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Simulation Based Approaches for Systems Engineering

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Presentation outline

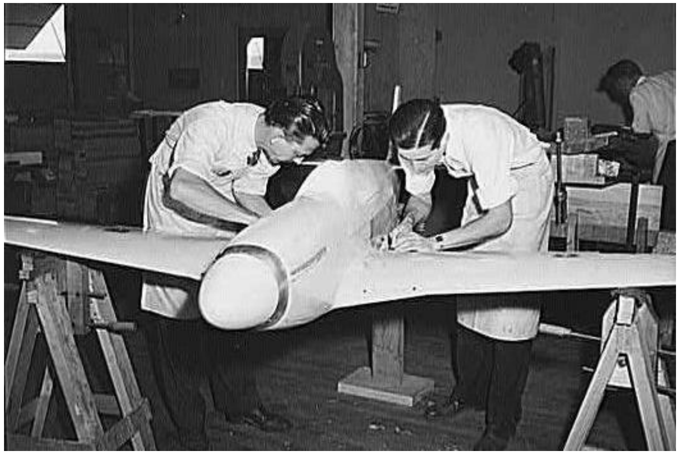
- Motivation and definitions
- Methodologies and tools
- Challenges from modeling and simulation
- Summary

Motivation and definitions

Models in engineering

$$h_s = \int_{T_1}^{T_2} c_P dt = \overline{c}_P (T_2 - T_1)$$

Mathematical model ~1895
Enthalpy or total heat
of superheated steam [1]



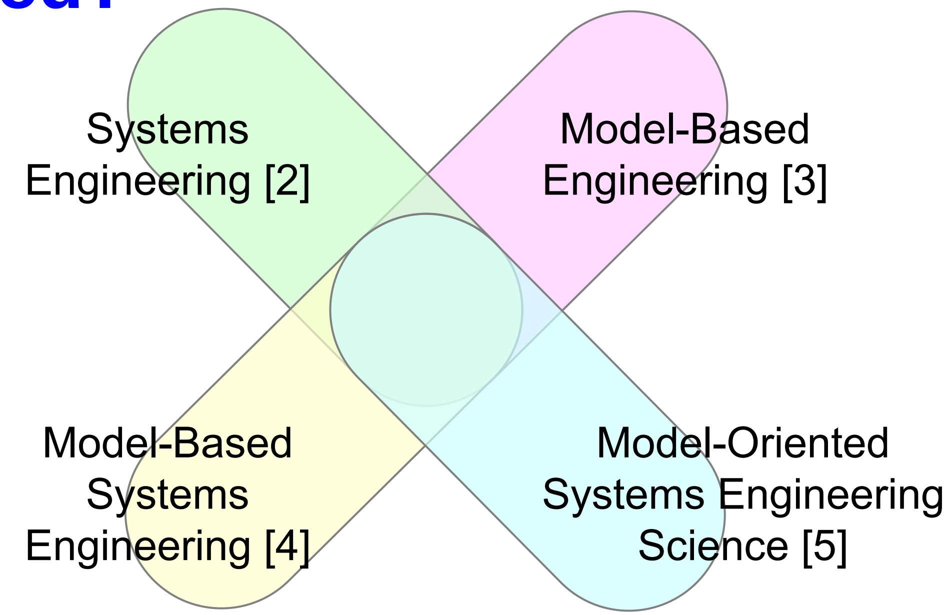
Physical model ~1942
Wind tunnel model
for P-51 Mustang

What's new?

- Complexity, scope, pervasiveness of models
- Dependence of process on models

[1] R. T. Kent, *Kent's Mechanical Engineers' Handbook: Power, Eleventh Edition*, John Wiley & Sons, New York NY, 1937.

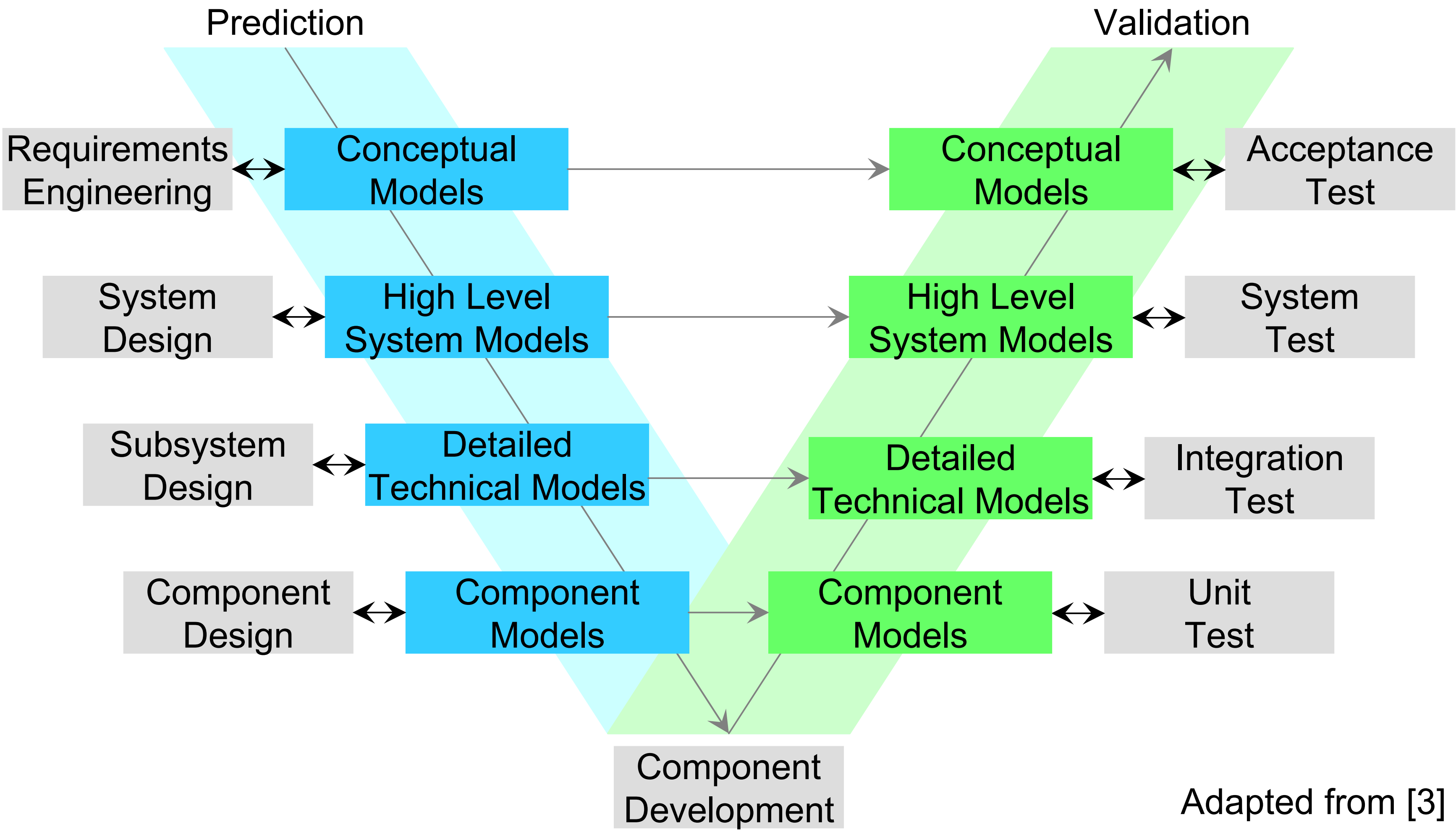
MBSE defined?



"Model-based systems engineering (MBSE) is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." [6]

[2] B. S. Blanchard and W. J. Fabrycky, *Systems Engineering and Analysis, Third Edition*, Prentice Hall, Upper Saddle River NJ, 1998.
[3] NDIA, *Final Report of the Model Based Engineering (MBE) Subcommittee*, NDIA Systems Engineering Division, M&S Committee, 2011.
[4] A. W. Wymore, *Model-Based Systems Engineering*, CRC Press, Boca Raton FL, 1993.
[5] D. W. Hybertson, *Model-Oriented Systems Engineering Science*, CRC Press, Boca Raton FL, 2009.
[6] INCOSE, *Systems Engineering Vision 2020*, INCOSE-TP-2004-004-02, Version 2.03, 2007.

MBSE "Vee"



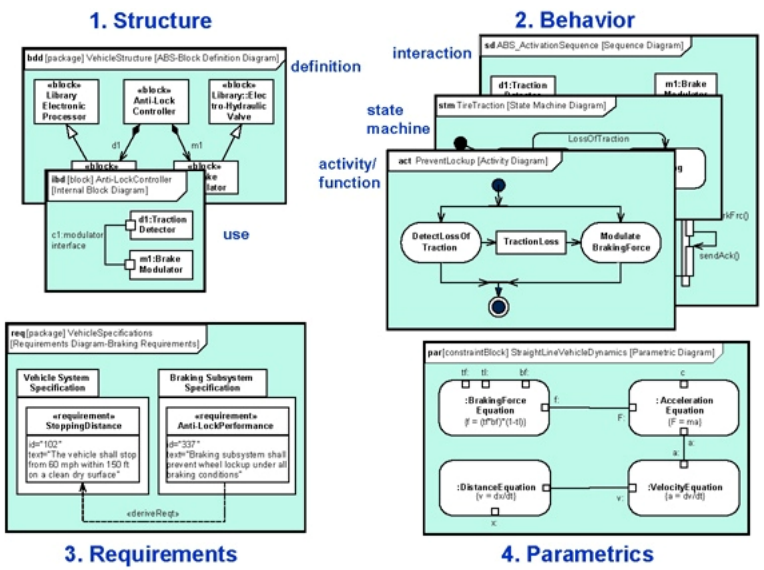
Adapted from [3]

Methodologies and tools [7]

[7] J. A. Estefan, *Survey of Model-Based Systems Engineering (MBSE) Methodologies*, INCOSE-TD-2007-003-02, Revision B, 2008.

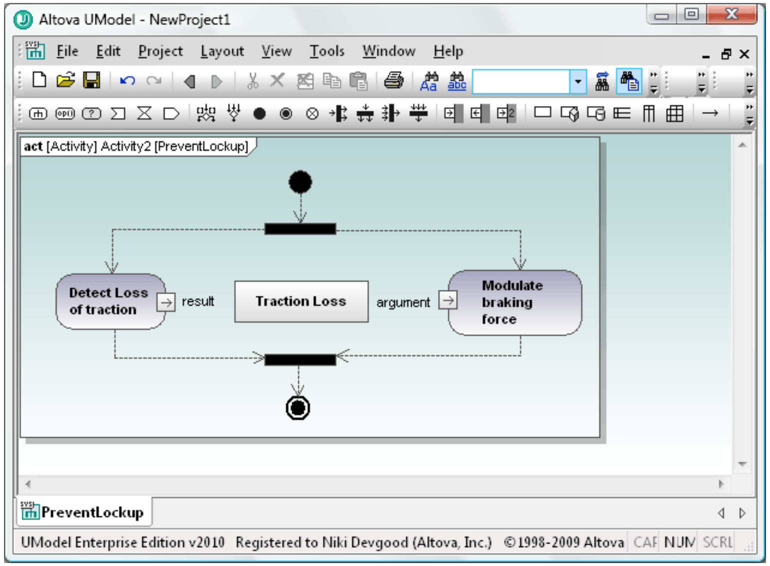
IBM Telelogic Harmony-SE

- Description
  - Systems and software engineering process
  - Process similar to “vee”
  - Repositories for requirements, models, test data
- Models and tools
  - OMG SysML models
  - Telelogic Rhapsody development environment
  - Telelogic Tau UML and SysML modeling tool



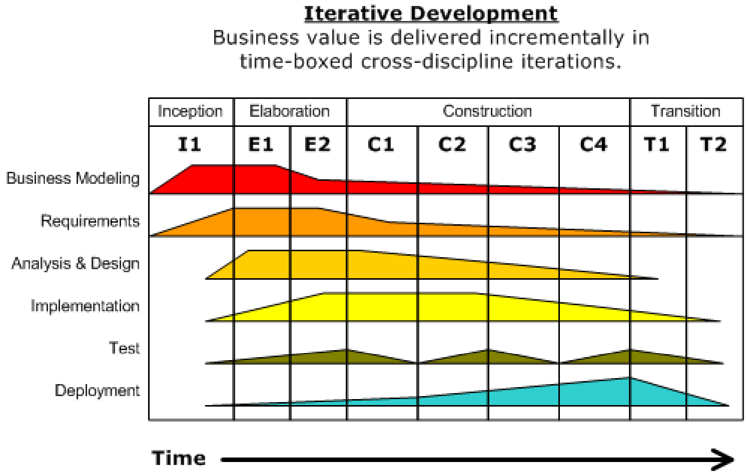
INCOSE Object-Oriented Systems Engineering Method

- Description
  - Top-down, model-driven process
  - Combines object-oriented concepts and classic SE process activities
- Models and tools
  - OMG SysML models
  - COTS SysML editors



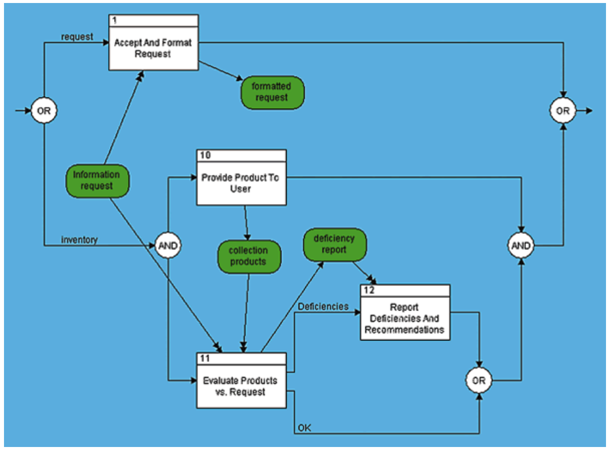
IBM Rational Unified Process for Systems Engineering

- Description
  - Process framework
  - RUP SE (systems) adapted for RUP (software)
  - Model viewpoints and levels define views
- Models and tools
  - OMG UML and SysML models
  - SE process framework tool as RUP SE plug in to Rational Method Composer



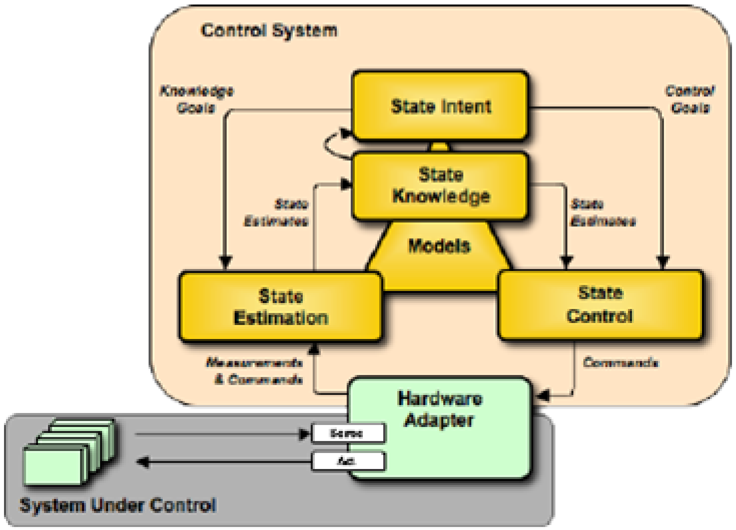
Vitech Model-Based System Engineering Methodology

- Description
  - Based on four conventional SE activities
  - Textual System Design Language expresses artifacts
  - Incremental SE process “onion model”
- Models and tools
  - Graphical system model diagrams
  - Integrated Vitech CORE tool set



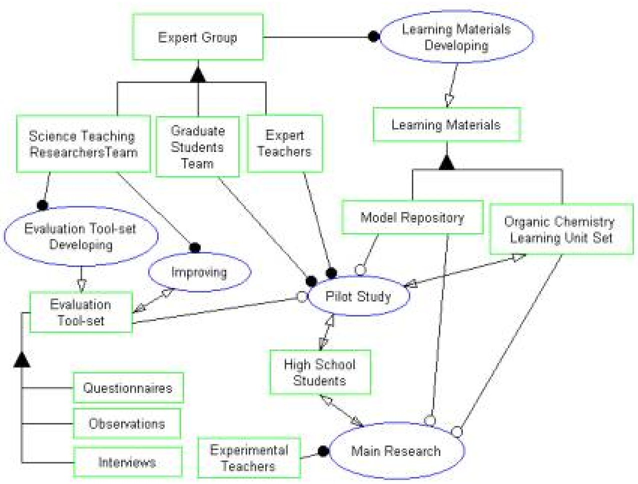
JPL State Analysis

- Description
  - System models describe system states over time
  - State: all system aspects of interest
  - Iterative process of state discovery and modeling
- Models and tools
  - State database, relational with SQL



Dori Object-Process Methodology

- Description
  - System function expressed with simple visual models
  - Basic concepts: object, process, state
  - Constrained natural language descriptions
- Models and tools
  - Object-Process Diagrams
  - Object-Process Language
  - OPCAT tool set



Challenges from modeling and simulation: Complex systems

Complex systems

"A system comprised of a (usually large) number of (usually strongly) interacting entities, processes, or agents, the understanding of which requires the development, or the use of, new scientific tools, nonlinear models, out-of equilibrium descriptions and computer simulations." [8]

"A complex system is one whose evolution is very sensitive to initial conditions or to small perturbations, one in which the number of independent interacting components is large, or one in which there are multiple pathways by which the system can evolve." [9]

Air traffic

Weather

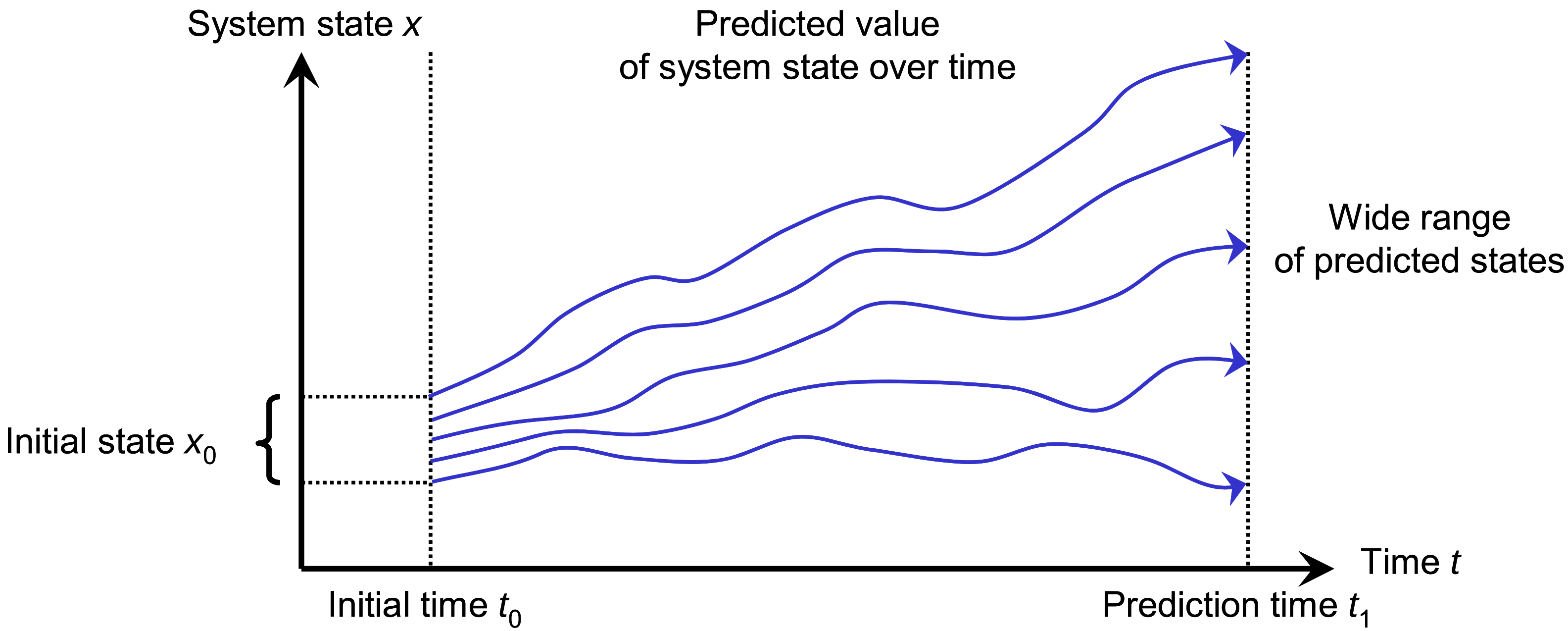
Stock market

[8] *Advances in Complex Systems*, http://www.worldscinet.com/acs/
[9] G. M. Whitesides and R. F. Ismagilov, "Complexity in Chemistry",*Science*, April 2 1999, Vol. 284 No. 5411, pp. 89-92.

Characteristics and challenges

- Defining characteristics
  - Sensitivity to initial conditions
  - Emergent behavior
  - Composition of components
  - Uncertain boundaries
  - Nesting
  - State memory
  - Non-linear
  - Feedback loops
- Challenges
  - Complex systems difficult to model
  - Models of complex systems difficult to validate

Sensitivity to initial conditions

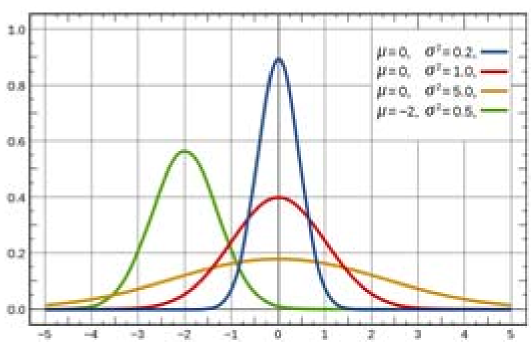


Complex systems evolution highly sensitive to initial state.
Small differences in state become magnified over time. [10]

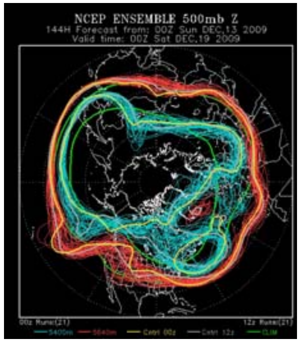
[10] L. Smith, *Chaos: A Very Short Introduction*, Oxford University Press, Oxford England, 2007.

Sensitivity to initial conditions

	Challenges	Mitigation
Modeling	• Implementation side effects • Sensitivity consistency • Input data precision	• Ensemble forecasting [10]
Validation	• Broad results distributions [11] • Input data precision	• Increased trials • Sensitivity analysis [12] • Precision compensation



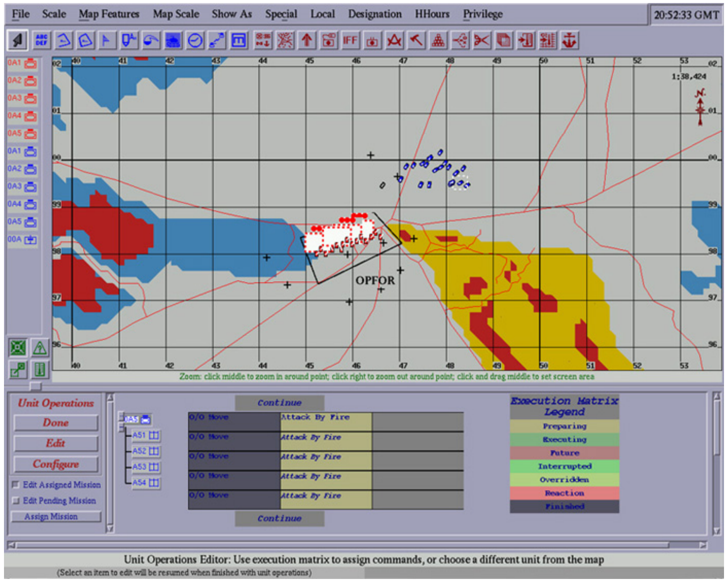
Distributions



Ensemble forecasting

[11] C. H. Brase and C. P. Brase, *Understandable Statistics: Concepts and Methods*, Houghton Mifflin, Boston MA, 2009.
[12] O. Balci, “Verification, Validation, and Testing”, in J. Banks (Ed.), *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, New York NY, 1998, pp. 335-393.

Emergent behavior



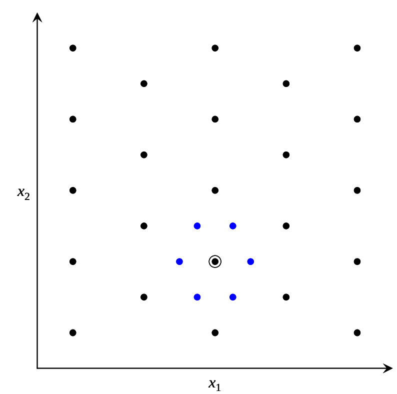
Behavior not explicitly encoded in agents or components emerges from interaction of agents or components with each other and environment. [13]

[13] G. Williams, *Chaos Theory Tamed*, Joseph Henry Press, Washington DC, 1997.

Emergent behavior

	Challenges	Mitigation
Modeling	• Incomplete observation • Indirect representation • Overabstraction	• Increased observation • Explicit modeling focus
Validation	• Face validation unreliability • Test case design	• Structured face validation [14] • Scenario space search

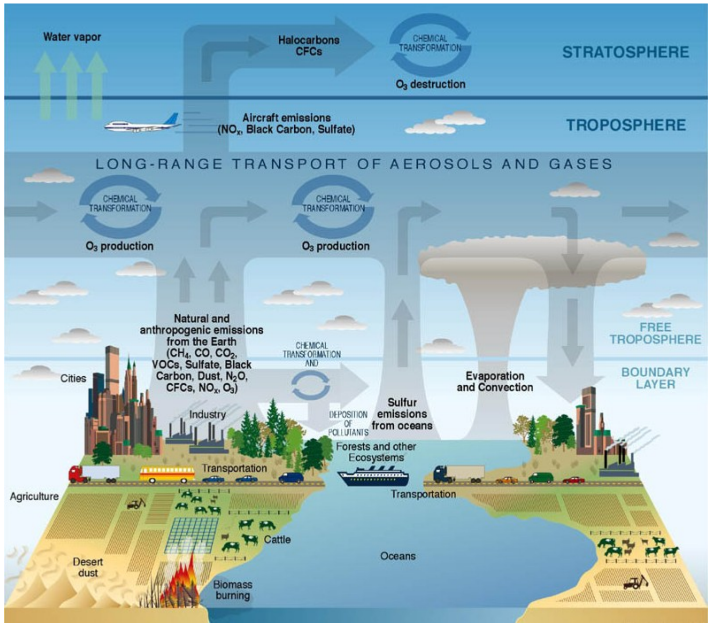
Face validation unreliability



Scenario space search

[14] G. Rowe and G. Wright, "Expert Opinions in Forecasting: Role of the Delphi Technique", in J. Armstrong (Ed.), *Principles of Forecasting: A Handbook for Researchers and Practitioners*, Kluwer, Boston MA, 2001.

Composition of components



Complex systems composed of interacting components.
Models of complex systems composed of submodels.

Composition of components

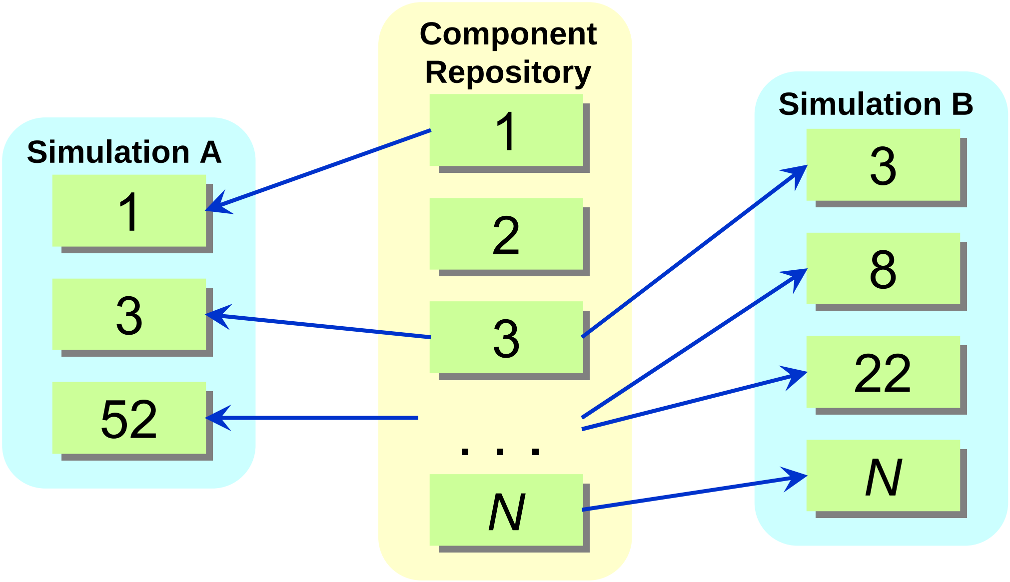
	Challenges	Mitigation
Modeling	• Interface compliance • Architecture selection [15] • Model correlation [16]	• Interface analysis [17] • Conceptual model comparison • Known problems [18]
Validation	• Weakest link validity • Error location • Statistical method unsuitability • Validity under composition [19]	• Uncertainty estimation [20] • Multivariate statistics [21] • Composition validation

[15] M. Shaw and D. Garlan, *Software Architecture, Perspectives on an Emerging Discipline*, Prentice Hall, Upper Saddle River NJ, 1996.
[16] M. Spiegel, P. F. Reynolds, D. C. Brogan, "A Case Study of Model Context for Simulation Composability and Reusability", *Proceedings of the 2005 Winter Simulation Conference*, Orlando FL, December 4-7 2005, pp. 437-444.
[17] O. Balci, "Verification, Validation, and Testing", in J. Banks (Ed.), *Handbook of Simulation: Principles, Methodology, Advances, Applications, and Practice*, John Wiley & Sons, New York NY, 1998, pp. 335-393.
[18] D. Gross and W. V. Tucker, "A Foundation for Semantic Interoperability", *Proceedings of the Fall 2007 Simulation Interoperability Workshop*, Orlando FL, September 16-21 2007.
[19] E. W. Weisel, R. R. Mielke, and M. D. Petty, "Validity of Models and Classes of Models in Semantic Composability", *Proceedings of the Fall 2003 Simulation Interoperability Workshop*, Orlando FL, September 14-19 2003, pp. 526-536.
[20] W. L. Oberkampf, S. M. DeLand, B. M. Rutherford, K. V. Diegart, and K. F. Alvin, *Estimation of Total Uncertainty in Modeling and Simulation*, Sandia National Laboratories, SAND2000-0824, April 2000.
[21] O. Balci and R. Sargent, "Validation of simulation models via simultaneous confidence intervals", *American Journal of Mathematical and Management Science*, Vol. 4, No. 3-4, 1984, pp. 375-406.

Challenges from modeling and simulation: Model composition

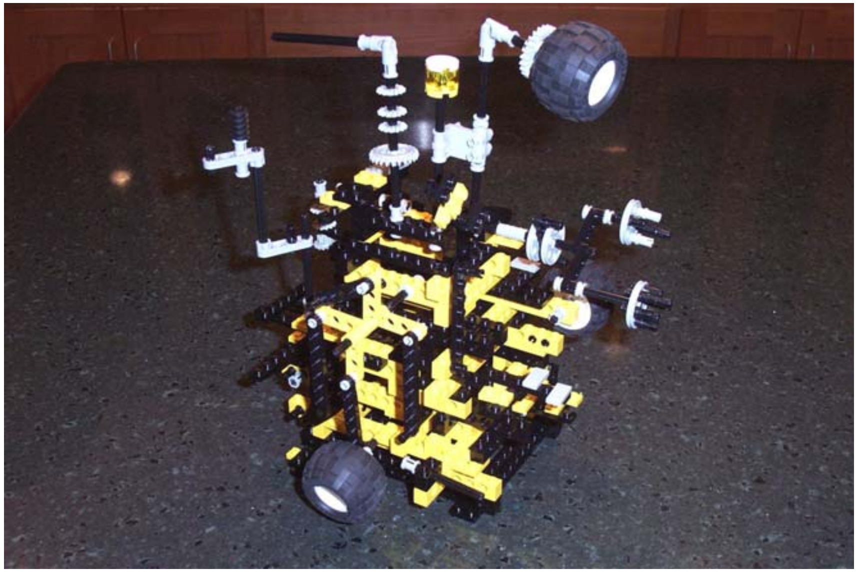
Composability

Composability. The capability to select and assemble simulation components in various combinations into simulation systems to satisfy specific user requirements. [22]



[22] M. D. Petty and E. W. Weisel, "A Composability Lexicon", *Proceedings of the Spring 2003 Simulation Interoperability Workshop*, Orlando FL, March 30-April 4 2003, pp. 181-187.

Syntactic and semantic composability



Syntactic composability
The components fit together.

Semantic composability
The components fit together in a meaningful way.

Validity under composition [23]

- Compositions of valid models considered for classes of models and validity relations
- Classes of models
  - Linear
  - Affine
  - Algebraic
  - Elementary
  - Computable
- Classes of validity relations
  - Equivalence
  - Step metric
  - Trajectory metric

[23] E. W. Weisel, R. R. Mielke, and M. D. Petty, “Validity of Models and Classes of Models in Semantic Composability”, *Proceedings of the Fall 2003 Simulation Interoperability Workshop*, Orlando FL, September 14-19 2003, pp. 526-536.

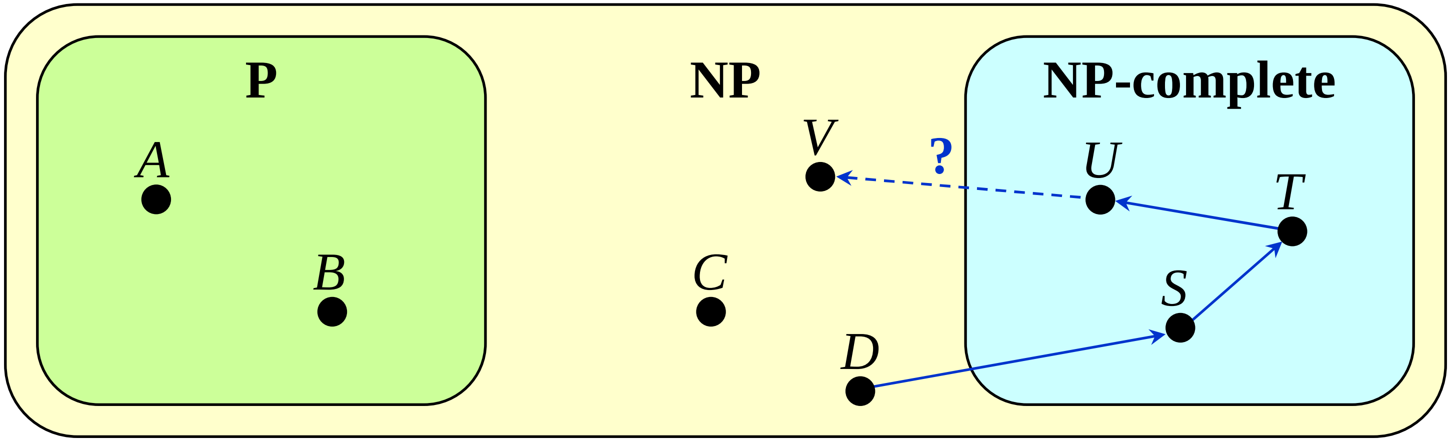
Given two models, separately valid under some validity relation, is their composition necessarily valid under the same validity relation?

Validity relation	**Model**				
	Linear	Affine	Algebraic	Elementary	Computable
Equivalence	Yes	Yes	Yes	Yes	Yes
Step metric	Yes	Yes	No	No	No
Trajectory metric	Conditional	Conditional	No	No	No

Most useful models here

NP-completeness theory, in a nutshell

- Classes of problems
  - P: solvable in polynomial time
  - NP: not solvable in polynomial time?
  - NP-complete: as hard as every NP problem
- To prove a problem is NP-complete, show that solving it solves a known NP-complete problem
- NP-complete problems computationally intractable



Selecting models to compose is NP-complete

Variants of **Component Selection**	Non-emergent	Emergent	Anti-emergent
Bounded	NP-complete [24]	NP-complete	NP-complete
Unbounded	NP-hard	NP-hard	NP-hard

General **Component Selection**

NP-hard, NP-complete with oracle [25]

[24] E. H. Page and J. M. Opper, "Observations on the Complexity of Composable Simulation", *Proceedings of the 1999 Winter Simulation Conference*, Phoenix AZ, December 5-8 1999, pp. 553-560.
[25] M. D. Petty, E. W. Weisel, and R. R. Mielke, "Computational Complexity of Selecting Models for Composition", *Proceedings of the Fall 2003 Simulation Interoperability Workshop*, Orlando FL, September 14-19 2003, pp. 517-525.

Summary

Summary

- Systems engineering depends on models
  - Models have always been used in engineering
  - MBSE is applied modeling
- MBSE methodologies and tools
- Challenges from M&S may impact MBSE

End notes

- More information
  - Mikel D. Petty, Ph.D.
  - UAHuntsville Center for Modeling, Simulation, and Analysis
  - 256-824-4368, pettym@uah.edu
- Slides: http://cmsa.uah.edu/?downloads
- Questions?

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