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A Modeling and Simulation Strategy for Uncertainty Reduction in System-of-Systems Engineering

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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

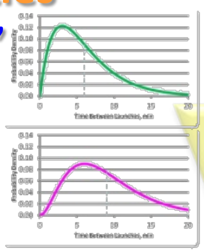
New "UQ Perspective" of M&S Uncertainty and Risk Analysis

M&S Input Uncertainties

Aleatoric Uncertainties

"Known Unknowns"

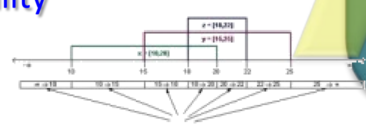
- Properly have explicit Probability Distributions
- Irreducible



Epistemic Uncertainties

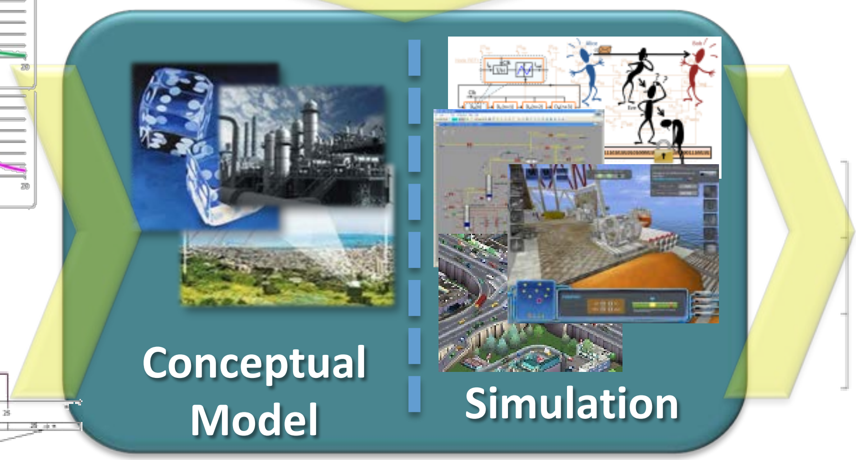
"Unknown Unknowns"

- Properly **No** Probability Distribution
- Reducible



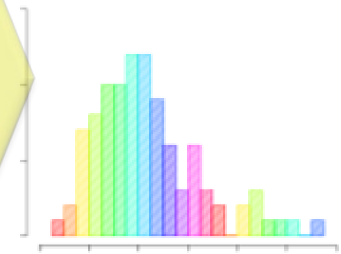
M&S Structural Uncertainties

Model-Rooted Uncertainties | **Software Uncertainties**



M&S Outcome Uncertainties

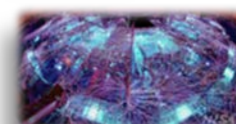
- Ranges
- Statistics
- Distributions



History: UQ at Department of Energy

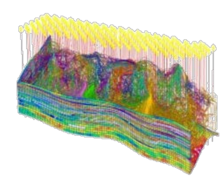
- DOE’s National Nuclear Security Admin
  - Since 2001
  - Participating laboratories
- Need: Confidence in M&S-based predictions
  - Treaty, Law, Affordability, Safety limit Testing

  - Shift from Test- to M&S-Based Confidence

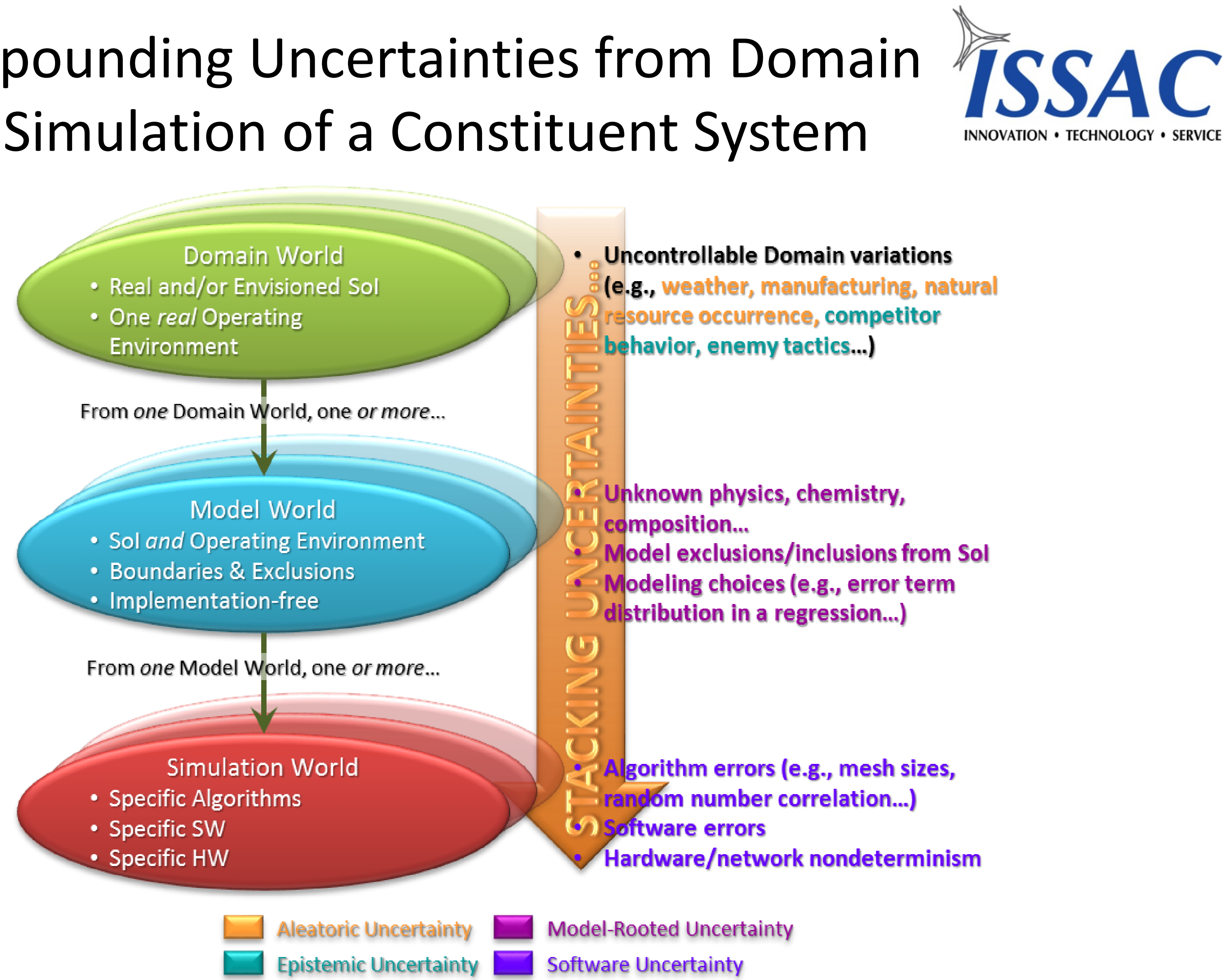


  - Forced reliance on M&S of imperfectly modeled Physics

  - M&S Input *and* Software Uncertainties



Compounding Uncertainties from Domain to Simulation of a Constituent System



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

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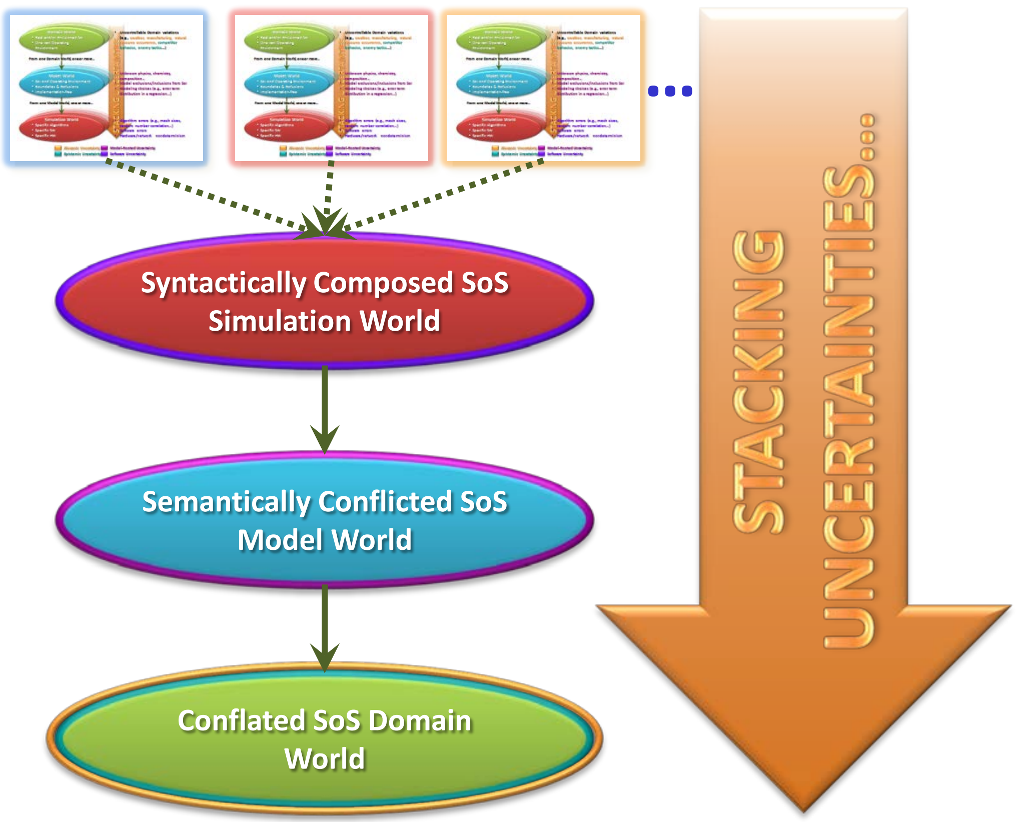

- Mismatched Simulation resolutions and fidelities
- Emergent errors from software composition
- Hardware/network nondeterminism

- Unanticipated emergent Model behaviors
- Conflicting semantics (SoI Model meanings)

- 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…

Aleatoric Uncertainty | Model-Rooted Uncertainty
Epistemic Uncertainty | Software Uncertainty

Quantification of Margins & Uncertainties (QMU)

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

Performance (M&S output) has uncertainty

Difference is *Margin*

Requirement *may* have uncertainty

$$\frac{Performance - Requirement}{Uncertainty} \gg 1$$

Uncertainty sums the (M&S output) uncertainties contributed by both Performance and Requirement

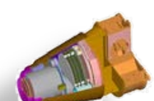
- Example when Performance must *exceed* a threshold Requirement
- ">>" ⇒ "High" Confidence

- Uses by DOE NNSA
  - Quantify confidence nuclear weapons will work

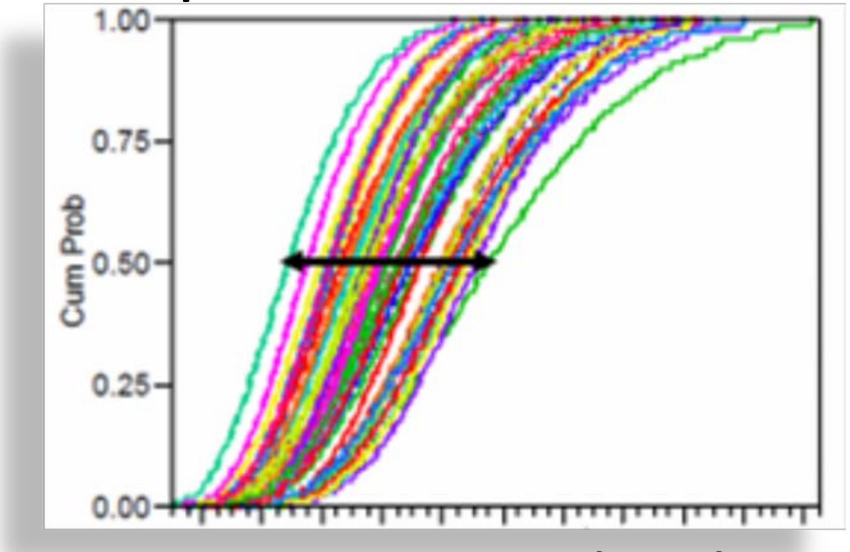
  - Identify risks

  - Prioritize research/engineering

  - Certification for Reliable Replacement Warhead (RRW)



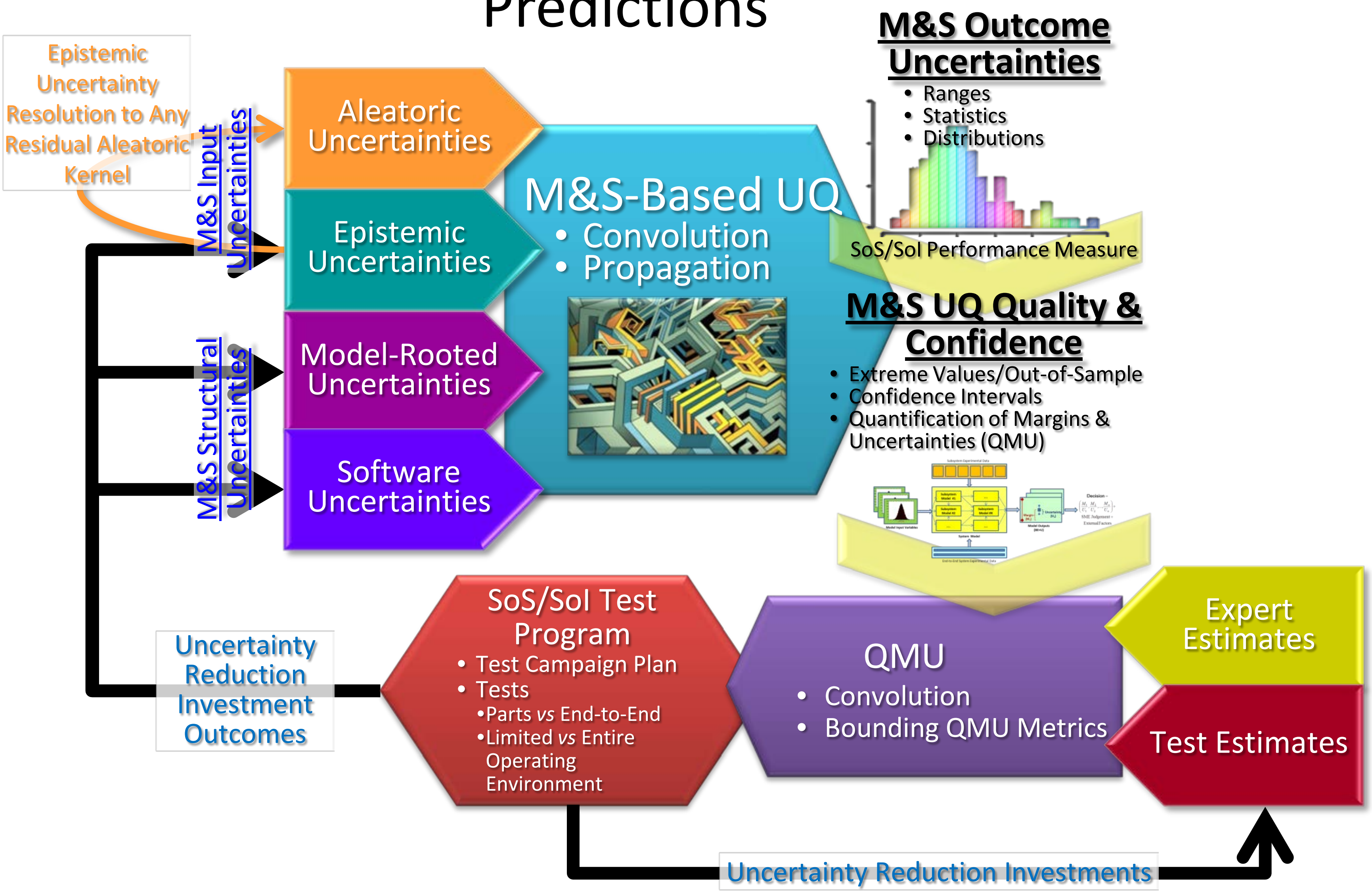
Example of QMU Involving Both Aleatoric and Epistemic UQ



% Threats Negated (MOE)

- 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 (50^{th}–percentile) level
- SoS M&S results (example values)
  - Median-Median % Negated: 83% ("horsetail" mid-point at 50^{th} percentile)
  - Worst-Case Median % Negated: 80% (leftmost 50^{th} percentile)
  - Best-Case Median % Negated: 85% (rightmost 50^{th} percentile)
- Suppose the SoS performance requirement is 70% Threats Negated
- $\boldsymbol{QMU = \frac{P-T}{U} = \frac{83-70}{85-80} = 2.6 \gg 1}$
- Conclusion: Reasonable confidence in M&S prediction of SoS performance with respect to both AUs and EUs

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



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 Metamodeling, 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

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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

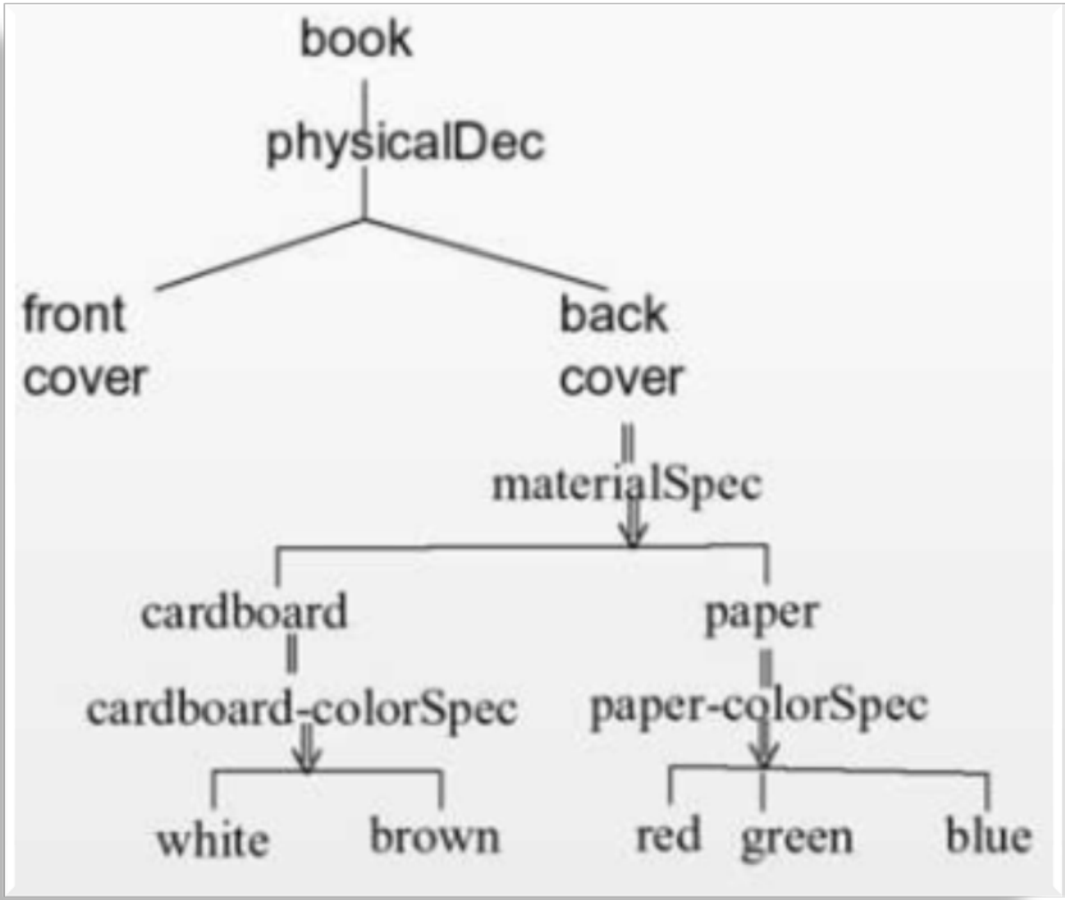
- **Set of instructions, rules, equations, constraints for generating I/O behavior—all representative of the system under study**
  - ❖**Inputs**
  - ❖**States**
  - ❖**State transitions**
  - ❖**Output**
- Definite, comprehensible, unambiguous semantics
- ***Explicit rules for expressing a Model in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

Simulator Frame

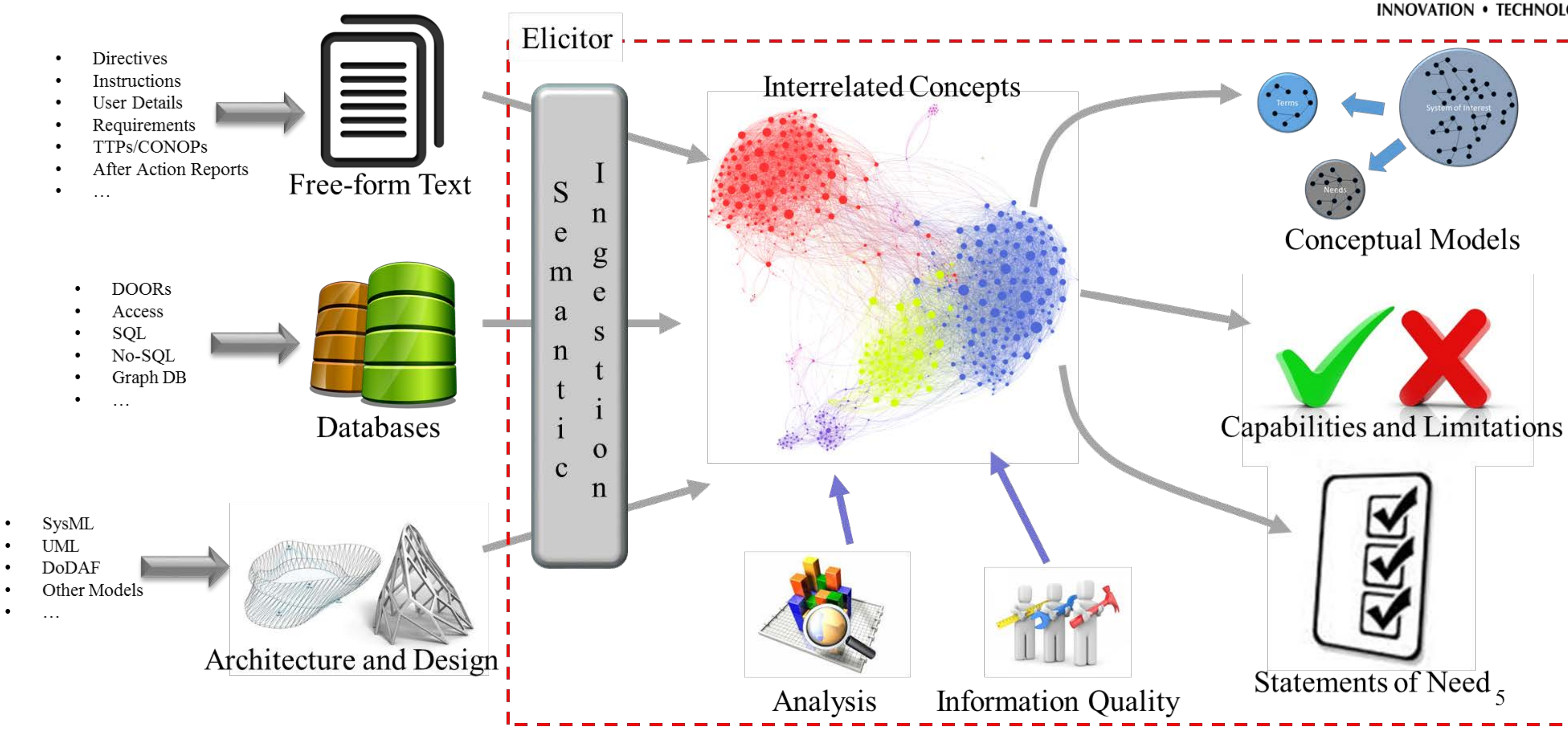
- **Agent capable of executing and generating behavior of Model as a set of instructions**
- Independent of both Model and Experimental Frames
- ***Correctly executes any Model and Experimental Frame constructed in accordance with the Zeigler M&S Framework***

- Legacy SoS M&S Architectures primarily reflect real SoS Architecture
- Legacy SoS M&S Architectures 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

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- 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