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Modeling and Validation Challenges for Complex Systems

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Presentation outline

- Background definitions
  - Complex systems
  - Modeling
  - Validation
- Modeling and validation challenges
  - Sensitivity to initial conditions
  - Emergent behavior
  - Component model composition
- Summary

Practical suggestions on developing and building models of complex systems; not theoretical limits of predictability of complex systems using models.

Background definitions

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." [1]

"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." [2]

Air traffic

Weather

Stock market

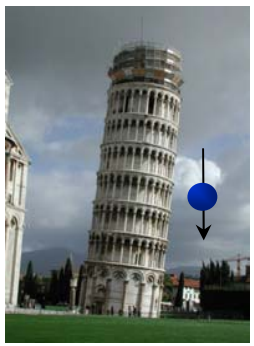
[1] *Advances in Complex Systems*, http://www.worldscinet.com/acs/
[2] G. M. Whitesides and R. F. Ismagilov, "Complexity in Chemistry",*Science*, April 2 1999, Vol. 284 No. 5411, pp. 89-92.

Characteristics of complex systems

- Defining characteristics
  - Sensitivity to initial conditions
  - Emergent behavior
  - Composition of components
  - Uncertain boundaries
  - Nesting
  - State memory
  - Non-linear
  - Feedback loops
  - . . .
- Any specific characteristic arguable

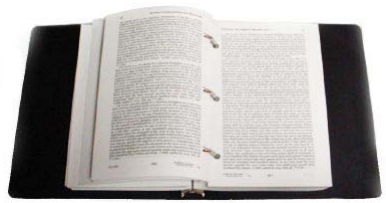
Modeling [3]

Simuland



Referent

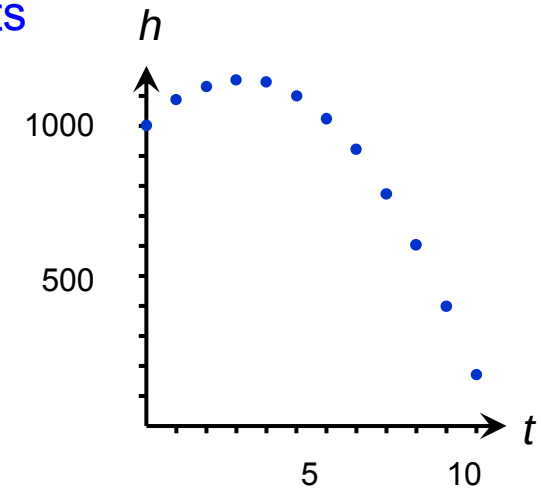
Observation



t	*h*
0	1000
1	1084
2	1136
3	1156
4	1144
5	1100
6	1024
7	916
8	776
9	604
10	400
11	164

Modeling

Results



Simulation

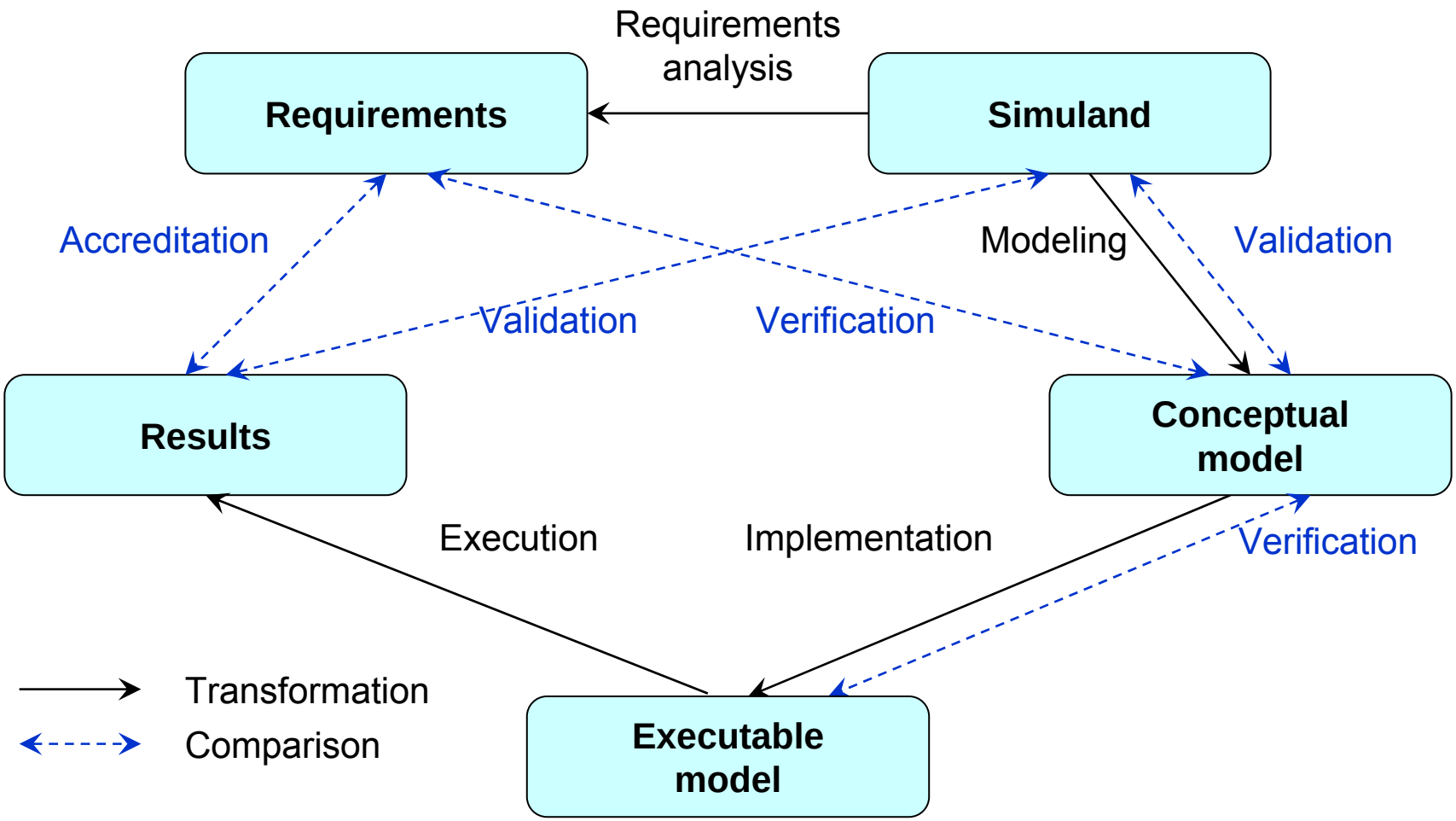
Model

$$h(t) = -16t^2 + vt + s$$

```
/* Height of an object moving in gravity.  */
/* Initial height v and velocity s constants. */
main()
{
  float h, v = 100.0, s = 1000.0;
  int t;
  for (t = 0, h = s; h >= 0.0; t++)
  {
    h = (-16.0 * t * t) + (v * t) + s;
    printf("Height at time %d = %f\n", t, h);
  }
}
```

[3] M. D. Petty, "Verification and Validation", in J. A. Sokolowski and C. M. Banks (Editors), *Principles of Modeling and Simulation: A Multidisciplinary Approach*, John Wiley & Sons, Hoboken NJ, 2009, pp. 121-149.

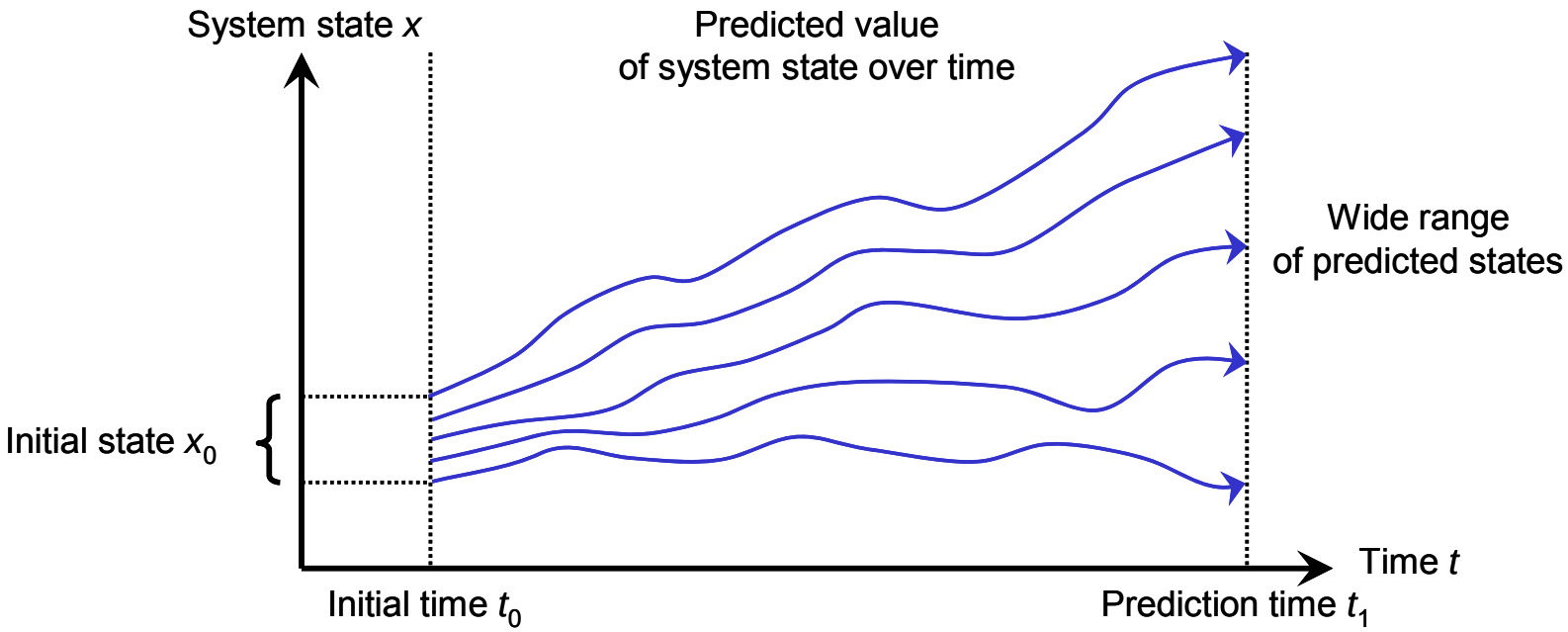
Validation [4]



[4] M. D. Petty, "Verification and Validation", in J. A. Sokolowski and C. M. Banks (Editors), *Principles of Modeling and Simulation: A Multidisciplinary Approach*, John Wiley & Sons, Hoboken NJ, 2009, pp. 121-149.

Modeling and validation challenges

Sensitivity to initial conditions: Description

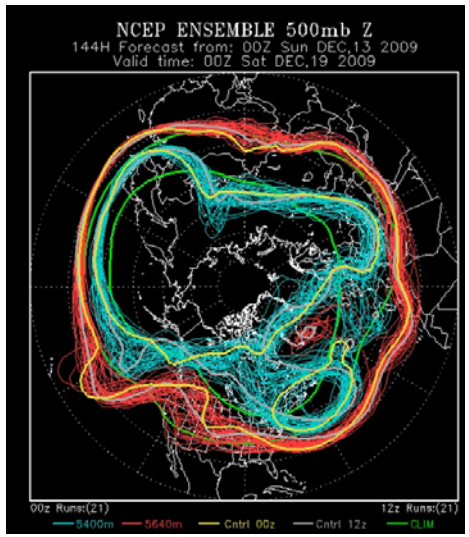


Complex systems evolution highly sensitive to initial state. Small differences in state become magnified over time. [5]

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

Sensitivity to initial conditions: Modeling

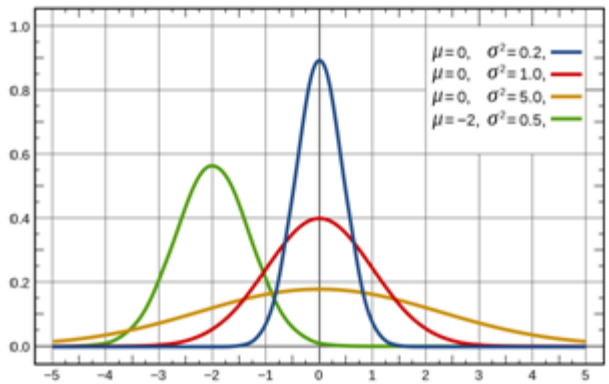
- Challenges
  - Model implementation side effects
  - Sensitivity consistency
  - Input data precision
- Mitigation methods
  - Ensemble forecasting [6]



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

Sensitivity to initial conditions: Validation

- Challenges
  - Broad results distributions [7]
  - Input data precision
- Mitigation methods
  - Increased trials
  - Sensitivity analysis [8]
  - Observation precision compensation



[7] C. H. Brase and C. P. Brase, *Understandable Statistics: Concepts and Methods*, Houghton Mifflin, Boston MA, 2009.
[8] 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.

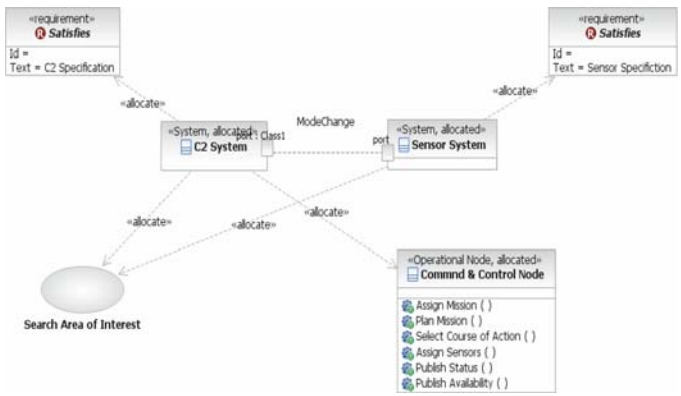
Emergent behavior [9]

Behavior not explicitly encoded in agents or components. Emerges from interaction of agents or components with each other and environment.

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

Emergent behavior: Modeling

- Challenges
  - Incomplete simuland observation
  - Indirect representation
  - Abstraction risk
- Mitigation methods
  - Increase simuland observations
  - Explicit conceptual model focus

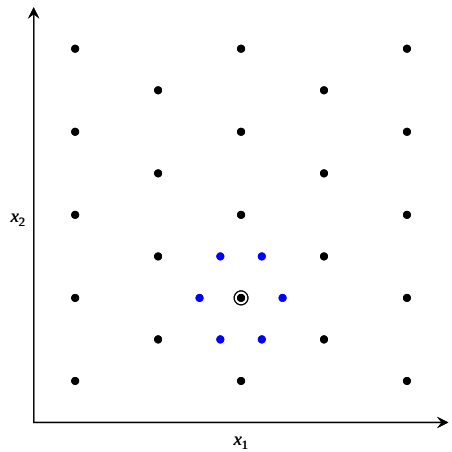


[10]

[10] J. S. Strickland, "Conceptual Modeling for an End-to-End C4ISR Systems Experiment Model", *AMSC Workshop on Conceptual Modeling*, Huntsville AL, October 26 2007.

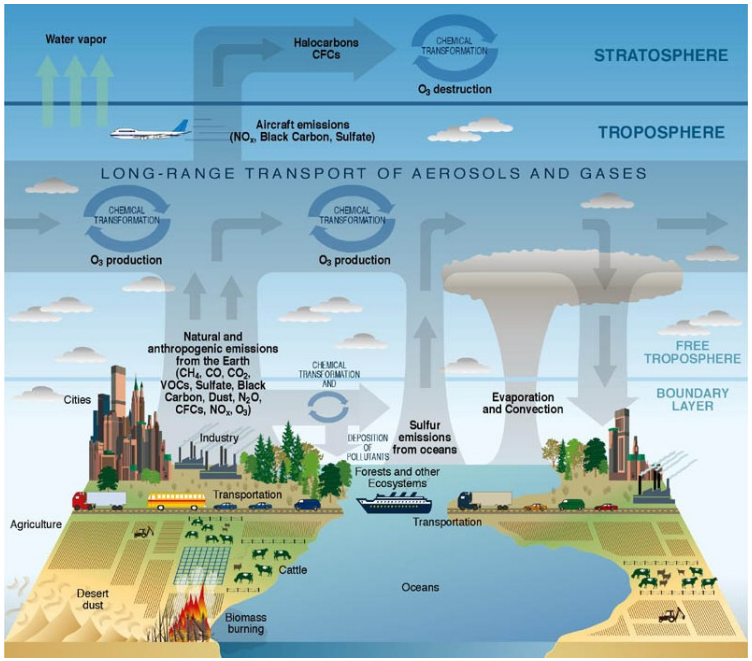
Emergent behavior: Validation

- Challenges
  - Face validation unreliability
  - Test case design
- Mitigation methods
  - Structured face validation [11]
  - Heuristic search in scenario space



[11] 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.

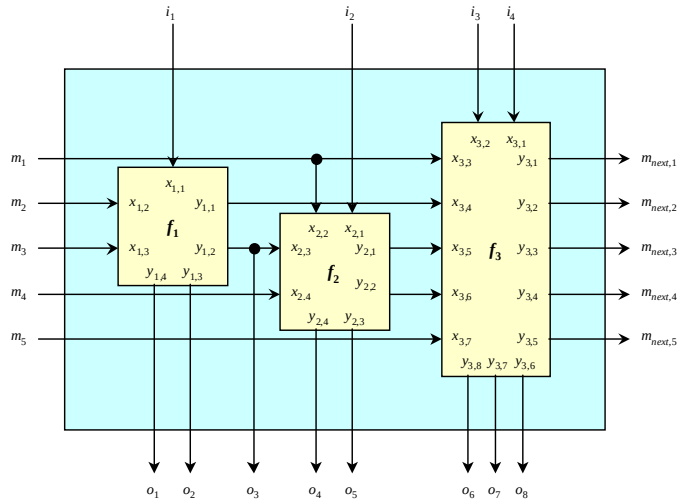
Composition of components



Complex systems composed of interacting components.
Complex system models composed of submodels.

Composition of components: Modeling

- Challenges
  - Interface compliance
  - Architecture selection [12]
  - Model correlation [13]
- Mitigation methods
  - Interface analysis [14]
  - Conceptual model comparison
  - Known interoperability problems [15]



[12] M. Shaw and D. Garlan, *Software Architecture, Perspectives on an Emerging Discipline*, Prentice Hall, Upper Saddle River NJ, 1996.

[13] 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.

[14] 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.

[15] 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.

Composition of components: Validation

- Challenges
  - Weakest link validity
  - Error location
  - Unsuitability of conventional statistics
  - Validity under composition [16]
- Mitigation methods
  - Uncertainty estimation [17]
  - Non-linear multivariate statistics [18]
  - Component and composition validation

[16] 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.
[17] 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.
[18] 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.

Summary

Summary

- Complex systems have defining characteristics
- These characteristics create challenges
  - Modeling
  - Validation
- Mitigation methods available for each

End notes

- More information
  - Mikel D. Petty, Ph.D.
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  - 256-824-4368, pettym@uah.edu
- Slides: http://cmsa.uah.edu/?downloads
- Questions?