Complex Adaptive Systems Modeling

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August 10, 2015

Agenda

- System of Systems
- Complex adaptive systems
- Cyber Complex Adaptive Systems (CyCAS)
- Modeling and Simulation
- CyCAS M&S

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Principles of System of Systems (SoS)

- Independence at managerial and operational levels
- Independent evolutionary paths,
- Geographical displacement
- Portray emergent behavior
- Holistic purpose and goals

Maier, M.W. Architecting Principles for Systems-of-Systems, Systems Engineering, 1(4): 267-284, 1998.

Background on Emergent Behavior

- Ashby: **Emergent behavior is the lack of understanding of the current system**

- Four schools of thought:
  - **Complex adaptive systems:**
    - **Macro-level patterns arising from interacting agents**
  - Non-linear dynamical systems theory
    - Concept of attractors
  - Synergistic school
    - Concept of order parameter influencing macro-level
  - Far-from-equilibrium thermodynamics
    - Concept of dissipative structures and dynamical systems

Emergent Behavior phenomenon

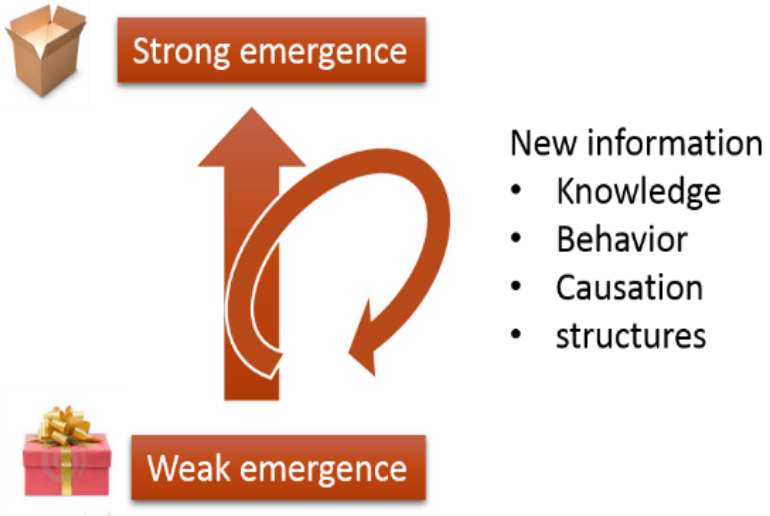
- A macro-level phenomenon
- Largely an observer phenomenon
  - It has to be tagged first before it can be addressed
- Knowledge exists at a higher level of abstraction than the system itself
  - This knowledge may be irreducible and non-decomposable
- Primarily addressed in disciplines like Economics, Psychology and Sociology
- Now incorporating: System of Systems

Emergence Behavior Types

- Weak
  - Traceable through interactions and local individual behaviors
  - No causal powers
  - Strictly Observer-based
  - Consistently reproduced in reduced complexity models
- Strong
  - New knowledge, definitions, classification
  - Causal behavior at multiple levels
  - Adaptive individual agents
  - Consistent with known properties but inconsistently reproduced in simulation

Open System

- Scale-free topology and clustering
- Upward/downward causation
- Persistent environment

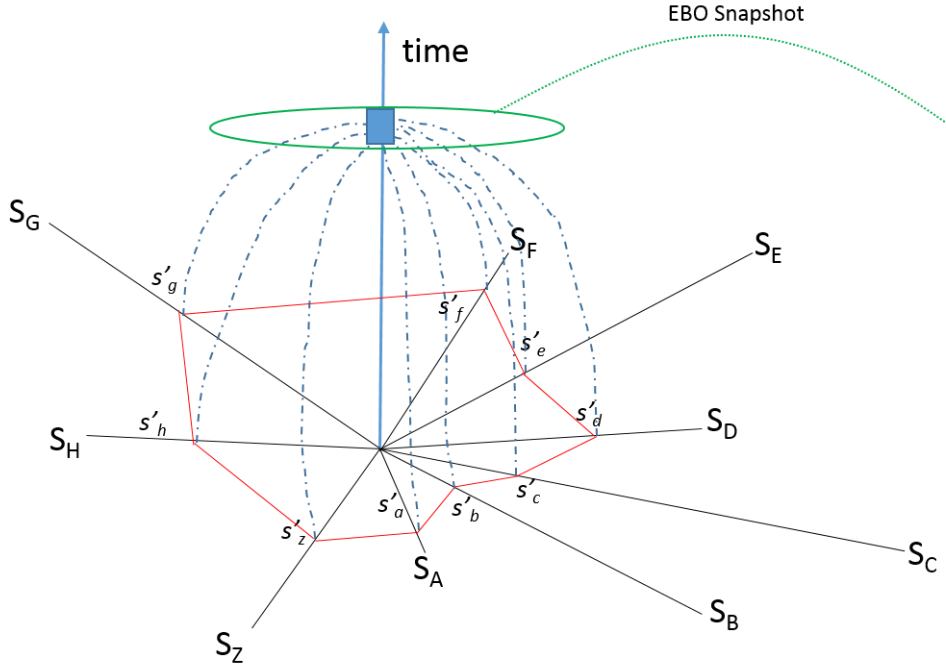


Closed system

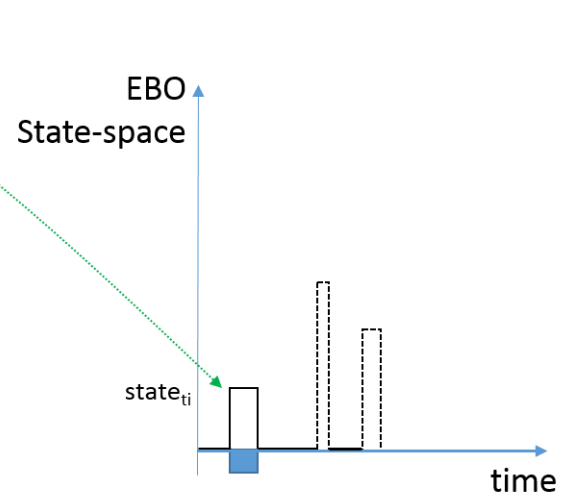
- Closure under coupling

Mittal, S., Attention-Focusing in Activity-based Intelligent Systems, Activity-based Modeling and Simulation, Zurich, Switzerland, 2014

Emergent Behavior Observer Spatiotemporal Snapshots and EBO Model Construction



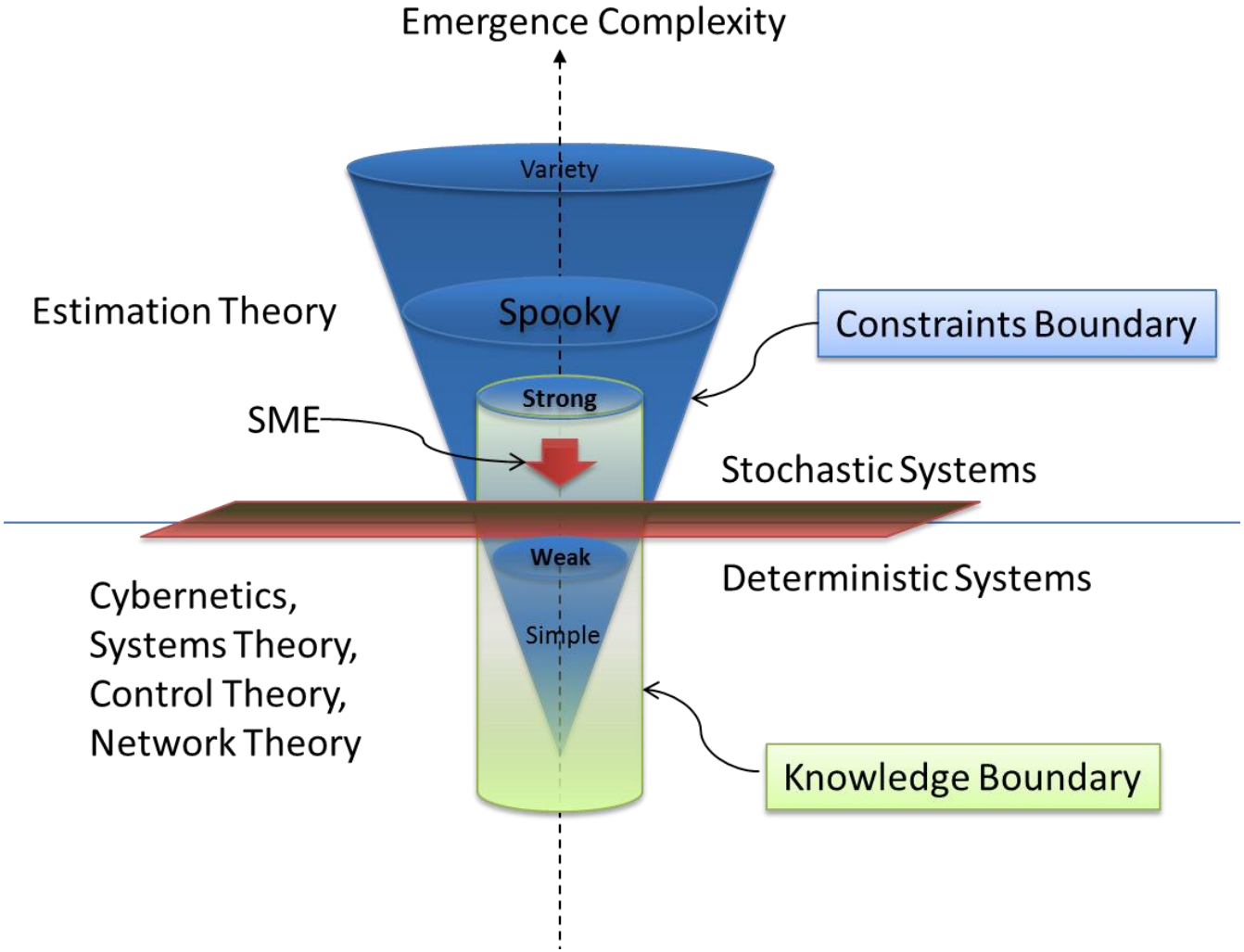
(a)
State-space correlation of different systems for a sustained duration at a certain frequency of interaction



(b)
EBO Behavior and Event-trace with EBO Snapshots

Mittal, S., Rainey, L.. Harnessing Emergence: The Design and Control of Emergent Behavior in System of systems Engineering, Summer Computer simulation Conference, 2015.

Emergency Complexity Cone



Mittal, S., Rainey, L.. Harnessing Emergence: The Design and Control of Emergent Behavior in System of systems Engineering, Summer Computer simulation Conference, 2015.

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Complex Adaptive Systems

- Characteristics
  - Display strong emergent behavior
  - Have positive- and negative-feedback loops
  - Large number of adaptive agents
  - Causal emergent behavior at multiple levels
  - Open System

Mittal, S., Emergence in Stigmergic and Complex Adaptive Systems: A Formal Discrete Event Systems Perspective, Cognitive Systems Research, 2012

The Words…

- Complex (-ity)
  - Structure (simple, star, mesh, small-world, etc.)
  - Behavior (simple, linear, non-linear)
  - Relationships (syntactic, semantic and pragmatic)
- Adaptive
  - In Structure
  - In Behavior
  - In medium-of-exchange
- Systems
  - Do we know the boundaries?
- The Whole:
  - Always a surprise element. Can't know enough!!!
  - Cascades

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Cyber Complex Adaptive Systems (CyCAS)

- Characteristics of CAS in Enterprise environments
  1. Human-in-the-System
  2. Multi-agent-System
  3. Control and Communications in Cyber environment
  4. Resource-constraints and economy of scale
  5. Emergent Attention and Second-order Cybernetics
  6. Phase Transition
  7. Structure of Knowledge
  8. Resilient or Anti-Fragile

Mittal, S., Model Engineering for Cyber Complex Adaptive Systems, European M&S Conference, France, 2014

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Architecture Frameworks

- **An Architecture Framework enables the development of an architecture**
  - **DoDAF**: Department of Defense Architecture Framework.
  - **MoDAF**: Ministry of Defense Architecture Framework
  - **TOGAF**: The Open Group Architecture Framework
  - **Zachmann** Framework
  - **NAF**: NATO Architecture Framework
  - **DNDAF**: Department of National Defense/ Canadian Armed Forced Architecture Framework
  - **FEAF**: The Federal Enterprise Architecture Framework

- **Tools & Standards**
  - UML/SysML
  - Formal languages: DEVS, Petri-nets, etc.

How to choose?

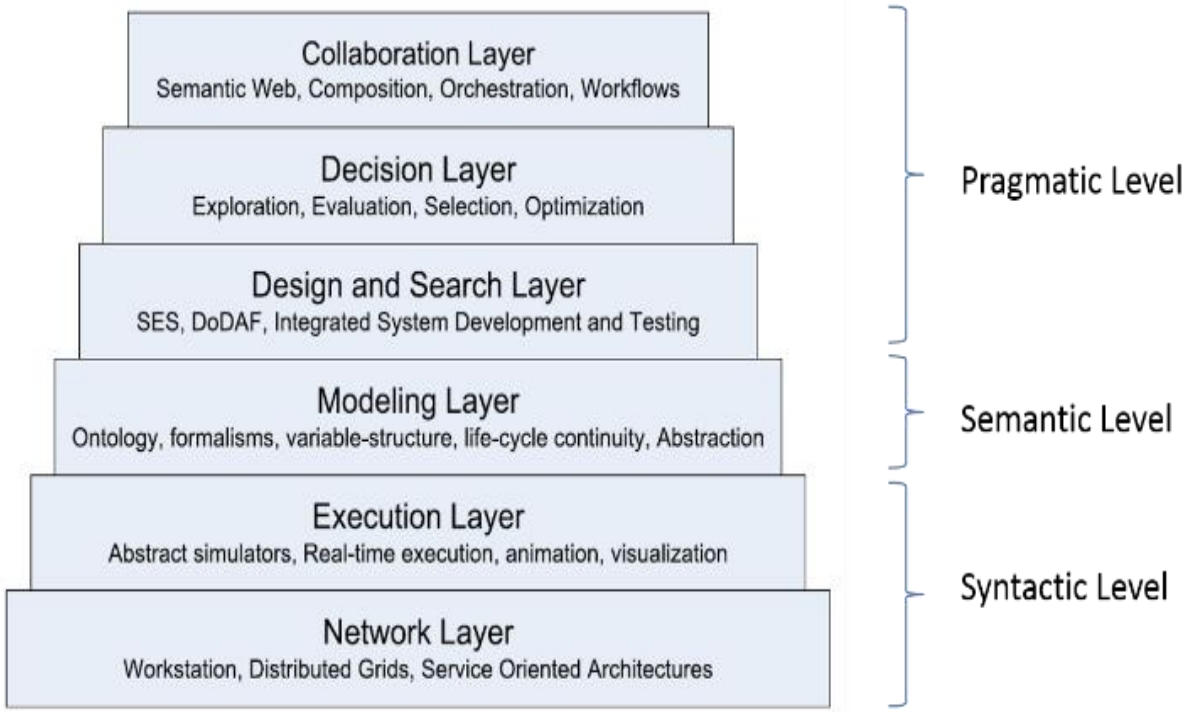
- Architectures facilitate design
  - Towards deployment
- Enterprise architecture stay within the Enterprise/agency
  - Architectures in-whole may not be extensible for information sharing
  - Uses one or multiple architectural styles

- What if the objectives are beyond the enterprise architecture itself?
- It has to be modeled through principles in
  - Complex systems M&S engineering
  - System-of-Systems M&S engineering

Complexity and System of Systems M&S

- Too many enterprise architectures and frameworks
- Major efforts are underway to align data, ontologies and architectures
- In the M&S domain, enterprise M&S architecture are described in
  - Joint Live, Virtual and Constructive (JLVC) Vision 2020
  - Cloud-enabled Modeling and Simulation (CEMS) Services
- Technical integration is solved but semantic interoperability is elusive
- Causality, control and emergent behaviors are not adequately addressed
- Software-based discrete event simulation v/s Systems-based Discrete event simulation
  - Systems Theory is largely ignored

M&S Architecture & Interoperability Levels



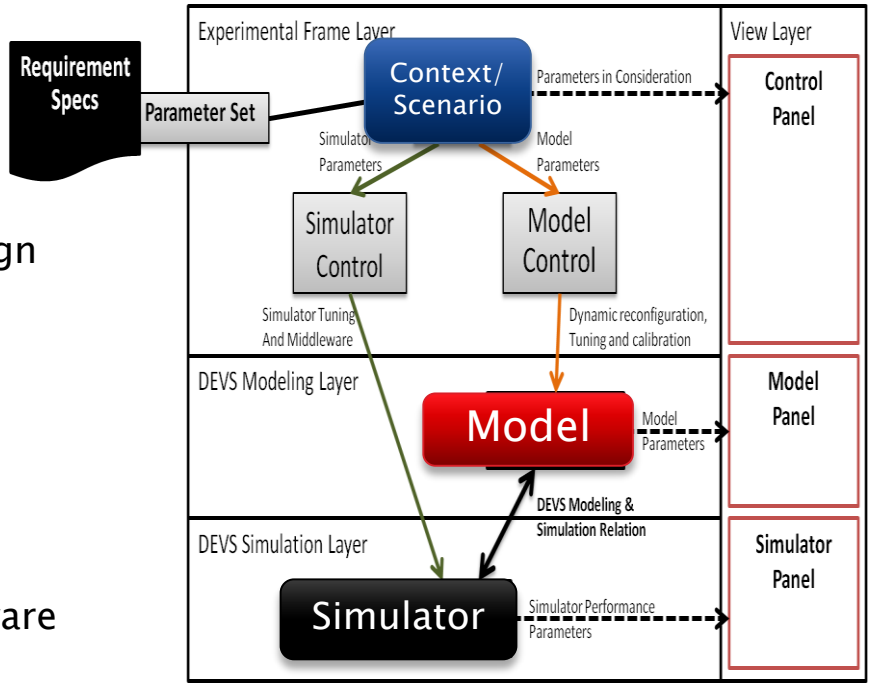
Mittal,, Zeigler, Martin, Sahin, Jamshidi, Modeling and Simulation for System of Systems Engineering, in M. Jamshidi (ed.) System of Systems Engineering: Innovations for 21st Century, 2009

Model-Simulator-View-Controller (MSVC) Framework

Pragmatic Level
Questions??
Analyze or Design

Semantic Level
Science

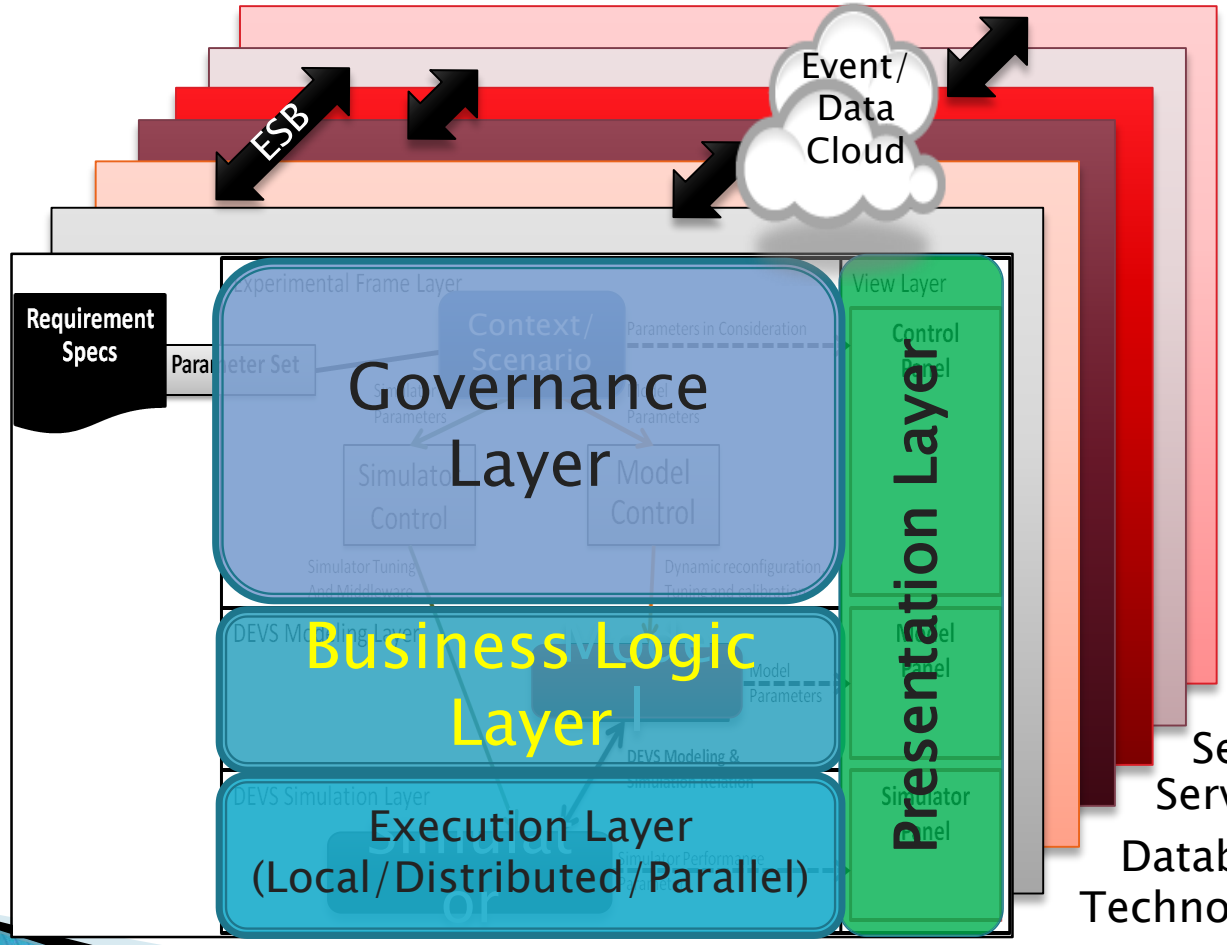
Syntactic Level
Hardware/Software



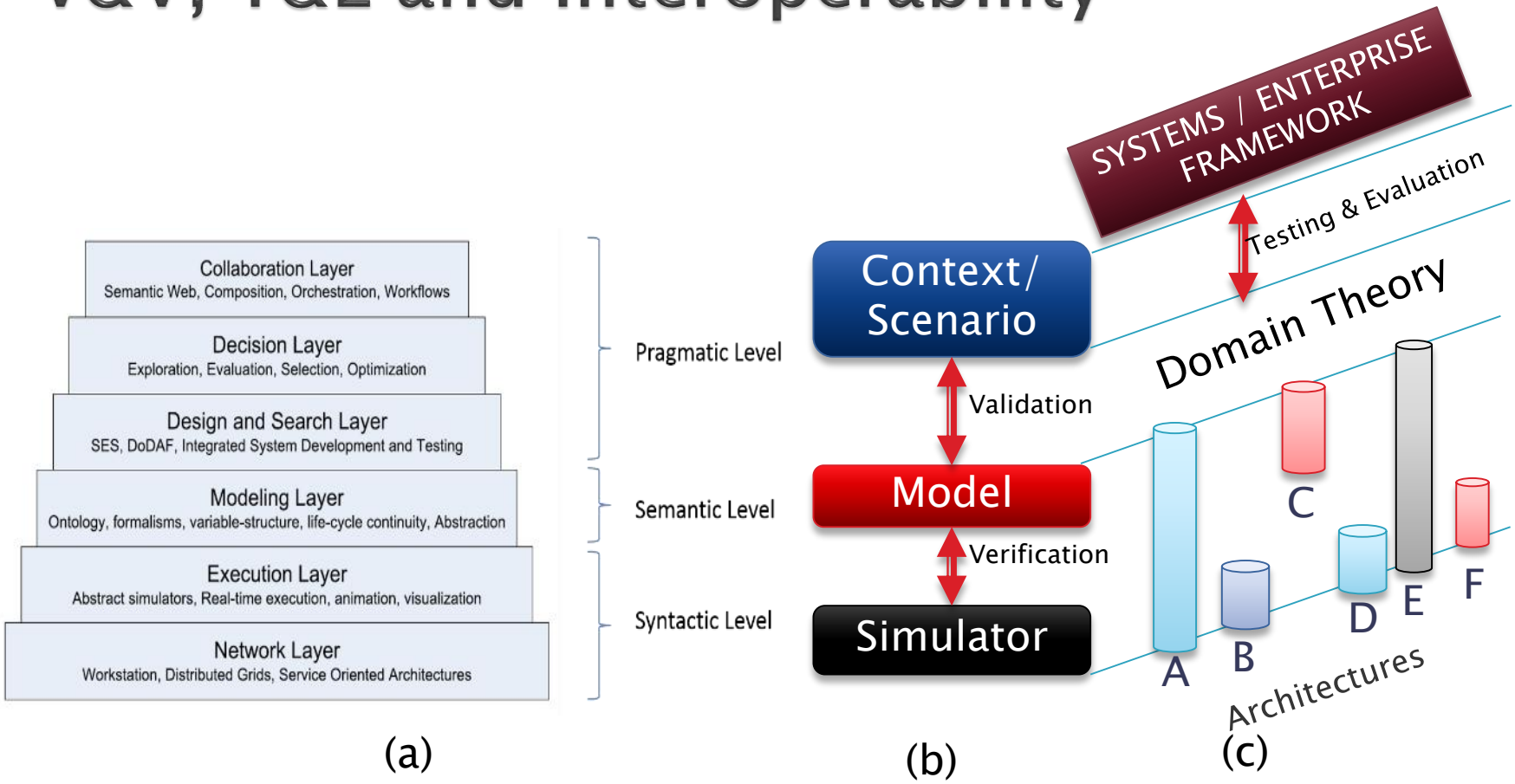
Tool building Plug-in based Environments

- Eclipse RCP
- Netbeans RCP
- Enterprise J2EE

Model-Simulator-View-Controller (MSVC) Framework and Enterprise Architecture Model



M&S Architecture, Systems Framework, V&V, T&E and Interoperability



Framework enables architectures to co-exist

Mittal, S., Model Engineering for Cyber Complex Adaptive Systems, European M&S Conference, France, 2014

The "Executable" part

- Software is an executable
- Model needs a Simulator

- Software architecture is also executable

- A Model-based software architecture leads to an Executable Architecture
  - Model is either domain dependent or domain agnostic (if abstract architecture is being modeled)
  - Simulator executes the model but has to be correctly implemented

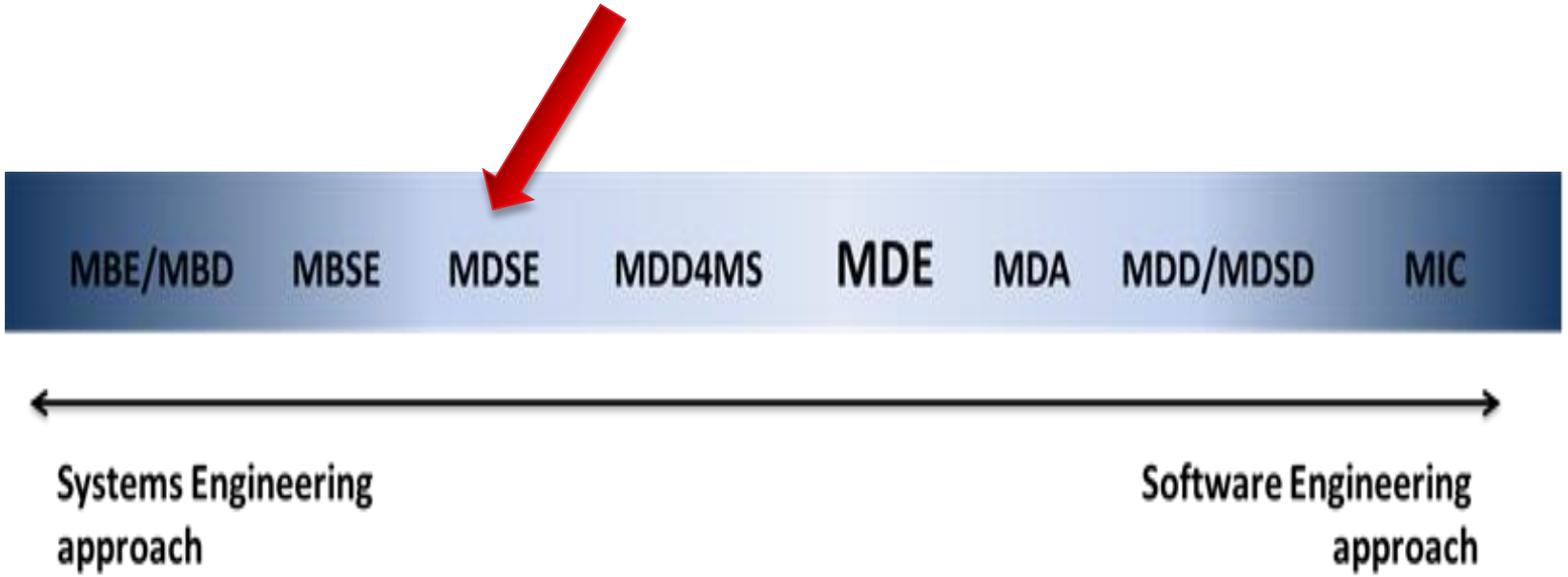
- Verification and Validation

Model-Based and Model-Driven Flavors

- **MBE/MBD: Model-Based Engineering/Design**
  - 1980s: Wymore and Zeigler
  - Design, development, integration, validation, verification, testing, documentation, maintenance
- **MBSE: Model-Based Systems Engineering**
  - Analysis and Design phases, systems complexity, team communication
- **MDE: Model-Driven Engineering**
  - 2000s
  - Focus on Transformations and metamodels: Usage of models in various phases.
  - Facilitates Domain-specific modeling
- **MDA: Model-Driven Architecture**
  - 2000s, OMG
  - MOF: Guidelines for specifying and structuring models: context independence
- **MDD/MDSD: Model-Driven Software Development**
  - 1990s: OMG, Eclipse, Microsoft and others
- **MIC: Model Integrated Computing**
  - 1990s: ISIS
  - Open integration framework to support formal analysis tools, verification techniques and model transformations

Models in Systems/Software Engineering

MDSE: Model-Driven Systems Engineering
Use of MDE to enhance the capabilities inherent in MBSE



Mittal, S., Martin, JLR, Model Driven Systems Engineering for Netcentric System of Systems with DEVS Unified Process, Winter Simulation Conference, 2013

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CyCAS Framework

- Computational model of CyCAS
- Assumptions
  - CyCAS is a digital CAS where the notion of Object is ubiquitous
  - System behavior is manifested through exchange of events in a netcentric environment
  - Human is the most complex and the least predictive element

Sandbox requirements

- Adhere to Systems Theory
- Variable Structure: a critical capability
- Structure
  - Control and Communication View
  - Resource and Constraints View
  - Knowledge View
  - Resilience View
- Behavior
  - Human View
  - Multi-agent View
  - Emergence View
  - Phase Transition View

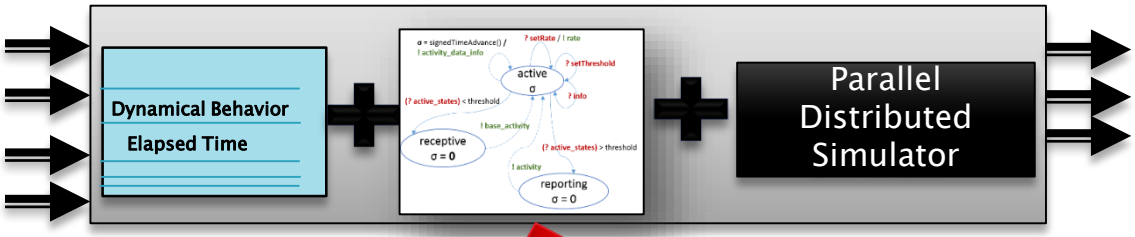
Mittal, S., Model Engineering for Cyber Complex Adaptive Systems, European M&S Conference, France, 2014

Multi-Agent View

- Many architectures and tools
  - JAMES II
  - Repast
  - NetLogo
  - MASON
  - FLAME
  - SOARS
  - SWARM
  - Etc…..

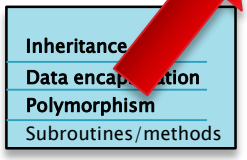
- Lack of closure-under-coupling property except DEVS-based JAMES II
- Most leverage Flat nature of agent-based systems and a shared communication channel

Software Agents and DEVS-based Agents

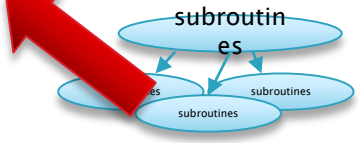


DEVS component-based Agent/System with underlying formal Systems Theory and closure-under-coupling

Software Agent



Object-Oriented Paradigm



Classical paradigm

CyCAS Views, Tool Capabilities and Metrics

ID	CyCAS Views	Tool Capabilities	Metrics
5.1	**Human View**	Cognitive architectures, Live, Virtual and Constructive (LVC) environments, user behavior modeling	Behavior quality, spread and quantification, cognitive plausibility, contextual realism, quantized context
5.2	**Multi-agent View**	Agent structure, behavior and interactions with other agents or environment, closed-under-composition	Ease of model-transformation and model integration, partial observability, group cohesion, shared goals
5.3	**Control and Communication View**	Hierarchical organization, logical structures and supervisory control (similar to DoDAF OV-7 and SV-7)	Degree of control (from centralized and totalitarian to completely decentralized and autonomous), feedback loops
5.4	**Resource and Constraints View**	Similar to DoDAF 2.0 System View 4, 5 resources. Constraints similar to policy considerations in DoDAF OV-6a	Utilization, availability, limitations, affordance
5.5	**Emergence View**	Multi-level instrumentation, Big Data, expected behaviors, causal behaviors, novel behaviors	Multi-level behavior validation and recognition, computational emergence, agent adaptation
5.6	**Phase Transition View**	System behavior transition matrix (similar to DoDAF SV-3)	Multi-level transition probabilities, credit assignment and new behavior detection and encoding
5.7	**Knowledge View**	Ontologies (data and its relationships)	Semantic network, semantic validity through SME and keyword-rank
5.8	**Resilience View**	Experimental frames	Degree of robustness at multiple-levels

Mittal, S., Model Engineering for Cyber Complex Adaptive Systems, European M&S Conference, France, 2014

Summary

- Emergent Behavior is a critical concept in SoS M&S
- Complexity in SoS and CAS exists at both structure, behavior and relationship levels
- Cyber CAS is a digital CAS
- CAS modeling begins with an architecture conceptualization
- System Architecture incorporates hardware-software, people, processes and procedures
- Executable architecture is a work-in-progress and requires MDSE methodology in conjunction with M&S Architecture Framework

Summary

- Enterprise Architecture is a CAS and portrays emergent behavior when becomes a part of system of system
- CAS needs a workbench with human-in-the-loop for Cyber CAS evaluation
- New class of analytics at the systems level need to be conceptualized and implemented at the enterprise architecture level
- An exciting field with lots of room for research, development and engineering!

Thank You!

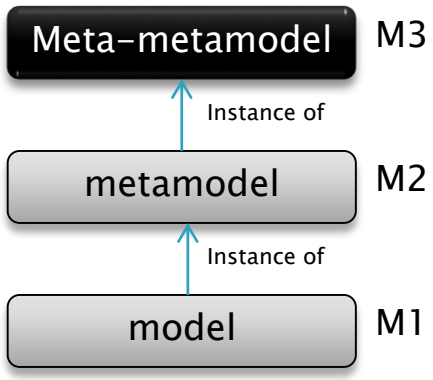
Questions & Comments…

MDE
Key Enabler promoting automated transformations

- Metamodeling

  M1, M2, and M3 Levels

- Domain Specific Languages
  - Defined at M2 Level
  - Oriented to a problem domain/context
  - Metamodeling process is called Domain Specific Modeling (DSM)



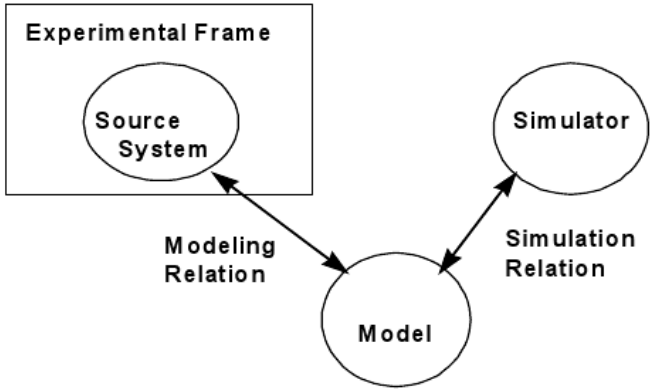
Theory of Systems M&S: Concepts (1/2)

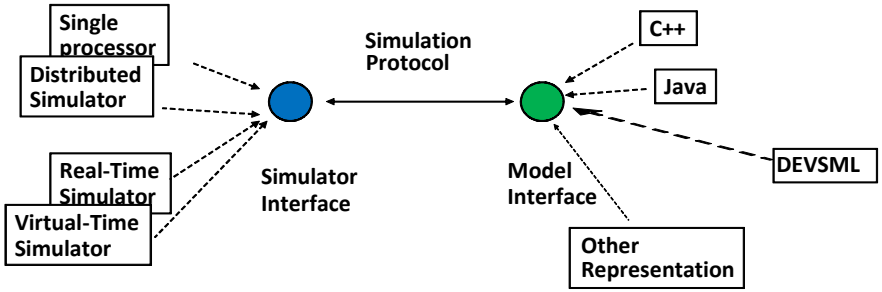
- System Specification Formalisms: Continuous or Discrete
  - DESS, DTSS, Quantized
- Hierarchy of Systems Specifications
  - Closed under composition

Level	Name	System Specification at this level	Elements from the Framework for M&S	Verification and Validation
4	Coupled Systems	Systems built from component systems with a coupling recipe	Model, Simulator, Experimental Frame	Structural Validity, simulator correctness
3	I/O System Structure	System with state and transitions to generate the behavior	Model, Simulator, Experimental Frame	
2	I/O function	Collection of input/output pairs partitioned according to initial state	Model, Source System	Predictive Validity
1	I/O behavior	Collection of input/output pairs from external black-box view	Model, Source System	Replicative Validity
0	I/O frame	Input and output variables and ports together with values over a time base	Source System	

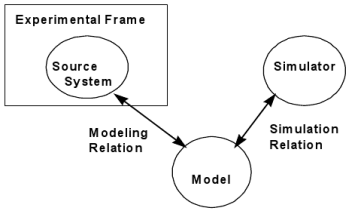
Theory of Systems M&S: Concepts (2/2)

- Source-System, Model, Simulator, Experimental-Frame

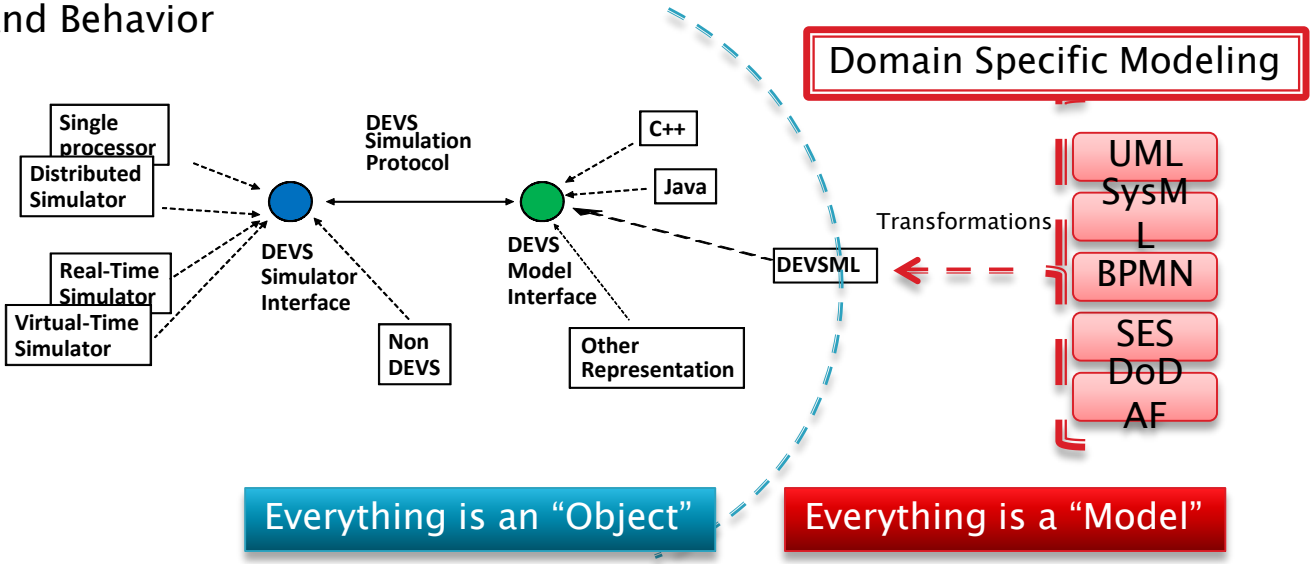




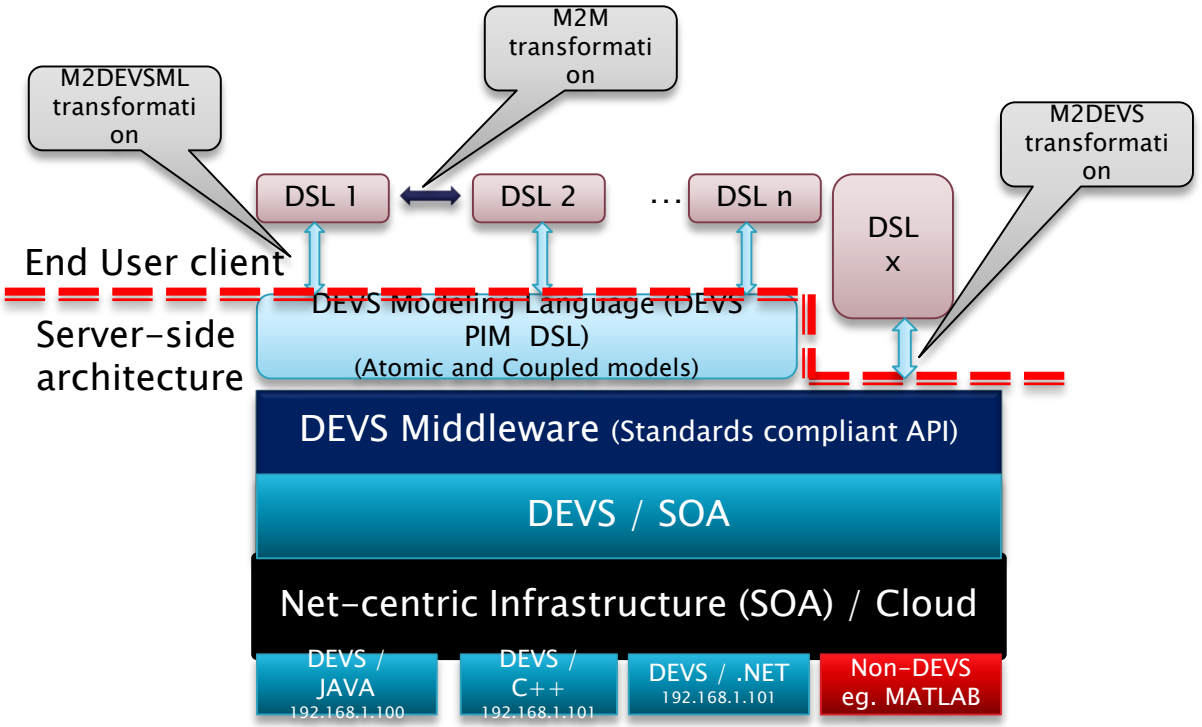
Object or Model?



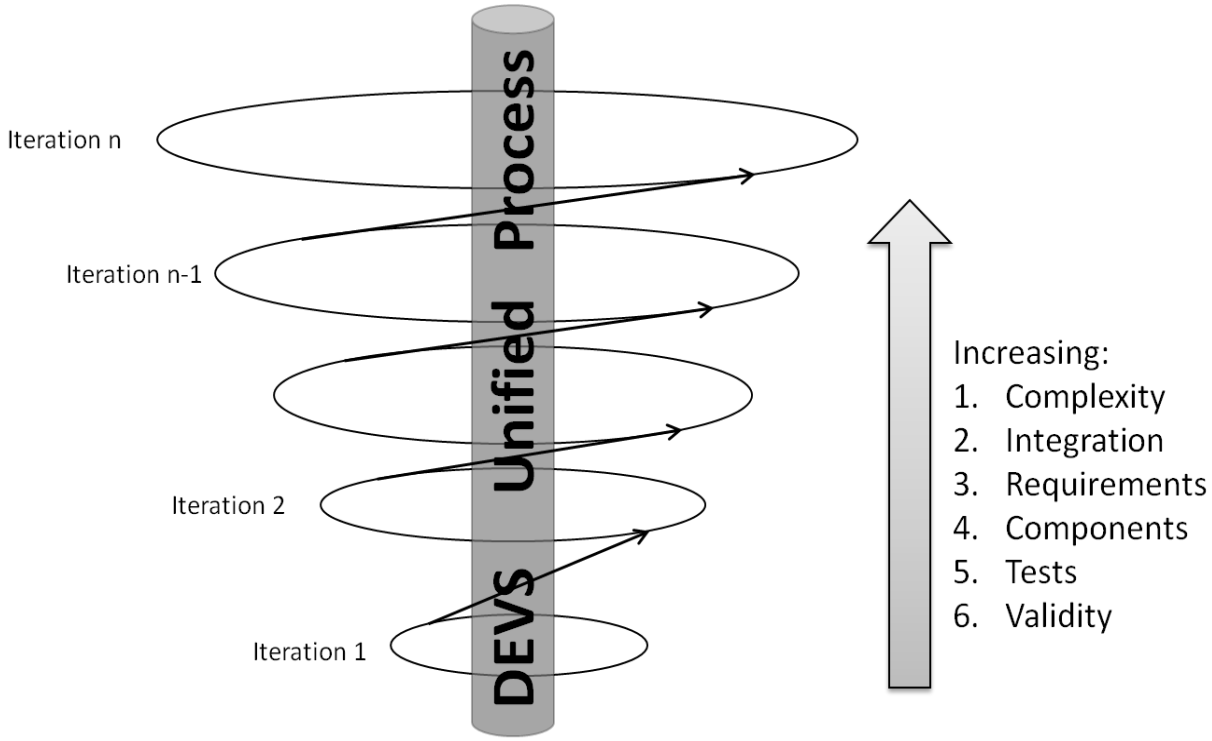
- Separation of Model and Simulator: a critical requirement
- Model develops abstractions and simulator executes a model
- The Abstraction chain, layered, hierarchy
- Model transformations
- Semantic anchoring
- Structure and Behavior



DEVSML Stack: Netcentric DEVS Virtual Machine



Spiral nature of DUNIP



RCIDS

Resource-constrained Complex Dynamical Intelligent systems

- Resource-constrained
  - Abstract notion of a limited resource (e.g. computational, energy, time, information, etc.)
- Complex
  - Presence of emergent behavior, irreducible to constituent components
- Dynamical
  - Temporal behavior, emergent response and stabilization periods
- Intelligent
  - The capacity of a system to process sensory input from the environment and act on the sensory input by processing the information to pursue a goal-oriented behavior.
- System
  - Conforms to Systems theory

Mittal, S., *Zeigler, B.P. (2014), Modeling attention switching in resource constrained complex intelligent dynamical systems (RCIDS), Symposium on Theory of M&S/DEVS, Spring Simulation Multi-conference, Tampa, FL*

Testing and Quality Assurance

- Relying on the underlying technologies
  - Black boxes
- Service Level Agreements
- Logging, Auditing and Instrumentation
- Timeliness
- Cross-cutting aspects
- However, that is after-the-fact!

- One possible approach
  - Model-based practices

Complex Natural systems

- Self-similar/fractal
- Complexity at each hierarchical level
- Information boundaries at each level
- Information transformation across levels
- Information sensed, processed, synthesized and actuated within each level
  - "Relevant" information crosses these boundaries
- How can this relevance be engineered in artificial systems?
- System "just-is". There is no intelligence here!!

(Barbasi 1993, Pinker 1997, Mittal 2012)