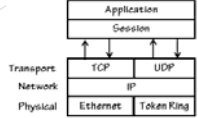
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Introduction:

Networked Computation

- A New Dominant Paradigm
 - Invention → Transport & Communications
 - Expansion → Worldwide Scope
 - Integration → Evolving Paradigm
- Aspects of New Paradigm
 - First Many-to-Many Mass Medium
 - Expanded Size of Systems $10^3 - 10^6$
 - Issue with scaling SE →
 - Systems of Systems Engineering
 - Effect: Functionally Smarter (About some things)
 - Increased Pace of Activity
- Good News – We can work together more closely.
- Bad News – We need to!
- What's it becoming?

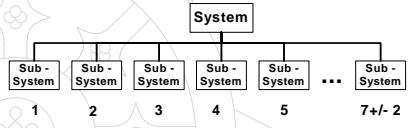
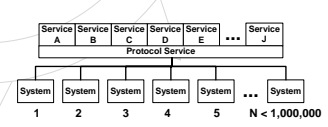



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Pattern Example:

Layered Interface Pattern

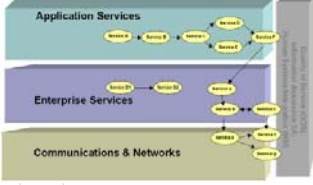
- Traditional Structures use *Modest Fanout Pattern*
 - *Problems for Large Systems:*
 - Too many levels
 - Managing complexity
 - Scaling
- *Solution: Layered Interface Pattern*
 - Plus Completing Patterns
 - Examples
 - Internet
 - FORCEnet

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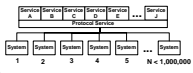
Creating Architecture: Applying a Pattern

- Gather & Summarize – Key Aspects of Design Problem:
 - Needs Statement
 - Requirements
 - Existing Footprint
 - Existing Patterns
 - Hotspots
- Gather the tools: Reference patterns
- Visualize: the new enhanced system
- Pick: Highest level pattern describing the revised system
- Apply the pattern
 - Bind it to the pre-existing systems



FORCEnet

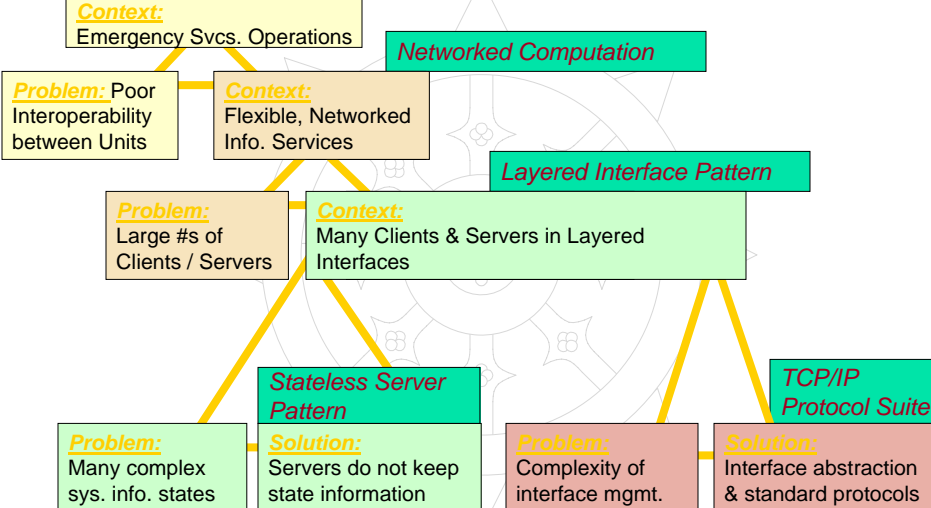
FORCEnet applying Layered Interface Pattern



Layered Interface Pattern

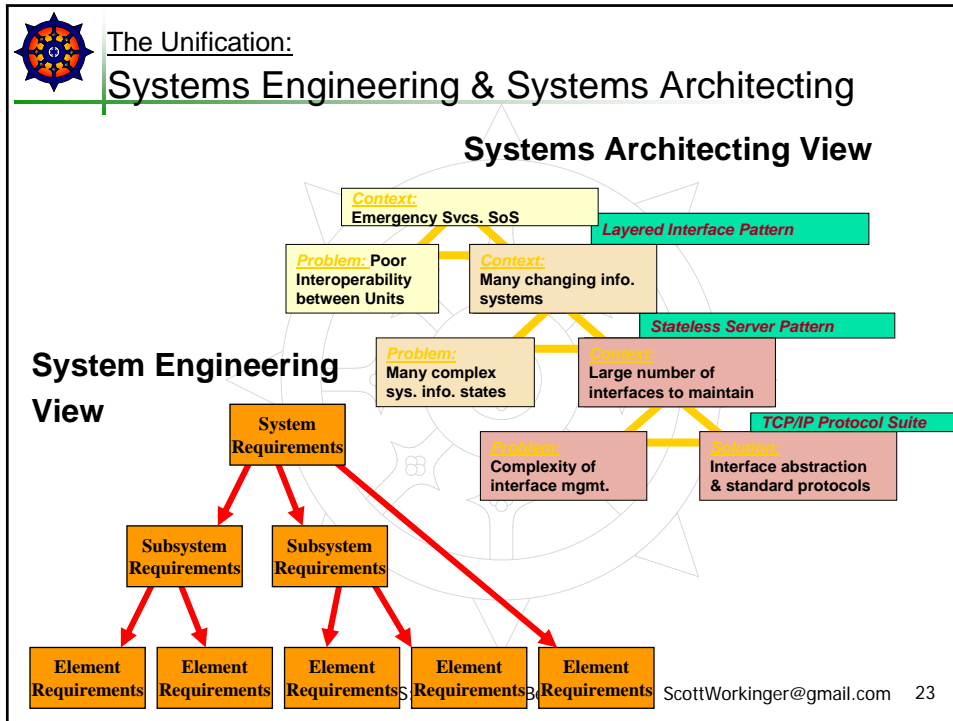
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Pattern Application is Recursive




Each solution becomes the context for the patterns applied at lower levels in the architecture

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Integration Topics

- Integration Strategies
- Design for Integration
- Interfaces
 - Coupling
 - Abstraction & Protocols
 - Constitutions
- Design for Emergence
- Interoperability
- Open Systems
- COTS
- Assessing Change Complexity



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The Importance of Interfaces

"The greatest leverage in architecting is at the interfaces."

- Eberhardt Rechtin, Director & Architect of NASA's Deep Space Network



Eberhardt Rechtin



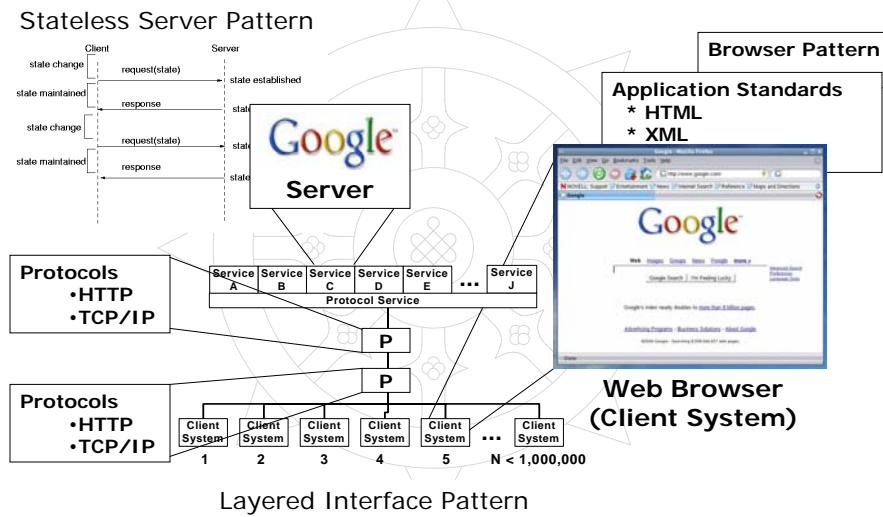
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A Snapshot:

Internet Patterns - 2008



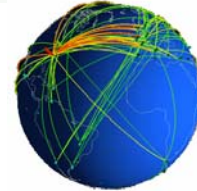
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Why Does the Internet Work?

- Architectural Patterns
 - Layered Interface
 - Stateless Server
 - Browser
- Interface Protocols
 - TCP/IP - Transmission Control Protocol/Internet Protocol
 - Application Protocols
 - Email (POP – Post Office Protocol, IMAP, SMTP,...),
 - File transfer (FTP – File Transfer Protocol)
 - Web page transfer (HTTP – Hypertext Transfer)
 - Stateless
 - Enables use of the Layered Interface Pattern
- Web Page Representation Standards – HTML, XML
 - Allow many people to use the same Browser Pattern



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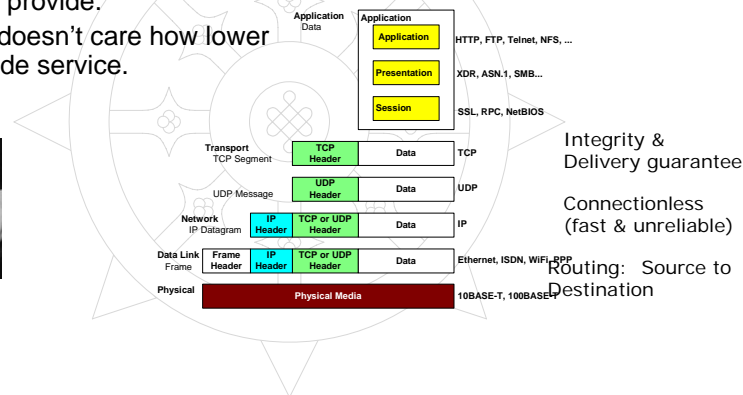
TCP/IP :

A World Class Protocol Suite

- Each layer provides services to the one above it.
- Upper layers provide services lower layers don't provide.
- Each layer doesn't care how lower layers provide service.



Homing Pigeon



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Designing for Emergence

"In the earliest days, this was a project I worked on with great passion because I wanted to solve the Defense Department's problem: it did not want proprietary networking and it didn't want to be confined to a single network technology."

- Vinton Cerf (Inventor of TCP/IP)

"We had no idea that this would turn into a global and public infrastructure."

- Vinton Cerf

"The Internet is based on a layered, end-to-end model that allows people at each level of the network to innovate free of any central control. By placing intelligence at the edges rather than control in the middle of the network, the Internet has created a platform for innovation."

- Vinton Cerf

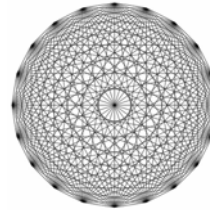
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What's Driving Internet Growth?

- No one owns the Internet
- Architecture was originally mixed-initiative
→ Designed for Emergence
- Today, there is no chief Internet architect
 - Standards bodies exist collaboratively such as the IETF (Internet Engineering Task Force)
 - Many efforts are individual
 - Many ad hoc collaborations are created, live for awhile and dissolve
- The Network Effect continues to drive outstanding new opportunities for value creation



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Lessons from the Internet: Architecture at the Interfaces

- ❑ Create a sound architecture
- ❑ Use abstraction
- ❑ Design for emergence:
 - Create structure that supports adding new capabilities easily.
 - Humility is an asset.
- ❑ Use interfaces to complete the architecture
- ❑ Be thorough about the details - Agreement & stability are more important than perfect performance.
- ❑ Make it as bullet-proof as possible. – The more successful you are, the more stress you can expect to see at the interfaces over time.
- ❑ With interfaces, originality is not always a virtue.
- ❑ Keep it as simple as practical...
- ❑ Be humble...

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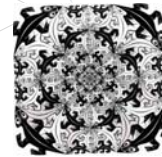
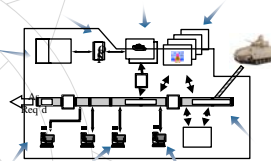
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Topics:

Testing & Evaluation

- ❑ DT&E and OT&E for Systems of Systems
- ❑ Validating the Functional Footprint
- ❑ Simulation
 - Testing to Validate Simulation
 - Simulation Complexity
- ❑ Evaluating SoS Interfaces
- ❑ Interoperability Evaluation
- ❑ Is it “Complex?” How do we know?
- ❑ Detecting Emergent Behavior
- ❑ Evaluating SoS Dynamics
 - Forms of Order
 - Noise
 - Stability
 - Dynamic Patterns



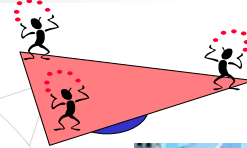
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Topics in Collaboration

- ❑ Leadership responsibilities & issues
- ❑ The myth of SoS teams
- ❑ When no-one owns the system
- ❑ Geographic Dispersal
- ❑ Control vs. Influence
- ❑ Maintaining Integrity
- ❑ Stakeholder Perspectives
- ❑ Collaboration Tools



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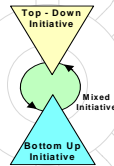
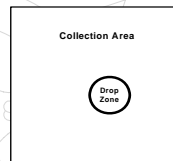
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Making the Paradigm "Real:"

Robotic Swarm Exercise

- ❑ Emergent Heap Building
- ❑ Analysis
- ❑ Robotic Swarm Architecture
- ❑ Attractor Cycle
- ❑ Development Models
 - Top / Down
 - Bottom / Up
 - Mixed Initiative
- ❑ T&E Evaluating Emergent Behavior
 - Initial Conditions
 - Changing Dynamics
- ❑ Collaboration & Conflict




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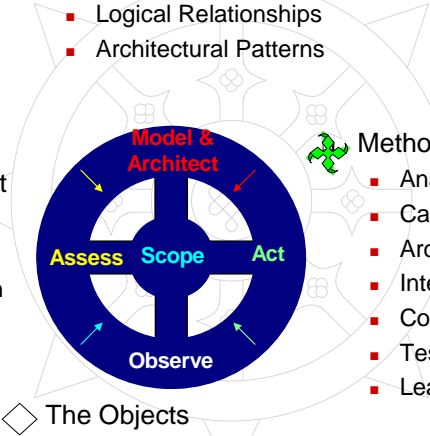
Education in a New Paradigm:

Complex Systems of Systems



- Modeling and Architecture
 - Complexity
 - Logical Relationships
 - Architectural Patterns
- Space
 - Defining
 - Viewing
 - Scoping
- Assessment
 - Structure
 - Behavior
 - Valuation
- ◆ The Objects
 - Systems of Systems
 - Interfaces & Protocols

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Further Information



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