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BLUF (Bottom-Line Up Front)

• Uncertainties about SoS capabilities are inherently greater than just the “sum” of the uncertainties about the constituent systems
  – Unresolved or even undiscovered residual conflicts among Intended Uses (e.g., Missions) and Functions, even with well-engineered Interfaces
  – Unanticipated SoS operational environment impacts that were inconsequential to and ignored in the constituent systems
  – Composing SoS M&S from constituent systems’ M&S compounds their uncertainties

• SoS Testing restrictions drive increasing reliance on M&S to predict SoS capabilities

• SoS M&S engineering needs a deliberate process to design and invest in successive Test and M&S refinement for progressive Uncertainty Reduction and increasing confidence

• ISSAC’s SoS M&S engineering perspectives, Lessons Learned and Best Practices
New “UQ Perspective” of M&S Uncertainty and Risk Analysis

**M&S Input Uncertainties**

**Aleatoric Uncertainties**
*Known Unknowns*
- Properly have explicit Probability Distributions
- Irreducible

**Epistemic Uncertainties**
*Unknown Unknowns*
- Properly No Probability Distribution
- Reducible

**M&S Structural Uncertainties**

**M&S Outcome Uncertainties**
- Ranges
- Statistics
- Distributions

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History: UQ at Department of Energy

• DOE’s National Nuclear Security Admin
  – Since 2001
  – Participating laboratories

• Need: Confidence in M&S-based predictions
  – Treaty, Law, Affordability, Safety limit Testing
  – Shift from Test- to M&S-Based Confidence
  – Forced reliance on M&S of imperfectly modeled Physics
  – M&S Input and Software Uncertainties

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Compounding Uncertainties from Domain to Simulation of a Constituent System

Domain World
- Real and/or Envisioned Sol
- One real Operating Environment

Model World
- Sol and Operating Environment
- Boundaries & Exclusions
- Implementation-free

Simulation World
- Specific Algorithms
- Specific SW
- Specific HW

Uncontrollable Domain variations
- (e.g., weather, manufacturing, natural resource occurrence, competitor behavior, enemy tactics...)

Unknown physics, chemistry, composition...
- Model exclusions/inclusions from Sol
- Modeling choices (e.g., error term distribution in a regression...)

Algorithm errors (e.g., mesh sizes, random number correlation...)
- Software errors
- Hardware/network nondeterminism

Aleatoric Uncertainty
Epistemic Uncertainty
Model-Rooted Uncertainty
Software Uncertainty

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SoS M&S Further Compounds the Stacking Uncertainties in M&S-Based Capability Predictions

- Partially overlapping, interacting, interdependent Domains
- Common and independent business environment factors
- Partially correlated operating risks
- Incomplete joint business processes, conflicting priorities, conflicting SoI primary missions...
- Mismatched Simulation resolutions and fidelities
- Emergent errors from software composition
- Hardware/network nondeterminism
- Unanticipated emergent Model behaviors
- Conflicting semantics (SoI Model meanings)

Aleatoric Uncertainty
Epistemic Uncertainty
Model-Rooted Uncertainty
Software Uncertainty
Quantification of Margins & Uncertainties (QMU)

- **Motivation**
  - 1992 CNTBT→M&S reliance to certify Nuclear Stockpile Surety
  - Only past nuclear tests, nonnuclear experiments, judgments
- **Analytically codify confidence in compliant performance**

- **Uses by DOE NNSA**
  - Quantify confidence nuclear weapons will work
  - Identify risks
  - Prioritize research/engineering
  - Certification for Reliable Replacement Warhead (RRW)

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Performance \(\rightarrow\) Requirement

Uncertainty

\(\gg 1\)

- Example when Performance must exceed a threshold Requirement
  - "\(\gg\)" \(\Rightarrow\) "High" Confidence

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Example of QMU Involving Both Aleatoric and Epistemic UQ

- Each “S-curve” represents an Aleatoric UQ (e.g., Monte Carlo or Latin Hypercube Simulation of the AUs) for some EU combination; Simulation Optimization searches among EU combinations for left- and right-most S-curves at the Median (50th-percentile) level
- SoS M&S results (example values)
  - Median-Median % Negated: 83% (“horsetail” mid-point at 50th percentile)
  - Worst-Case Median % Negated: 80% (leftmost 50th percentile)
  - Best-Case Median % Negated: 85% (rightmost 50th percentile)
- Suppose the SoS performance requirement is 70% Threats Negated

\[ QMU = \frac{P-T}{U} = \frac{83-70}{85-80} = 2.6 \gg 1 \]
- Conclusion: Reasonable confidence in M&S prediction of SoS performance with respect to both AUs and EUs

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Process for Progressively Reducing Uncertainty in M&S-Based SoS Capability Predictions

M&S-Based UQ
- Convolution
- Propagation

M&S Outcome Uncertainties
- Ranges
- Statistics
- Distributions

M&S UQ Quality & Confidence
- Extreme Values/Out-of-Sample
- Confidence Intervals
- Quantification of Margins & Uncertainties (QMU)

SoS/Sol Test Program
- Test Campaign Plan
- Tests
- Parts vs End-to-End
- Limited vs Entire Operating Environment

QMU
- Convolution
- Bounding QMU Metrics

Expert Estimates
- Test Estimates

Uncertainty Reduction Investments

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Some Lessons Learned about M&S-Based Predictions of SoS Capability

• Fidelity Morass
  – Nagging, wrongful Stakeholder perception conferring undeserved Fidelity to Physics-Based M&S
  – A “wicked problem,” like the War on Poverty

• SoS M&S VV&A ≠ Merely demonstrating Syntactic Composition by the SoS M&S’s ability to execute each planned Scenario

• Failing to confront at least Semantic Composition almost guarantees a SoS M&S Incident Report

• Modeling Epistemic Uncertainties with probability distributions will introduce bias into estimates of best-/worst-case SoS capability performance

• Because it may generate many uninformative SoS M&S experiments, Statistical Design of Experiments is a costly, not necessarily effective approach to Epistemic Uncertainty Quantification
Some Best Practices for M&S-Based Predictions of SoS Capability (1 of 2)

• Caveat: Highly subjective and experiential to ISSAC 😊

• Commingling Effects-Based and Physics-Based M&S for Intended Use, Understanding, Performance and increased Fidelity

• For Semantic Composability, refactor Models, *not* Simulations

• Apply the Zeigler M&S Framework and use the Zeigler System Entity Structure (see Appendix)...
  – To describe the Domain and Semantics of the constituent systems
  – To help organize the constituents’ Domains and Semantics into those of the SoS
  – To illuminate and resolve the omissions and overlaps in the SoS Domain and Semantics
Some Best Practices for M&S-Based Predictions of SoS Capability (2 of 2)

• Use a tool like the ISSAC Elicitor™ (SBIR product) to discover and qualify Concepts, Relationships and M&S Requirements from its analysis of the constituents’ SE artifacts and Simulation Conceptual Models (see Appendix)

• Formally apply User Requirements Notation (URN; ITU Z.151) to identify architecturally significant requirements of SoS M&S resulting from Non-Functional Requirements (e.g., runtime performance, reliability, etc.); use in conjunction with Model-Based Systems Engineering with SysML

• UQ application
  – Use Interval Simulation and Simulation Optimization for EUQ
  – Use Metamodelling, sometimes with Optimization, to explore the EU space affordably and rapidly
  – Prescribe and follow a progressive Uncertainty Reduction process
  – Employ metrics for Quantification of Margins and Uncertainties
  – Invest in Test to improve confidence in SoS M&S-based capability predictions
Appendix
Zeigler M&S Framework Enables Model Refactoring for SoS M&S Integration

**Experimental Frame**
- Specification of conditions under which the System is observed or experimented with
- Objectives for modeling and analysis
- Measurement capability, “observer”
- Simulation database schema
- Components
  - **Generator** of inputs
  - **Acceptor** monitors execution, terminates run appropriately
  - **Transducer** observes and analyzes output
- May contain Models “outside” the subject System needed to support execution of Model Frame
- **Explicit rules for expressing an Experimental Frame in the Zeigler M&S Framework**

**Model Frame**
- Set of instructions, rules, equations, constraints for generating I/O behavior—all representative of the system under study
- **Inputs**
- **States**
- **State transitions**
- **Output**
- Definite, comprehensible, unambiguous semantics
- **Explicit rules for expressing a Model in the Zeigler M&S Framework**

**Simulator Frame**
- Agent capable of executing and generating behavior of Model as a set of instructions
- Independent of both Model and Experimental Frames
- **Correctly executes any Model and Experimental Frame constructed in accordance with the Zeigler M&S Framework**

**Legacy SoS M&S Architectures**
- Primarily reflect real SoS Architecture
- Do not align especially well to Zeigler M&S Framework
System Entity Structure is an Ontology of the Entire Family of Alternative Designs of a System-of-Systems
ISSAC’s Elicitor™

- The Elicitor™ is a tool for the ingestion, interpretation, analysis, deconfliction and exploration of concepts and needs and the fusion of data and information into knowledge and actionable knowledge.

- The Elicitor™ provides the identification and qualification of concepts, relationships and requirements based on the knowledge surrounding complex systems and SoSs.
Metamodeling with HASP

• Metamodeling is the process of creating models of models, or surrogate models

• Metamodeling comprises the analysis, construction and development of the frames, rules, constraints, models and theories applicable and useful for modeling a predefined class of problems

• Metamodeling with HASP, an ISSAC Elicitor component, provides a mechanism for the capture, analysis and exploitation of architectural notions, event flows, boundary conditions, SoS employment strategies, expert beliefs and behavioral constructs of constituent components – blending effects- and physics-based modeling and leveraging both aleatoric and epistemic uncertainty