On Modeling and Simulation Methods for Capturing Emergent Behaviors for Systems of Systems

S. Balestrini-Robinson
Research Engineer
Georgia Institute of Technology
Atlanta, GA 30332
santiago.balestrini@asdl.gatech.edu

J. M. Zentner
Research Engineer
Georgia Institute of Technology
Atlanta, GA 30332
zentner@gatech.edu

T. R. Ender
Research Engineer
Georgia Institute of Technology
Atlanta, GA 30332
tommer@gatech.edu

12th Annual Systems Engineering Conference
National Defense Industrial Association

October 26-29, 2009
San Diego, CA

Georgia Institute of Technology

The Need for Modeling and Simulation

- System-of-Systems Engineering (SOSE) problems require a different approach than traditional Systems Engineering (SE)
- Good Modeling and Simulation is crucial to good Decision Making
  - Good decisions are based on good analysis
  - Analysis is based on models
- If models are not appropriate→ analysis will not be insightful→ decisions will not be sound

Definitions

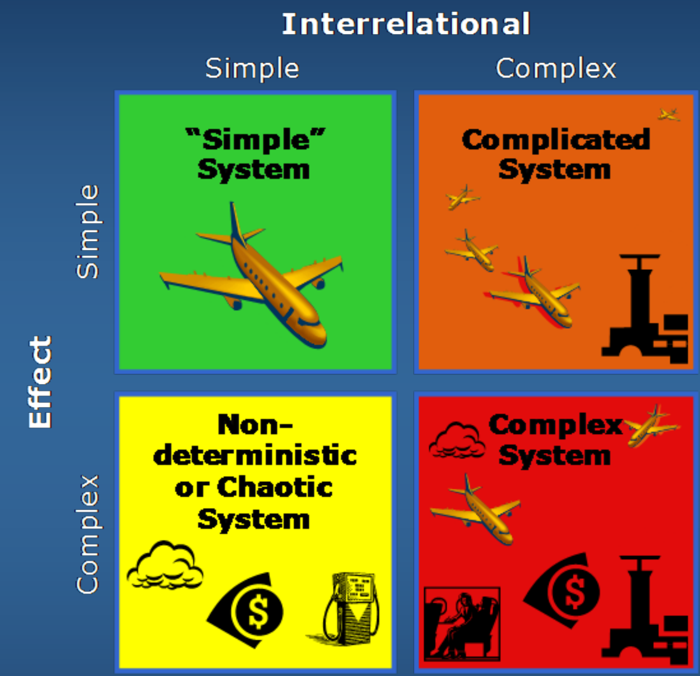
- System: a collection of components organized to accomplish a specific function or set of functions (IEEE)
- System-of-Systems: “a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities” [DoD Def. Acq. Guidebook 2004]
    - Emergent behavior, Evolutionary Development, Operational Independence of the Elements, Managerial Independence of the Elements, Geographic Distribution [Maier1996]

Definitions

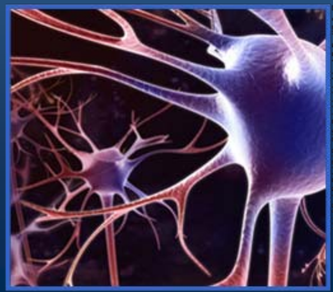
- Emergence
  - Macro level behaviors (patterns) that cannot be predicted from studying the micro level behaviors in isolation
- Complex Systems
  - Systems composed of a (1) large number of entities, with (2) non-trivial interaction networks (not too simple or too complete) , whose (3) impacts on one another are non-linear, and whose overall behavior tends to display emergent characteristics
- Modeling & Simulation
  - Model: An abstract representation of a system developed to aid in the understanding and/or predicting of its behavior.
  - Modeling: A rigorous method for creating and testing models.
  - Simulation: The exercise--either statistically or over time--of a model.

What is a Complex System?

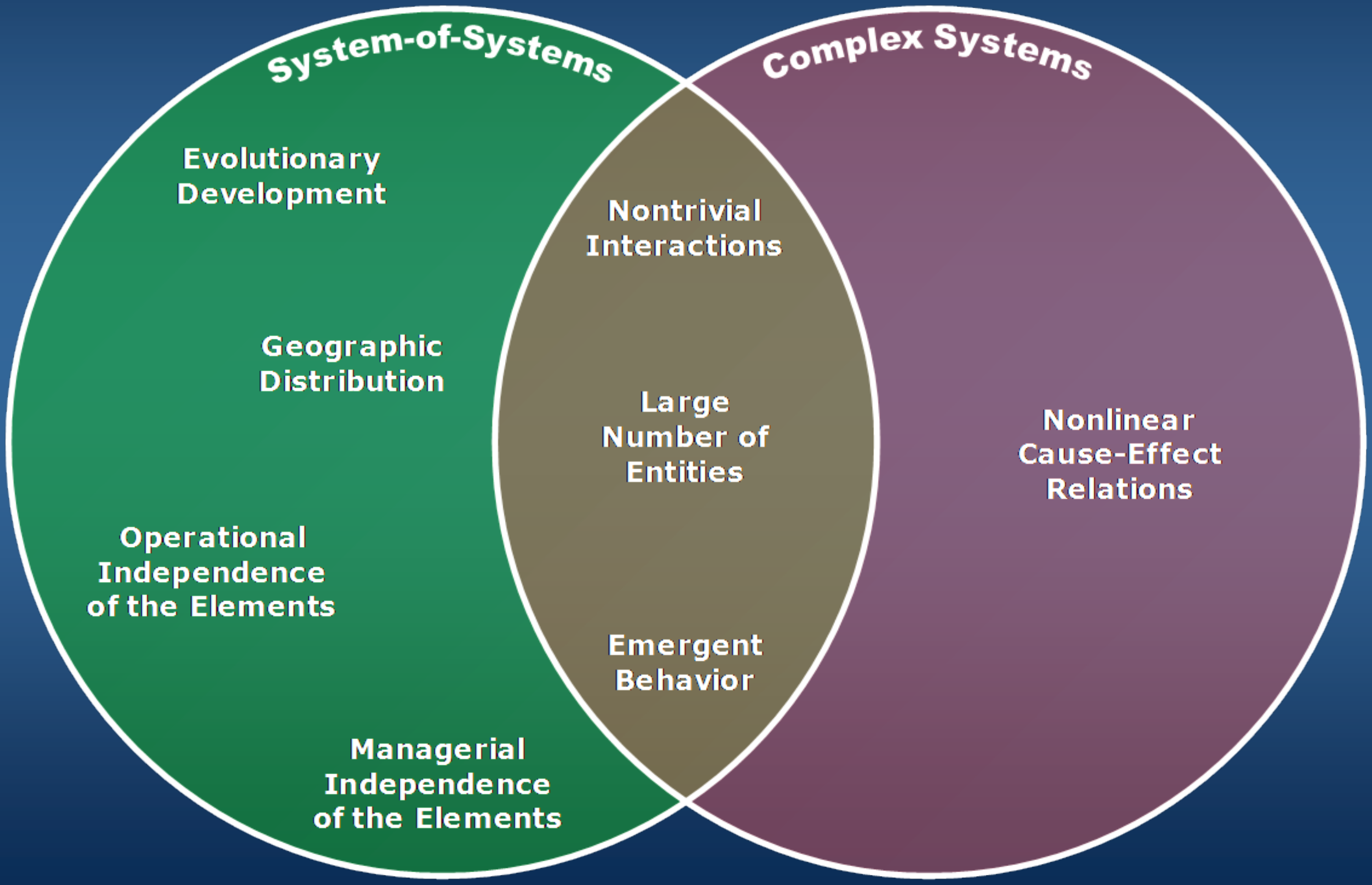
- “A whole comprehending in its compass a number of parts, *esp.* (in later use) of interconnected parts or involved particulars; a complex or complicated whole” [Oxford English Dictionary]
- Definition (Interrelational)
  - A system composed of
    - a large number of (heterogeneous) entities
    - interacting nonlinearly
    - of the parts through non-trivial networks
    - which produce a macro-level pattern that cannot be inferred from the analysis in isolation
- Definition (Effect)
  - “A measure of uncertainty in understanding what it is we want to know or in achieving a functional requirement” [Suh2005]
- “It is exceedingly difficult to discern causality in a complex system from observation alone… Researchers must watch a very large number of [events] before the patterns become evident” [Cares2005]




Source: www.sciencedaily.com

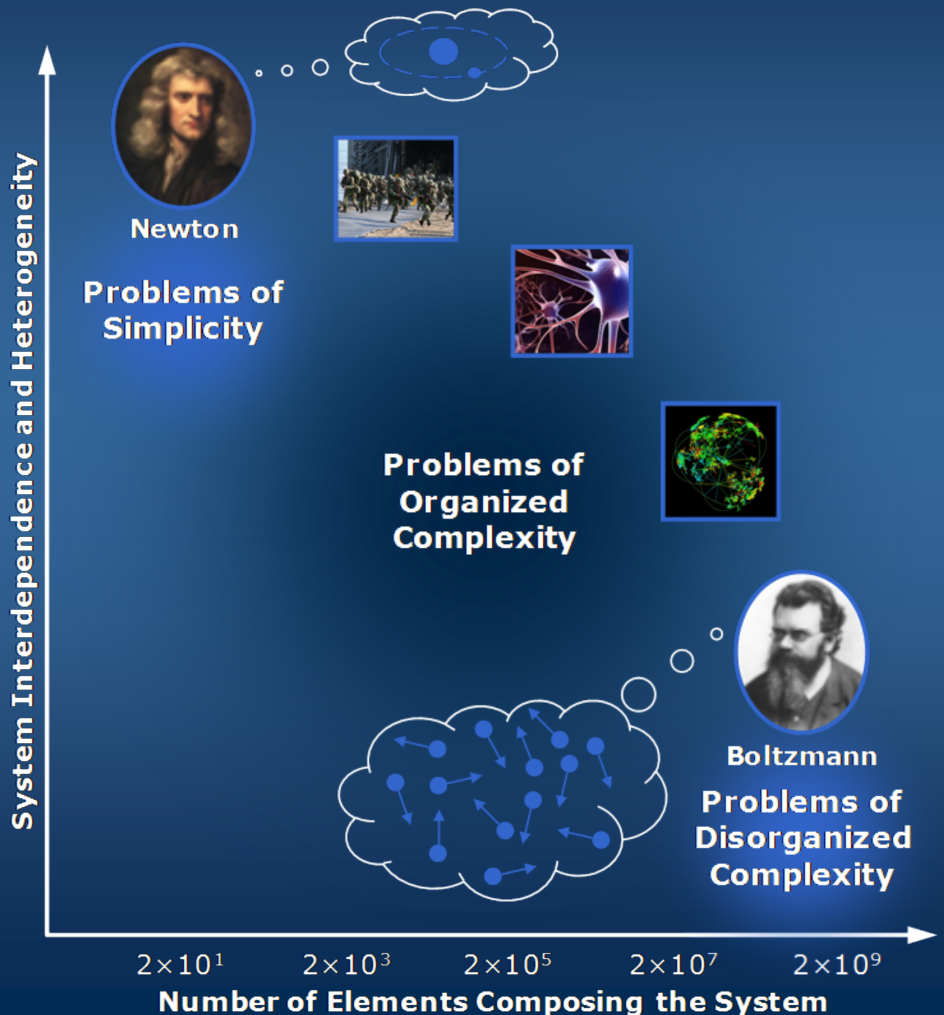

Source: www.3dscience.com

Complex System vs. System-of-Systems

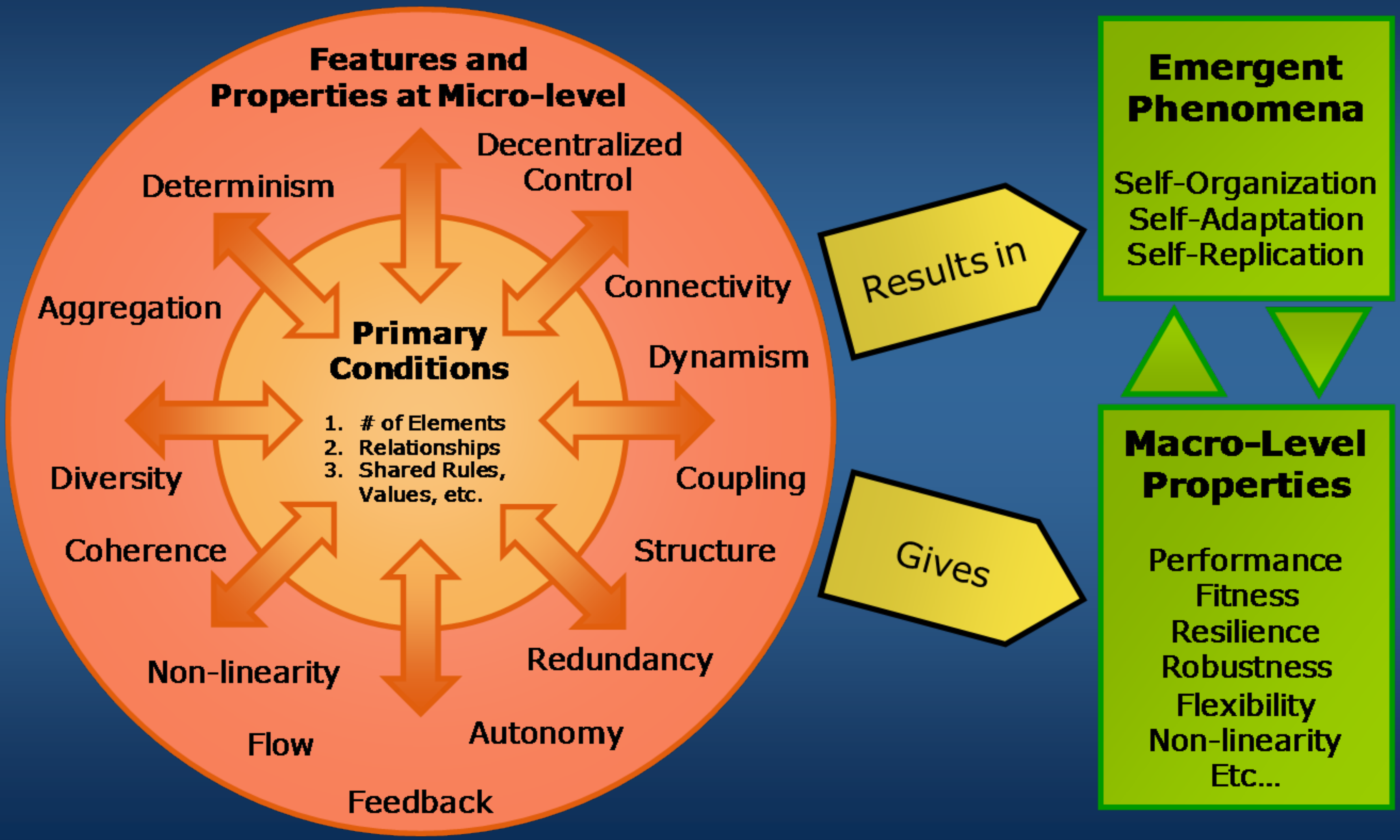


The Evolution of Science towards Complexity

- In 1947, Weaver analyzed the history of science from the 17th century and noticed a pattern
- Recognizes that there were two main efforts until then
  - Between the 17th and 19th centuries science focused on problems with only a handful of variables (< 4)
  - In the 20th century statistical methods were developed to handle problems with large number of variables (> 10^9)
- This left a considerable range of the problems faced by science without solid foundations
- The advent of the computer enabled the study of the area in-between the two camps
- This in-between field has come to be known as *complexity science*



Characteristics of Complex Systems



Adapted from Couture, M., 2007

Modeling Techniques

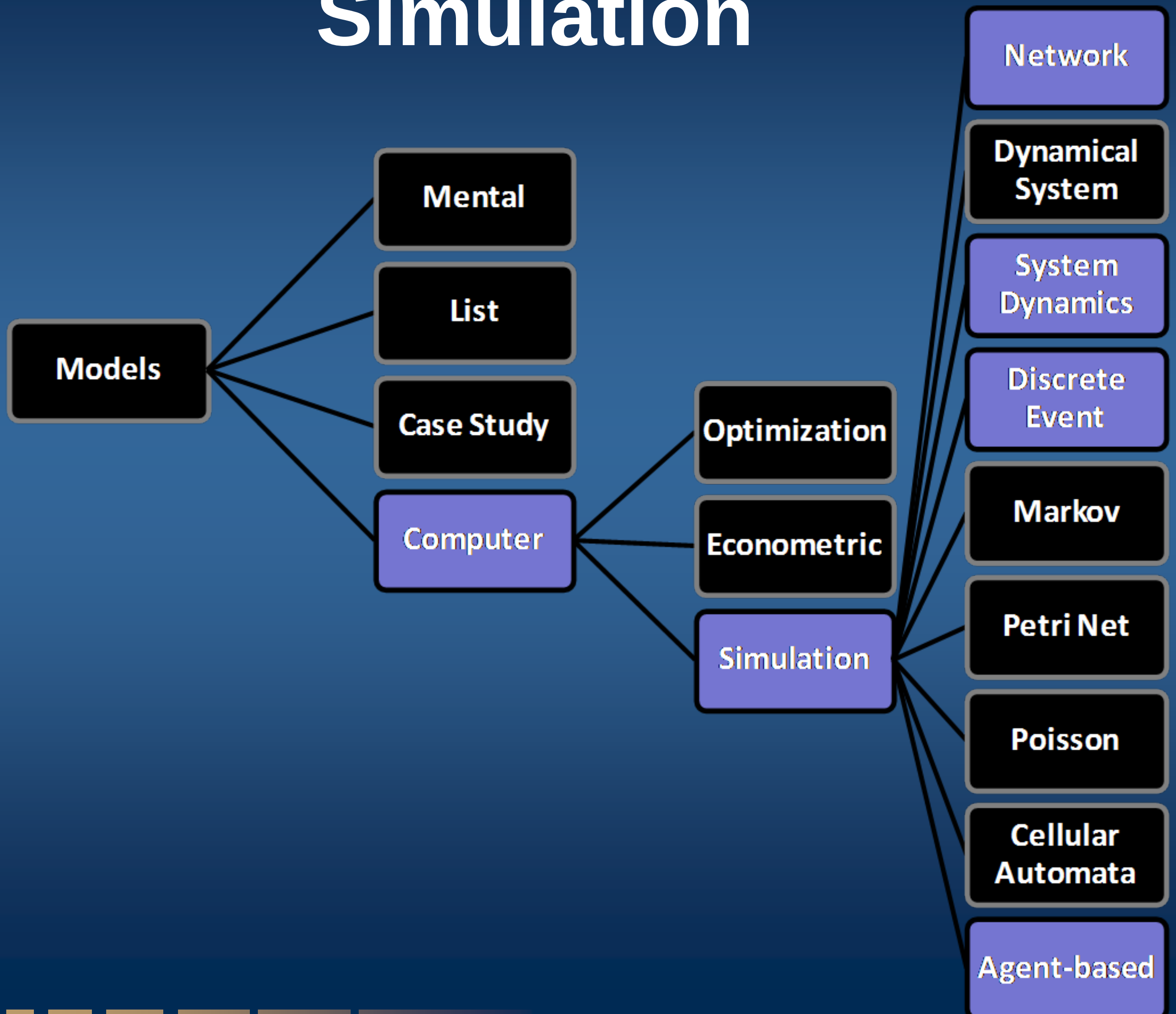
- Experts undergoing efforts to develop an ontology of simulation techniques
  - to establish a common vocabulary and capture domain expert knowledge
  - Current efforts centered around sub simulation categories,
    - e.g., Discrete Event Simulation Taxonomies*, Agent-based Simulation Taxonomies†
  - Still no definite general simulation taxonomy
- Mental Models
  - We can only take a few factors into account when making a decision
  - Suited to linear problems
  - ([Hogarth1987], [Kahneman1982])
- Spreadsheet (a.k.a. List) Models
- Case Studies
- Computer Models
  - Optimization Models
  - Econometric Models
  - Simulation Models (not all inclusive)
    - Network Analysis
    - Markov Simulation
    - Petri Net Simulation
    - Discrete Event Simulation
    - Dynamical Systems
    - System Dynamics Simulation
    - Cellular Automata
    - Agent-based Simulation

Model for insights, for explanation, not numbers

* [Sulistio2004], [Fishwick1998], [Fishwick2004], [Miller2004], [Silver2006]
† [Brenner2007]

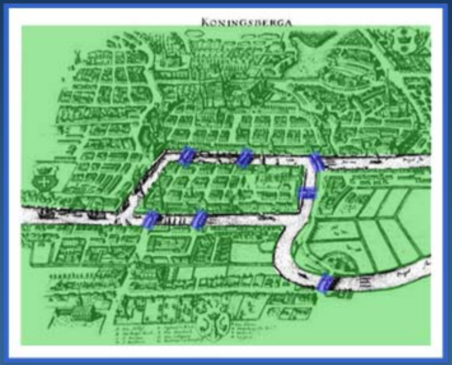
List of techniques based on [Ferguson2006], [Gustafsson2007], [Volovoi2004]

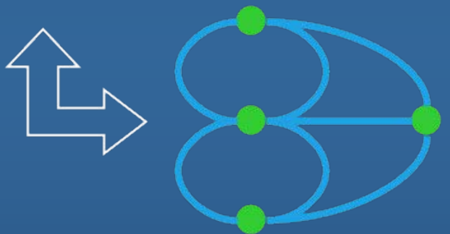
A Taxonomy of Modeling and Simulation



Network Models

- In 1736 Leonhard Euler published *Seven Bridges of Königsberg* and gave birth to the study of graphs
- Graphs are "…mathematical structures used to model pairwise relations between objects from a certain collection"
- Depicted in diagrammatic form as a set of dots (for the points, vertices, or nodes), joined by curves (for the lines or edges)
- Different types of network models
  - e.g., Flow Graphs, Bipartite Graphs, Multi-layered Graphs, etc…
- Large number of algorithms to compute characteristics of the graph
- Suitable for capturing functional complexities, traditionally not suitable for capturing space and time dependent effects
- Recent efforts have developed algorithms for quickly generating random graphs that mimic characteristics of real networks
  - e.g., scale-free, small-world networks, etc..





Discrete Event Simulation

- Formulated by Geoffrey Gordon (1960s)
- "Modeling approach based on the concept of entities, resources and block charts describing entity flow and resource sharing" [Borshchev2003]
- "A global entity processing algorithm, typically with stochastic elements" [Borshchev2003]
- Primarily investigates the performance over time of an interconnected system subject to internal (e.g. process failure) and external (e.g. environmental conditions) random variability [Morecroft2006]
- Any model that requires free movement of entities or a very detailed movement pattern is not easily simulated with DES
  - No intrinsic capability to capture spatial effects
- Generally preferred by the logistics communities to model supply chains
  - Supply networks are not as simple

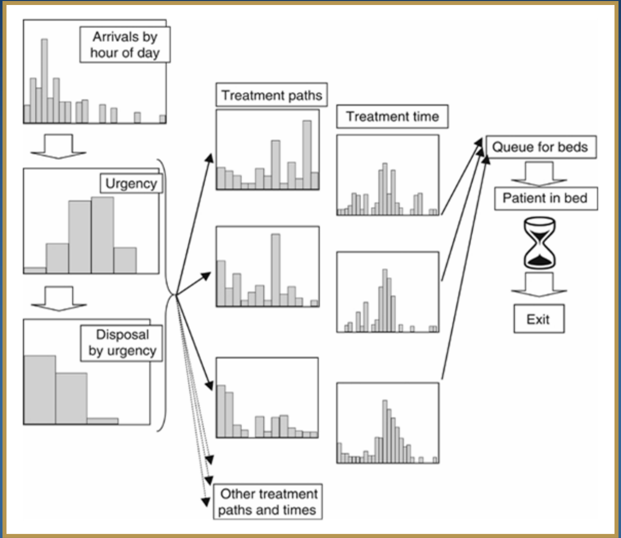
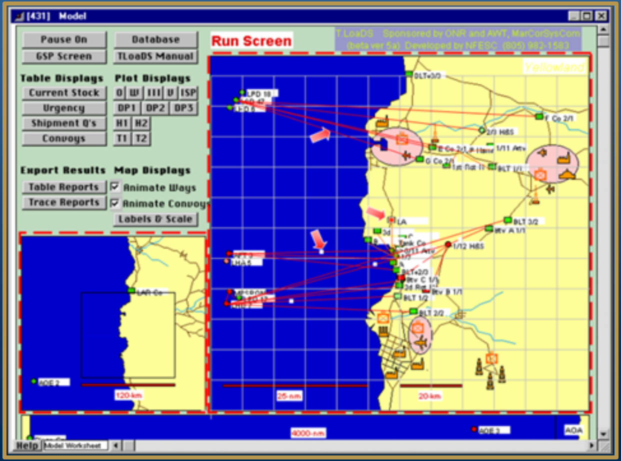


Image Source: http://www.palgrave-journals.com



T.LOADS & C.LOADS, SIW Log Forum, March 28, 2001.

System Dynamics

- Formulated by Jay W. Forrester (1950s)
- System Dynamics is a
  - Top-down modeling approach, where the aggregate behavior of the system is modeled directly
  - methodology for studying and managing complex feedback systems, such as one finds in business and other social systems
- “Mathematically, an SD model is a system of differential equations” [Andrei2003]
- If the model works only with aggregates, the items in that same stock are indistinguishable, they have no individuality
- “The modeler needs to think in terms of global structure dependencies and has to provide accurate quantitative data for them” [Andrei2003]
- Feedback is the key word here, if X affects Y but X also depends on Y, their effects cannot be studied in isolation, a holistic approach must be taken to account for their interdependency
- Shortcomings of System Dynamics
  - Difficult to determine which portions of the problem should be modeled
  - Must understand things from an aggregated level
  - Hard to obtain accurate aggregated data, especially when there is no real system to base it on

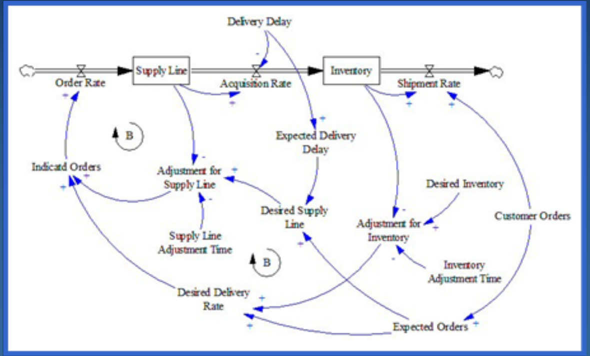


Image Source: http://www.control.hut.fi

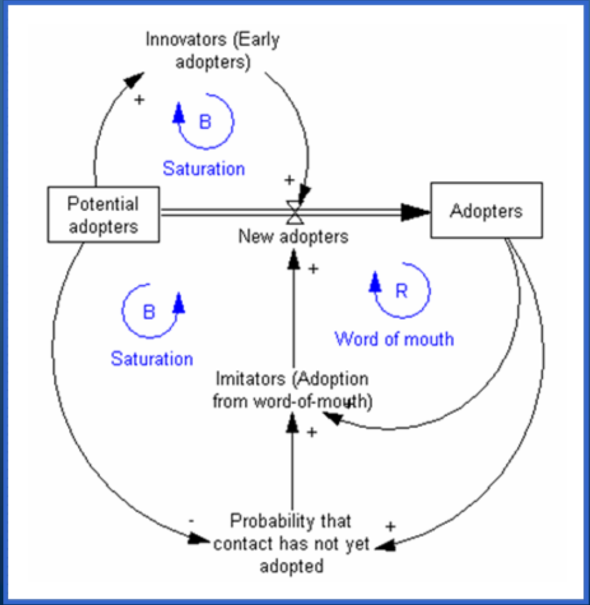


Image Source: http://www.wikimedia.org

Agent-Based Models

- Many definitions of an agent
- Behavior defined at individual level, and aggregated behavior emerges from the interaction of individual behaviors
- “Agent-based models (ABM) are examples of complex adaptive systems, which can be characterized as those systems for which no model less complex than the system itself can accurately predict in detail how the system will behave at future times” [Bankes2002]
- Shortcomings of Agent-based Modeling
  - Hard to determine which portions of reality should be modeled
  - Which portions of the model can be characterized as independent stochastic events, and which have to represent reality more accurately?
  - Complete knowledge of every interaction at the individual levels may not be available
  - Playing it safe and attempting to model as much as possible can create a model that is too complicated to execute efficiently and may convolute the results to the point that understanding is impaired
  - Need to run very large number of simulations because the interactions diminish the effectiveness of the Central Limit Theorem [Cares2007]

Simple entities that interact with each other and the environment while obeying simple rules

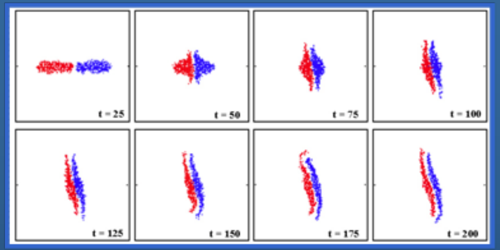


Image Source: www.cna.org

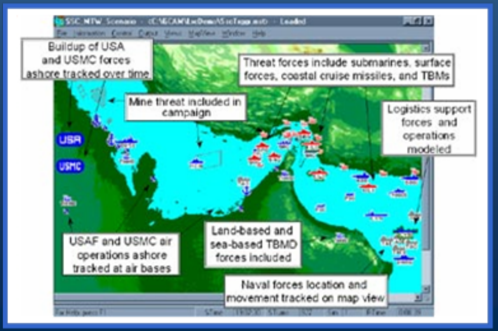
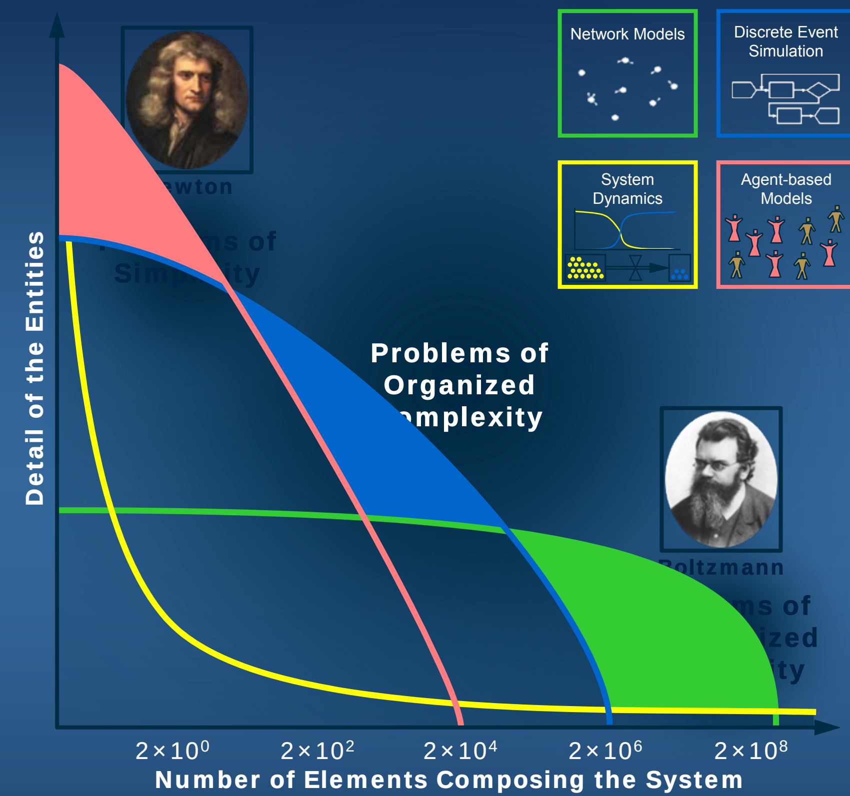


Image Source: www.spa.com

Modeling Techniques and the Paradigm of Complexity

- The question of how much can be modeled can be considered to be a question of
  - how many entities?
  - in how much detail?
- The modeling techniques map to a distinctive Pareto-front in the continuum
  - Notional plot based on literature reviews of different applications of the modeling techniques
  - As more entities are modeled, the techniques require that the entities be simplified
    - System Dynamics is an exception, because in its pure form it assumes that there are an infinite number of entities
  - Anything in the below or to the left of the line is a dominated solution



Modeling Techniques for Complex Systems

- No ideal method
  - ***ABM*** most suitable, but most difficult to implement and validate
  - ***NM*** are the easiest to implement but do not capture the dynamic behaviors or intelligence
- Methods are not exclusive, but complementary
- Others techniques considered but not discussed:
  - Markov Simulation, Petri Net Simulation, Dynamical Systems, Cellular Automata

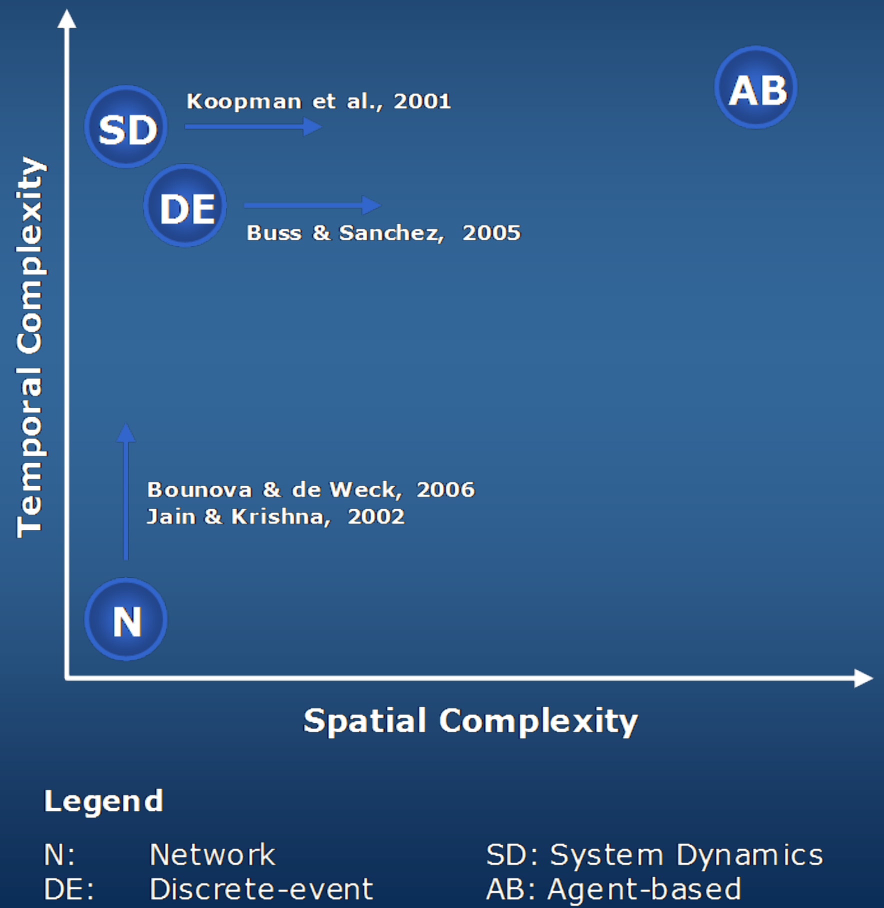
Complexity \ Technique	Network Models	Discrete Event Simulations	System Dynamics Models	Agent-based Models
Nonlinearity	Very Poor	Very Good	Very Good	Excellent
Interactions	Very Good	Poor	Poor	Very Good
Intelligent Agents	Very Poor	Poor	Poor	Excellent
Represent Hierarchies	Very Good	Good	Good	Excellent
Emergent Behavior	Poor	Poor	Poor	Excellent
Adaptation	Very Poor	Poor	Poor	Excellent
Dynamic Behavior	Poor	Very Good	Very Good	Very Good
Ease of Creation	Excellent	Poor	Good	Very Poor
Ease of V&V	Very Good	Good	Good	Very Poor

Legend: = Excellent = Very Good = Good = Poor = Very Poor

Complementary: Coarse modeling can guide detailed modeling

Extending Existing Techniques

- Models are an attempt to capture complexities of reality
- Some modeling approaches can capture certain complexities better than others
- Techniques have been extended, e.g.,
  - Buss & Sanchez, 2005 describes how DES can be used for spatially explicit models
  - Bounova & de Weck, 2006 describes a state-space-like augmented network model that can capture high-level dynamics



Extending techniques increases effort of model creation and V&V

New versus Integration

New Modeling Technique

- Develop a new technique for modeling complex systems architectures
- Advantages
  - Tailor it to the complex problems described in this body of work
- Disadvantages
  - Disregards decades of advances in modeling
  - Time consuming
    - Limited resources, limited time
  - How do we obtain buy-in from M&S community

Integrate Existing Techniques

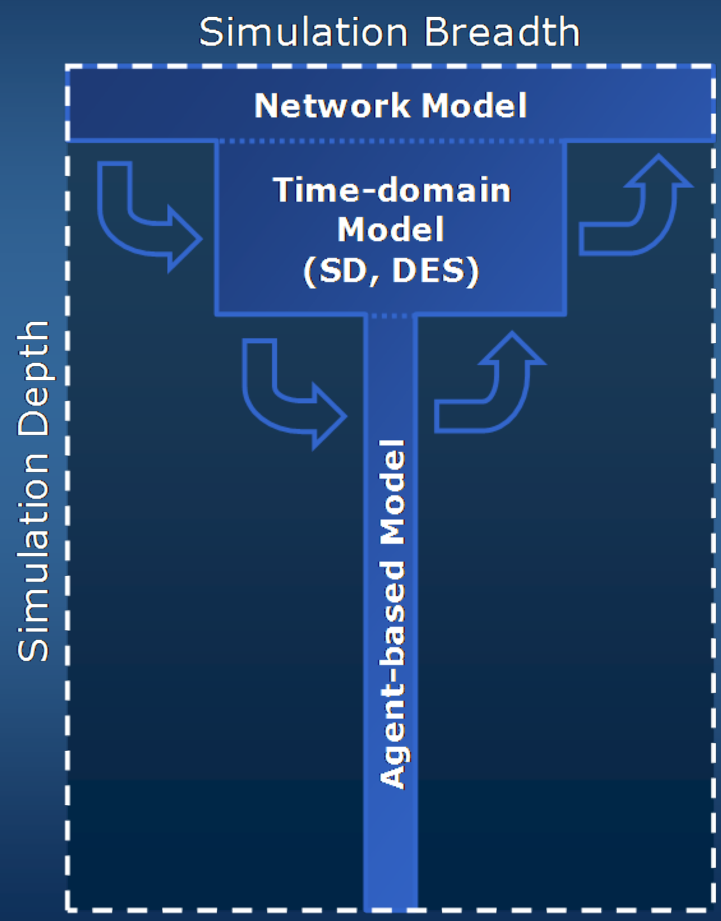
- Develop a process for using existing techniques to model complex systems
- Advantages
  - Leverages advances in the field of simulation and mathematics
- Disadvantages
  - Unproven approach
  - No standardized method for integrating modeling techniques

"If I have seen a little further it is by standing on the shoulders of Giants"

Isaac Newton

How do we Integrate the Candidate Techniques?

- Simulation Breadth
  - What systems are modeled, the extent to which an architecture is represented in the model
  - e.g., if modeling a sea base, do we include the ships traveling from CONUS to ISB, or just ISB to Sea Base?
- Simulation Depth
  - Detail with which the characteristics are modeled
  - e.g., if modeling a sea base, do we model how ships circumnavigate obstacles (decision making, spatially explicit information), or simply set a distance for their travel



References

- Brenner, T. & Werker, C., A Taxonomy of Inference in Simulation Models, *Computational Economics,* **2007**, *30*, 227-244
- Borshchev, A. & Filippov, A., From System Dynamics and Discrete Event to Practical Agent Based Modeling: Reasons, Techniques, Tools, *The 22nd International Conference of the System Dynamics Society,* **2004**
- Bounova, G. & de Weck, O., Augmented Network Models for Engineering System Design, *International Conference on Complex Systems 2006 (ICCS2006),* **2006**
- Buss, A. H. & Sánchez, P. J., Simple Movement and Detection in Discrete Event Simulation, *Proceedings of the 2005 Winter Simulation Conference,* **2005**, 992-1000
- Cares, J. R., Distributed Networked Operations *Alidade Press,* **2005**
- Ferguson, R., Modelling Social Systems, **2006**
- Fishwick, P. A., A taxonomy for simulation modeling based on programming language principles, *IIE Transactions,* **1998**, *30*, 811-820
- Fishwick, P. A. & Miller, J. A., Ontologies for Modeling and Simulation: Issues and Approaches, *Proceedings of the 2004 Winter Simulation Conference,* **2004**
- Gustafsson, L. & Sternad, M., Bringing consistency to simulation of population models – Poisson Simulation as a bridge between micro and macro simulation, *Mathematical Biosciences,* **2007**, *209*, 361-385
- Jain, S. & Krishna, S., Large extinctions in an evolutionary model: The role of innovation and keystone species, *Proceedings of the National Academy of Sciences,* **2002**, *99*, 2055-2060
- Kahneman, D.; Slovic, P. & Tversky, A. *(ed.),* Judgment Under Uncertainty: Heuristics and Biases, *Cambridge University Press,* **1982**
- Koopman, J. S.; Jacquez, G. & Chick, S. E., New Data and Tools for Integrating Discrete and Continuous Population Modeling Strategies, *Annals of the New York Academy of Sciences,* **2001**, *954*, 268-294
- Maier, M. W., Architecting principles for systems-of-systems, *Systems Engineering,* **1998**, *1*, 267-284
- Miller, J. A.; Baramidze, G. T.; Sheth, A. P. & Fishwick, P. A., Investigating Ontologies for Simulation Modeling, *Proceedings of the 37th annual symposium on Simulation, IEEE Computer Society,* **2004**
- Morecroft, J. & Robinson, S., Comparing Discrete-Event Simulation and System Dynamics: Modelling a Fishery, *Proceedings of the 2006 OR Society Simulation Workshop,* **2006**, 12
- Silver, G. A.; Lacy, L. W. & Miller, J. A., Ontology Based Representations of Simulation Models Following the Process Interaction World View, *Proceedings of the 2006 Winter Simulation Conference,* **2006**, 1168-1176
- Sulistio, A.; Yeo, C. S. & Buyya, R., A taxonomy of computer-based simulations and its mapping to parallel and distributed systems simulation tools. *Software - Practice and Experience,* **2004**, *34*, 653-673
- Volovoi, V., Modeling of System Reliability Using Petri Nets with Aging Tokens, *Reliability Engineering and System Safety,* **2004**, *84*, 149-161
- Weaver, W., Science and Complexity, *American Scientist,* **1948**, *36*, 536

Questions and Comments?

Evaluation of Simulation Techniques

Modeling Technique	Common Applications	Characteristics
Network Analysis	Biology, IT, telecommunications	Enables holistic analysis Space-time implicit
Markov Simulation	Queuing theory, statistical physics	Very Limited Scalability
Petri Net Simulation	Reliability, manufacturing, fault diagnosis	Limited Scalability
Discrete Event Simulation	Queuing theory, ecology, manufacturing	Efficient for sparse events Spatially implicit
Dynamical Systems	Electrical circuits, mechanics, e.g., RLC circuit, SMD system…	Used for Hi-Fidelity Modeling of physical systems
System Dynamics Simulation	Population, ecology, economy	Macro-level Analysis Spatially implicit
Cellular Automata	Ecology, real estate, artificial biology, self-replication	Spatially fix; Elements share the same rules
Agent-based Simulation	Ecology, population, artificial biology, combat simulation	Time and spatially explicit Scalability