Introduction to Modeling

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Workshop on
"What Are National Security Threats?"
The University of Chicago and Argonne National Laboratory

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***Center for Complex Adaptive Agent Systems Simulation (*CAS*²)**
Decision & Information Sciences Division, Argonne National Laboratory

ARGONNE: OPERATED BY THE UNIVERSITY OF CHICAGO FOR THE UNITED STATES DEPARTMENT OF ENERGY

Provide Context for how Social/Cultural Theory, Regional Studies Fit into Modeling

- Modeling Methodologies and Approaches
- Model Examples
- Modeling Processes
- Modeling Issues: Validation

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Context for Modeling and Its Intended Use

- **Reasons we do modeling and simulation:**
  - We are constrained by linear thinking: We cannot understand how all the various parts of the system interact and add up to the whole
  - We cannot imagine all the possibilities that the real system could exhibit
  - We cannot foresee the full effects of cascading events with our limited mental models
  - We cannot foresee novel events that our mental models cannot even imagine
- **We model for insights, not numbers; for explanation**
  - As an exercise in "thought space" to gain insights into key variables and their causes and effects
  - To construct reasonable arguments as to why events can or cannot occur based on the model
- **We model to make qualitative or quantitative predictions about the future**

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An Array of Modeling Approaches Available for Social and Cultural Research

more descriptive

more process oriented

- "Accounting" and Data Models
- Statistical Modeling, Inductive Inferencing (Data Driven Models)
- Social Network Analysis (SNA)
- Dynamic Social Networks (DSN)
- Systems Dynamics (SD)
- Agent-based Modeling/Complexity (ABMS)

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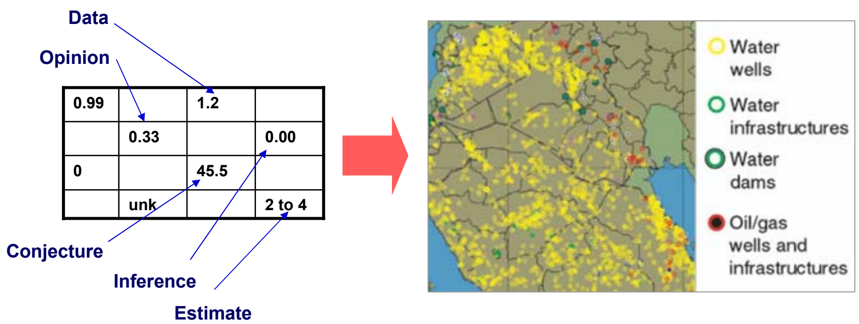
"Accounting" and Data Models

- Descriptive Data => Spreadsheet => Visualization (Situational Awareness)

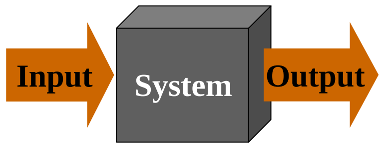


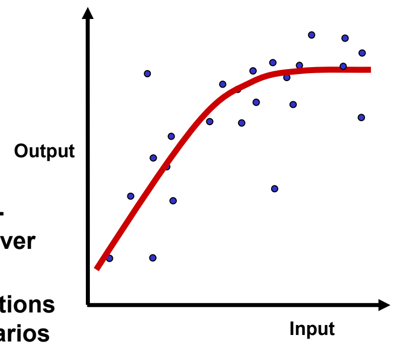
Inductive Inferencing (Data Driven Models)

- Inductive Inferencing
  - Text Processing: Text -> Derived Associations, Patterns (visual or objective)
  - Probabilistic inferencing of uncertain relationships (e.g., Bayesian Analysis)
- Data Mining
  - Data Mining: Data -> Structural Relationships Characterizing Correlations Among Data Items
- Generally, inductive inferencing tools map data to a reduced set of more useful information, but do not have representations of real-world processes that may underlie the data.

Statistical Representation/Regression/Response Surface

- Output = f($Input_1$, $Input_2$, $Input_3$, …., $Input_n$) where f is a statistically derived relationship





- Difficulties
  - Derived relationship is brittle – changes in system structure over time are not captured
  - Not sensitive to many assumptions or amenable to "what-if" scenarios

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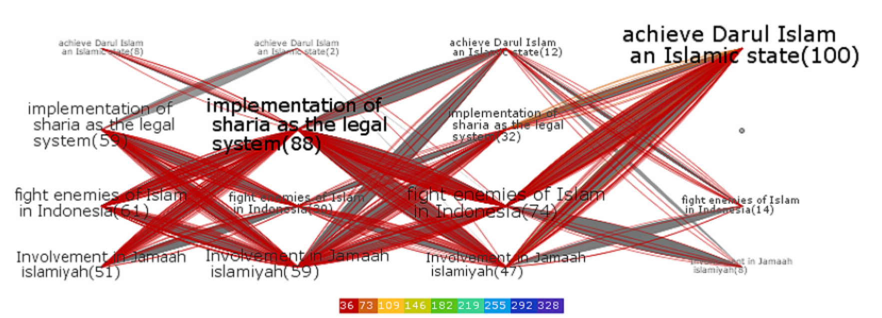
Cultural Simulation Model

- Text and Concept Association Map:



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"Modeling Philosophies" for Social Science Modeling

- **Two kinds of models based on modeling philosophy**
  - **Small elegant models that capture the (asserted) essential elements and features of he real-world system**
  - **Large, complex, detailed models that capture as many of the characteristics of the real-world as possible**
- **The "essential tension between model transparency and veridicality" (*K. Carley, 2002)***

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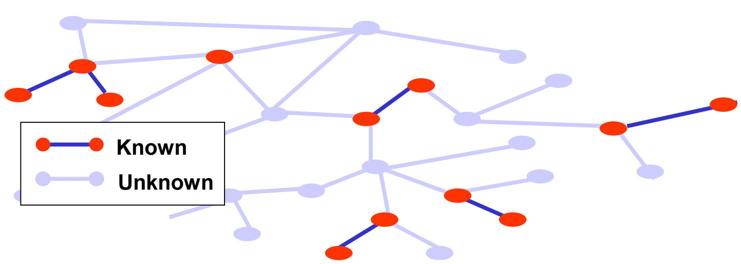
Social Network Modeling

- **Network nodes are people (groups), links are relationships (contacts)**
- **Who is connected closely to whom (path length, clustering)?**
- **Who is key in the network (centrality)?**
- **Can we infer a large network structure from a very small amount of data (hidden networks)?**



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"…networks lie at the core of the economic, political, and social fabric of the 21st century…"

- **Social and communications networks lie at the core of both conventional military operations and the war on terrorism. … the current state of knowledge about the structure, dynamics, and behaviors of both large infrastructure networks and vital social networks at all scales is primitive.**
- **… investment in network science is both a strategic and urgent national priority.**

-- from "*NETWORK SCIENCE,"* a report by the National Research Council (NRC) Board on Army Science and Technology (BAST) Committee, National Academy of Sciences, Washington, D.C., 2005.

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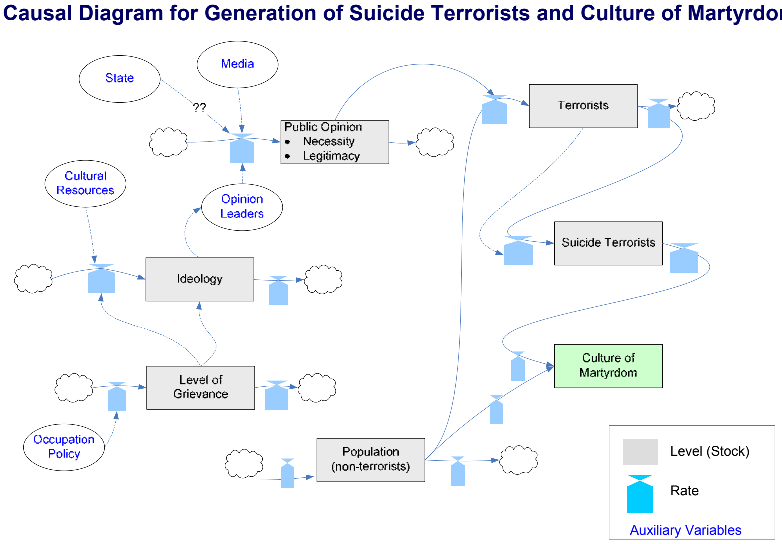
Systems Dynamics Models Begin with a Causal Diagram

Causal Diagram for Generation of Suicide Terrorists and Culture of Martyrdom



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System Dynamics Simulations Are Fairly Straightforward Structurally

- **Systems dynamics (SD) simulations consist of a set of lagged difference equations that are solved forward in time**

$$\mathrm{State}_{t+1} = \mathrm{State}_t + \mathrm{Rate}_t$$

$$\text{where } \mathrm{Rate}_t = f(\mathrm{State}_{t-1}, \ldots, \mathrm{State}_0)$$

- **Difficulties**
  - **Systems Dynamics is an aggregate, macro-level, model of a system**
  - **SD models have a fixed dynamic structure – not able to reproduce the process of moving from one structure to another**
  - **SD models typically include "soft" variables that are difficult to translate into numerical values**

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Dynamic Multi-Level Cultural Modeling

- **Extremal movements may draw upon civilizational themes to recruit from religious movements in order to organize terrorist networks that attack states and state assets, and which may also draw on rogue state resources**
- **Such multilayer interactions can be represented by agent-based models**

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On to Agent-based Simulation… → What Is an "Agent?"

- **An agent is…**
  - **An individual with a set of characteristics or attributes**
  - **A set of rules governing agent behaviors or "decision-making" capability, protocols for communication**
    - Respond to the environment
    - Interact with other agents in the system
- **Agents are diverse and heterogeneous**
  - **This makes it interesting!**

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Complex Systems Science

modelling systems of interacting components

- 'Interesting' systems operate at a variety of temporal and spatial scales
- Similar emergent properties are found in many domains, such as branching structures
  - Tree roots and branches
  - Neurons
  - Blood vessels
  - Road systems
  - Drainage basins
- The challenge is to understand why similar properties emerge across different domains.

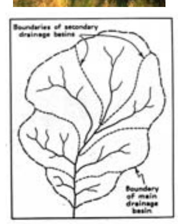


FIG. 11-16
Each stream, no matter how small, has its own drainage basin, the area from which the stream and its tributaries receive water. This basin displays a pattern reminiscent of a tree leaf and its veins.

http://photography.pauljames.de/jpg/branches.jpg
http://cti.itc.virginia.edu/~psyc220/neurons.gif
http://archive.mainroads.qld.gov.au/qldmotorways/logan.gif
http://www.astro.washington.edu/labs/clearinghouse150/labs/Mars/images/tributar.jpg

What is a Complex System?

University of Michigan Centre for the Study of Complex Systems
http://www.pscs.umich.edu/

- A complex system displays some or all of the following characteristics:
  - Agent-based
    - Basic building blocks are the characteristics and activities of individual agents
  - Heterogeneous
    - The agents differ in important characteristics
  - Dynamic
    - Characteristics change over time, usually in a nonlinear way; adaptation
  - Feedback
    - Changes are often the result of feedback from the environment
  - Organization
    - Agents are organized into groups or hierarchies
  - Emergence
    - Macro-level behaviours that emerge from agent actions and interactions

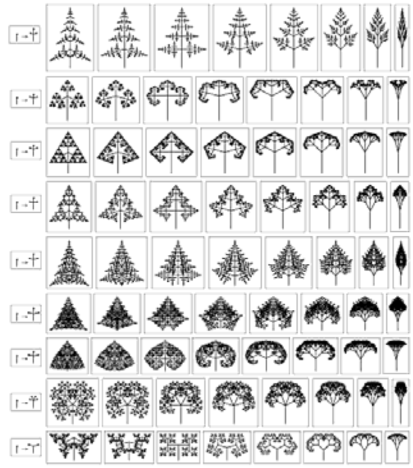
Emergence

1. What parts of a system do together that they would not do by themselves: collective behavior.
2. What a system does by virtue of its relationship to its environment that it would not do by itself: e.g. its function.
3. The act or process of becoming an emergent system.

- How behavior at a larger scale of the system arises from the detailed structure, behavior and relationships on a finer scale
- Both (1) and (2) have to do with relationships, the relationships of the parts, or the relationship of the system to its environment.
- When parts of a system are related to each other we talk about them as a network

Tools to think about emergent properties

- The success stories of complex systems science are where we can understand an emergent property in terms of a relatively limited set of underlying rules or processes that play out over space and time.
  - Networks
  - Distributed agents
  - Recursive processes – grammars eg L-systems
- Simple rules give rise to complex designs

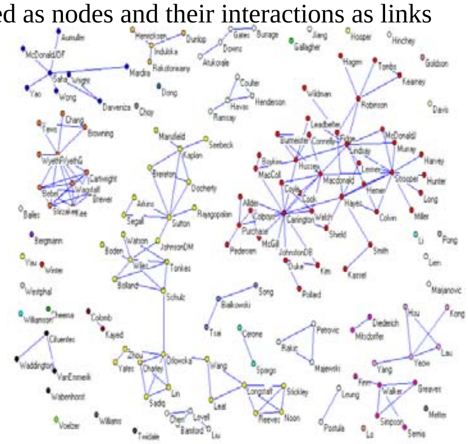


Limiting patterns produced by substitution systems of the type shown in the previous picture. The patterns on each row are obtained from rules that are set up to give branches with particular relative lengths. The angles between the branches are taken to increase by 15° in successive pictures across the row. Note that pictures shown on different rows are scaled differently—so that the initial vertical stem does not always appear with the same height. The similarity between pictures on this page and overall branching patterns and shapes of leaves in many kinds of plants is striking.

http://www.wolframscience.com/preview/set2.html

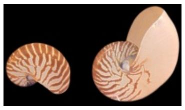
Networks

- System components can be modelled as nodes and their interactions as links
- E.g.
  - World wide web
  - Communication systems
  - Power grids
  - Genetic regulatory networks
  - Neural networks
- Toolkit includes network analysis, s.a. Pajek, Leximancer

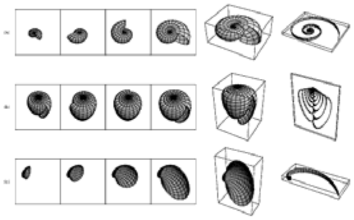


Collaboration graph for researchers in ITEE

Agents



- Basic building blocks are the characteristics and activities of individual agents*
- Simple rules give rise to complex designs
  - E.g.
    - ant trails (pheromones)
    - shell shapes and patterns
    - evolutionary systems



- Toolkit includes cellular automata (CA); Starlogo; Matlab

*University of Michigan Centre for the Study of Complex Systems http://www.pscs.umich.edu/

http://www.wolframscience.com/preview/set2.html

Recursive processes

- E.g.
  - fractals
  - plant growth patterns (branches, roots)
- Toolkit is based on grammars, such as L-studio

http://www.cpsc.ucalgary.ca/Research/bmv/lstudio/flyer.pdf

Insights from modelling

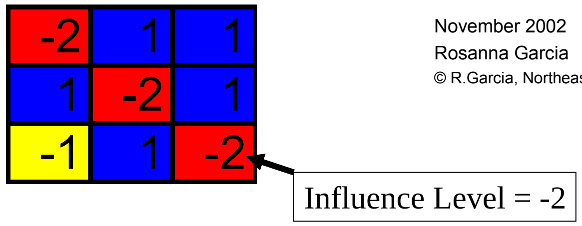
- Simple rules and simple initial conditions can give rise to the most computationally complex behaviour (in a rigorous and formal sense).
- Insights can be gained by studying the space of behaviours of very simple systems

Conclusions

- Complex systems are the rule, not the exception
- Complex systems arise from interactions between agents
- Complex systems are characterized by global, emergent properties
- Many characteristics of complex systems are common across problem domains
  - Insights gained in economics may be applicable to biology
- Complex systems are usually studied using computational modelling approaches

Excel-Example

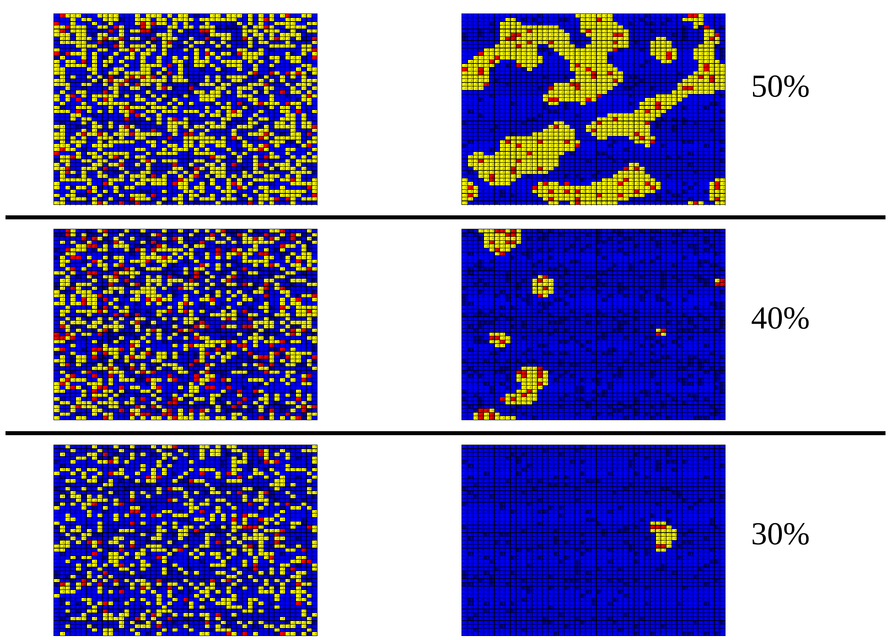
CA Diffusion Model with ‘Seeds’



November 2002
Rosanna Garcia

Indifference Point = 0
SUM (Surrounding Squares) = 2(-2) + 5(1) –1 = 0

Therefore: cell remains negative



50%

40%

30%

Netlogo

http://ccl.northwestern.edu/netlogo/

This particular cellular automaton is called the Parity Model. There is only one rule, which all the cells follow. The rule is that each cell looks at its four neighbours (the ones immediately to its left, right, above and below) and if an odd number of them (that is, 1 or 3) of them are 'on', it switches itself 'on'. If there are an even number 'on' (2 or 4), it switches itself off.

by Nigel Gilbert (Submitted: 9/15/2002)

Difference Between ABM & CA

- Cellular automata (CAs) are always homogeneous and uniformly densely populated on the grid (all cells are identical), whereas in ABM the agents are heterogeneous and do not necessarily occupy all spaces within the grid.
- CAs frequently won’t interact with agents outside their immediate ‘neighborhood’

Some Interesting Agent-based Models

- Housing Segregation (Schelling)
- Artificial Societies (Epstein & Axtell)
- Puebloan Simulation (Kohler, Gummerman, Reynolds)
- Threat Anticipation Model (MacKerrow)

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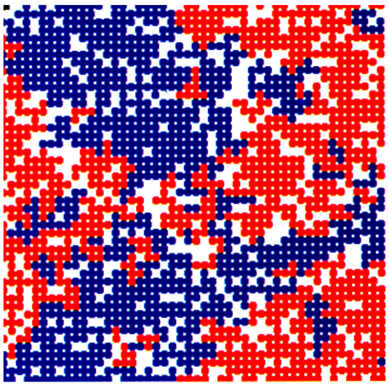
The Schelling Model Is a Simple Agent-based Simulation

- **Randomly seed blue and red agents across the square**
- **Apply "agent movement rules" repeatedly for all agents**

Agent Movement Rules in Schelling Model:

1. Agent computes fraction of neighbors who are its own color
2. If number greater than preference, agent is satisfied – don't move
3. Else, agent looks for nearest unoccupied site that satisfies its preference and moves there



Results for Preference Factor set to 25%

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Nigel Gilbert

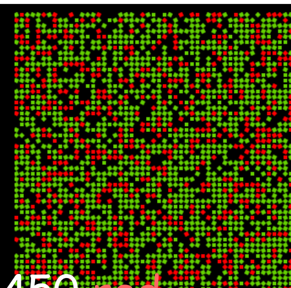
University of Surrey

Guildford UK

- Thomas Schelling proposed a theoryt to explain the persistence of racial segregation in an environment of growing tolerance
- He proposed: If individuals will tolerate racial diversity, but will not tolerate being in a minority in their locality, segregation will still be the equilibrium situation

†Schelling, Thomas C. (1971) Dynamic Models of Segregation. Journal of Mathematical Sociology 1:143-186.

a segregation model



- grid 500 by 500
- 1500 agents, 1050 green, 450 red

  so: 1000 vacant patches
- each agent has a tolerance

  A green agent is 'happy' when the ratio of greens to reds in its Moore neighbourhood (i.e. in the 8 surrounding patches) is more than its tolerance

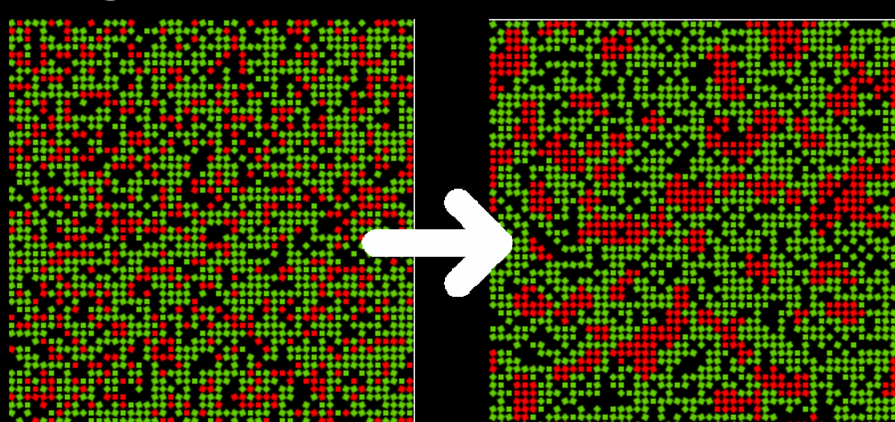
  and vice versa for reds

tipping

- unhappy agents move along a random walk to a patch where they are happy
- emergence is a result of 'tipping'

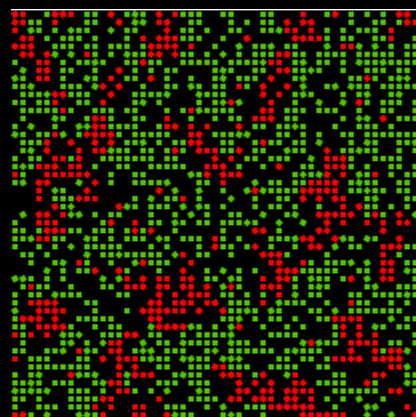
  If one red enters a neighbourhood with 4 reds already there, a previously happy green will become unhappy and move elsewhere, either contributing to a green cluster or possibly upsetting previously happy reds so on…

values of tolerance above 30% give a clear display of clustering: 'ghettos'

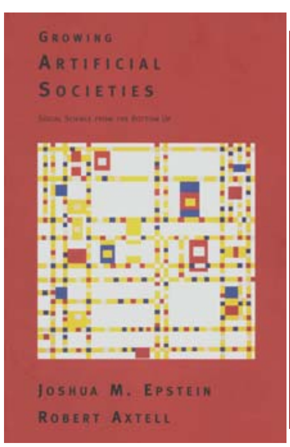


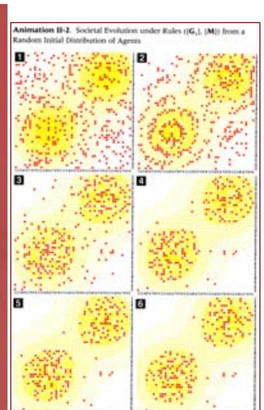
clusters remain even when agents come and go

5% of agents 'die' and are replaced with agents of random colour every timestep



Sugarscape Was the First Comprehensive Computational Study of Artificial Societies





- *Sugarscape Agents Have…*
  - *Life, Death, Disease*
  - *Trade: Sugar, Spice*
  - *Wealth*
  - *Sex, Reproduction*
  - *Culture*
  - *Conflict, War*
  - *Externalities: Pollution*

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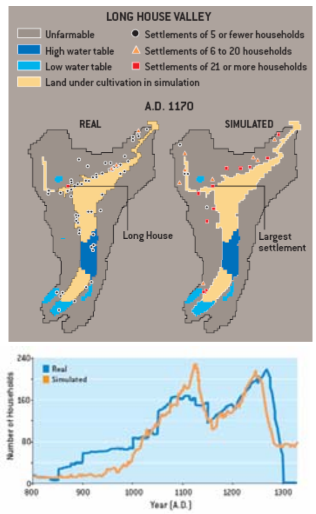
The Puebloan Agent Model Traces Household Movements As They Seek The Best Plots for Growing Maize



- Researchers constructed the model by entering environmental data—precipitation, water-table fluctuations etc. — on a digitized map of the valley.
- By A.D. 1170, the simulation shows the population clustering along the valley's northwestern margin, matching the actual pattern found by archaeologists.
- Although the simulated settlements are more aggregated than the real ones, the location of the largest settlement in the simulation is within 100 meters of the valley's biggest ruin, the Long House

Reference: Kohler, Timothy A., George J. Gumerman and Robert G. Reynolds, 2005, "Simulating Ancient Societies," *Scientific American*, July.

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Cultural Algorithms - The Framework for Simulating Social and Cultural Changes

- Agents generated plans for procuring resources
  - The plans that proved most productive were selectively transmitted to a "belief space" in which individual experiences were generalized to produce rules
  - These rules in turn guided the behavior of other agents in the simulated world
- In another experiment, cultural algorithms were employed in the in the Mesa Verde simulation to see what happens when households in a kinship network exchange maize with one another
  - Households employed cultural algorithms to decide which kin they wish to interact with, determining from past experience the kinds of exchanges that are most likely to lead to mutual benefits
  - If generalizations can be made about the best kinds of exchanges, this knowledge enters the belief space, where it becomes available to other households
  - Modeled "generalized reciprocity": the exchange, among close kin, of gifts that do not have to be repaid in full measure (Marshall Sahlins, UChicago)

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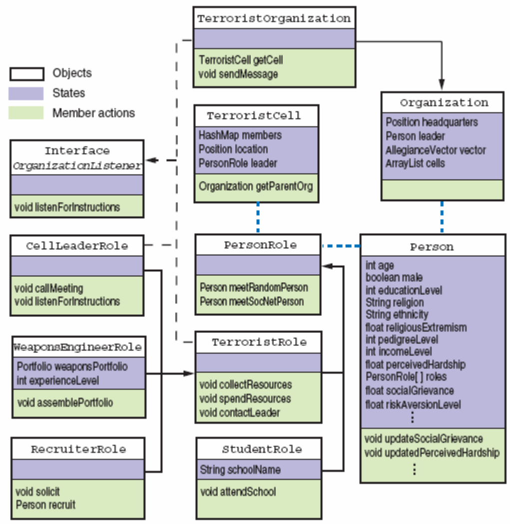
Agent-based Threat Anticipation (TAP) Model (Los Alamos: E. Mackerrow)

Objects in the TAP Model

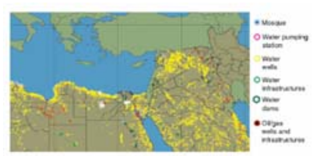


Objects learn and adapt based on their history, current state, and the states of other objects.

Simulation is built upon many different instances of these object types, each with different attributes.

The object architecture allows for flexibility: the PersonRole class, and its inherited subclasses, allow a construct where any one Person object can play multiple roles.

Interfaces allow for specification of required actions that can be implemented differently, depending upon the type of object implementing the interface



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Issues in Modeling

- Validation
- Using Models for Decision Making

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Validation Science Initiative at Argonne

- What Kinds of Models Can Existing Social Science Theory Reasonably be Expected to Support?
- Validation Frameworks
  - What constitutes a validated model? Validated theory?
  - Is there social science theory in the model? Is theory relevant?
  - Has the theory been validated in the way it is used?
  - Are theories (multi-scale) used together appropriately? Conflicting? Gaps?
  - Do the theory implementations allow for empirical model validation?
- Validation Resources
  - Scientific validation philosophy, literature
  - Social science theory validation
  - Traditional model validation (for decision support)
  - Agent-based model validation: examples, literature
  - Human/social behavior representation and validation

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Toward Model Use: V&V

- Model verification and validation (V&V) are essential parts of the model development process if models to be accepted and used to support decision making
- *Verification*

  Verifying that the model does what it is intended to do from an operational perspective
- *Validation*

  Validating that the model meets its intended requirements in terms of the methods employed and the results obtained

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Other Aspects Related to V&V

- ***Independent Verification & Validation*: The V&V of a model is considered *independent* (IV&V) when it is conducted by knowledgeable people other than the original model developers.**
- ***Accreditation* (IVVA) is the process of determining whether a model is useful for a particular purpose and is applicable to answering a specific set of questions.**
- ***Certification* is the process of ensuring that a model meets some specified standard or set of standards**

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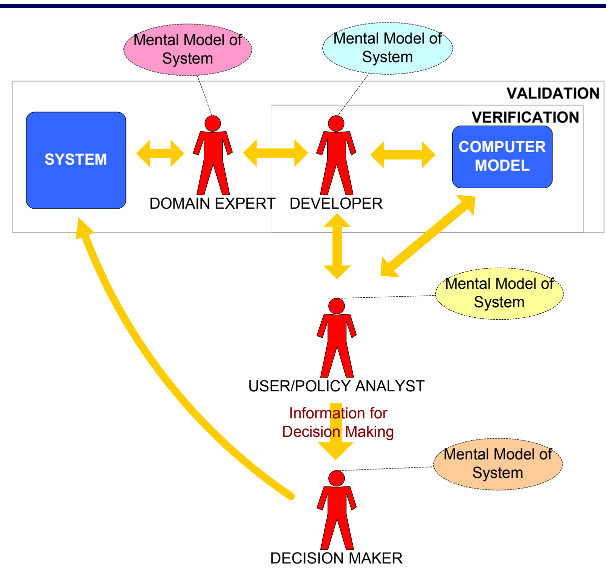
An Information Focused View of Model V&V



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Pathways to Validation

- Cases
  - Exploration of critical cases
  - Exhaustive exploration of cases
- Using models as exploratory e-laboratories
  - Rapid prototyping
- Multiple models
- Maximally diverse model ensembles
- Using subject matter experts
  - Evaluation
  - Role playing, participatory simulation
- Computational simulations as a special cases of analytical modeling

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The Challenge of Validating Theory

- Theory validation relates to the technical details of the model and how it relates to the relevant disciplines, knowledgeable expertise and underlying theories
- V&V is required at multiple scales
  - Agent-to-agent interactions
  - Organizations
  - Society and culture
- Validation of theory
  - What theory is used in the models
  - How the theory is used in the models
  - How the theories are combined in the models

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Conclusions

- **Theory to Computation**
  - **Need for an Overarching Conceptual Framework**
  - **Need for a Process:**

    Theory → Conceptual Models → Computer Models
- **From basic research to Manhattan Project results**
  - **Progress needed in social and complexity sciences**
  - **No relativity, quantum breakthroughs yet in social science**

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