



Agent Based Models

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Complex Systems

- A system composed of interconnected components that collectively exhibit one or more properties not obvious from the properties of the individual components
- A large number of interacting components, whose collective activity is nonlinear and typically exhibits hierarchical self-organization under selective pressures
- A system's complexity may be:
 - Disorganized – large number of parts
 - Organized – exhibiting emergent properties



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Special Aspects of Complexity


- Complex adaptive systems
 - Collection of heterogeneous interconnected components that have the capacity to change and learn from experience
- Nonlinear systems
 - The behavior of the system cannot be expressed as a sum of the behaviors of the components (or their multiples).
 - Superposition does not apply
 - The net response caused by two or more independent factors is the sum of the responses caused by each factor individually
- Chaotic systems
 - sensitive to initial conditions
 - arbitrarily small perturbations may lead to significantly different futures
 - topologically mixing
 - periodic orbits must be dense.

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What is Computational Modeling?

- **Analysis of complex socio-technical systems using simulation**
- **Types**
 - Multi-agent
 - Expert System
 - General System
 - Markov
 - ...
- **Why**
 - Complexity
 - Dynamics
 - Time
 - Ethics


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General Approach to Complex Systems


- Either – Multi-agent models
 - Expect outcomes dependent on actions of large number of heterogeneous actors
 - Realism of agents depends on level of model
- Or – System dynamic models
 - Expect outcomes based on system wide interactions
 - Realism of system depends on purpose of model
- Process intense models
 - Detailed emulation of processes
 - Multiple factors interacting in non-linear ways
- Multi-level models
 - Different learning strategies needed at different response levels (person, organization / institution, nation)
 - Require different kinds of data, analysis, tools at each level
- Empirically grounded
 - Multi-prong approach to real data
 - Moving from face validation to tuning to validation

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Computational Modeling

- Computer Simulation
- Computer Model
- Computational Model
- A computer program, or network of computers and programs, that attempt to simulate an abstract model of the system
- A part of mathematical modeling

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In Comparison to Traditional Formal Models

- Larger scale
 - E.g., more events, actors, entities, time periods ...
- Focus on process not equilibrium
- Mix of simulated and real as opposed to completely algorithmic
 - E.g., simulated actors using real equipment
- Handle more complexity
- Statistical interpretation of results

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Computational Techniques

- Important tool for social theorists and methodologists.
- Multi-agent models particularly valuable.
- Enable the researcher to:
 - Examine the relations among groups and individual agents.
 - Witness the way in which these relations enable, constrain, and affect agent and group behavior.
 - Examine emergent phenomena.
 - Understand complexity.
 - Explore space of possibilities.
- Key areas:
 - Nature of social processes e.g., coordination, cooperation, competition.
 - Understanding, facilitating, or inhibiting change, evolution, emergence.
 - Effect of scale.
 - Effect of technology.
 - Dangerous or extreme situations
 - Alternative histories/futures

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The Many Faces of Computational Models

- Models as theory
 - The model does the task it seeks to explain
 - Social Turing test
- Models as agents
 - Tournament participants
 - Substituting for humans in the lab
- Models as virtual world
 - Social theory from the ground up
 - A-life
- Models as empirically grounded theory
 - Empirical data as integral part of model
 - May be ethnographic
- Models as hypothesis generators
 - Response surface analysis
 - Systematic generation of hypotheses

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Agent Based Models

- A computer simulation that represents individual agents in a dynamic system
- 'Agents' represent heterogeneous individuals who interact with each other and their environment
 - May or may not be rule based
- Macro-scale behaviors emerge from micro-level interactions

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Why Computational Analysis Is Important

- Socio-technical systems are complex
 - Many variables (3+) – e.g., personnel, resources, tasks, procedures
 - Unexpected interactions (3 way or more)
 - Complex interactions involving three or more variables
- Socio-technical systems are dynamic
 - As culture changes structure can change
 - As resources are consumed structure adjusts
- Effects and/or processes are non-linear
 - E.g., impact of population growth on culture
 - E.g., impact of stress on individual performance
- Experiments are costly – especially for large groups
- Field studies may be too invasive or dangerous
- Interest is in the dynamics of the system not the final state
- Problem is knowledge intensive and not well formulated mathematically

Under these conditions simulation is valuable

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Why Use Computational Modeling and Analysis?

- *Ethical*: Cannot test policies on real populations
- *Preparatory*: Can create hypothetical situations with more potency than existing ones – Can examine wide range of scenarios – Enabling systematic imaginative thinking
- *Cost effective*: Creating new technologies, procedures and legislation for data collection is expensive
- *Faster*: Real time evaluation of existing systems is too time consuming
- *Appropriate*: The world and the simulation are complex non-linear dynamic systems
- *Flexible*: Response to novel situations requires rapid evaluation of previously unexamined alternatives

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How to Use Computational Models

- Test bed for new ideas
- Predict impact of technology or policy
- Develop theory
- Determine necessity of a posited mechanism
- Decision making aids
- Forecast future directions
- What if training tools
- Suggest critical experiments
- Suggest critical items for surveys
- Suggest relative impact of different variables (factors)
- Suggest limits to statistical tests for non-linear systems
- Substitute for person, group, tool, etc.. in an experiment
- Hypotheses generators

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Definition: Agent-Based Simulation

- Agent-Based Simulation: A simulation of the interactions and attributes of 'autonomous' entities.
 - Agents have **agency** – they take actions that affect their world or other agents.
 - Agents usually have **bounded rationality** – they do the best thing they can do with their current understanding of the world.

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Turn-Based Simulation

- Turn-Based Simulation: A type of agent-based simulation, each agent is given a turn to act. Once every agent has been given a turn, a new round of turns begins.
 - The order of agents in the turn may be **static** (fixed at the beginning) or **dynamic** (where it changes every round). The order is dynamic in Construct – to avoid primacy effects.
 - A turn may have multiple phases, what happens in each turn is based on the simulation.
 - Agents may not participate in every phase of every turn, they participate in the phases that apply to their situation.

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Modeling

- To Model: To represent something in or of the world, removing those details not pertinent to the reason to model.
 - Models can be **physical**, where they represent an object or class of object (e.g., a scale model of a Spanish Galleon), or **abstract**, where they usually represent a process (e.g., recipes are process models describing how food is made).
 - Models must remove details, or they are not models – they are the thing itself. The choice of what details to remove is an art, not a science.

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Information Diffusion

- Information Diffusion: The process by which knowledge moves through a social group
 - Knowledge can be of varying “sizes” – but the “size per bit” should be consistent in each simulation. “James was seen with Sally at Seviche” can be a knowledge bit, as can “F-22 Pilot Operations”, but they should not be the same number of bits inside the same simulation.
 - Social Groups are defined by the networks of interacting actors. This makes the simulation **network-centric**.

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Belief Dispersion

- Belief Dispersion: The change in beliefs of actors in a social group over time.
 - Beliefs cannot be evaluated for truth.
 - Knowledge can contribute to or deny a belief.
 - Belief: “Cats are better house-pets for a family than dogs.”
 - Supporting Evidence: “Cats tend to live longer than most breeds of dog.”
 - Contrary Evidence: “Most cats must have explicit socialization training early if they are going to be as affectionate as most breeds of dogs.”

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Balance

KISS **VERIDICALITY**

Purpose

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Kitchen Sink Approach

People buy into model and suggest changes
Ease of adding features
Lack of a minimal theory
Not experiment directed

Everything in the model and model everything

characterized by:
large, many parameters,
many untested modules

VERIDICALITY **KISS**

I can do it!!

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Illustrative Approach

Parsimony and illustration rule characterized by:
small model, single virtual experiment, few parameters, one module

What is the basic idea?

Features depend on experiment

Theory driven

Focus on illustration of feasibility

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Emulative Approach

What can be managed?

Built via blocks
Empirically grounded
Addresses applied issues

Sufficient unto the task

characterized by:
large, partly tested modules

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Shifting the Balance

The purpose of the model may shift the balance between simplicity and veridicality.

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Intellective or theory building models

Engineering, emulation, or wind tunnel application models

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Taking a Building Block Approach

Build & Test

Build & Test

Build & Test Build & Test

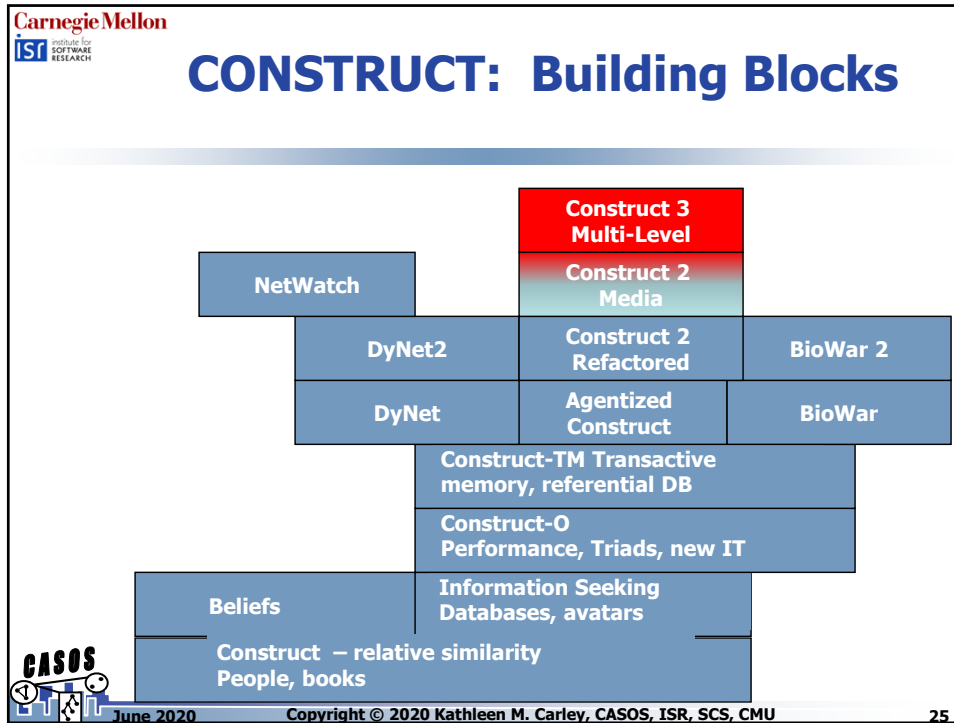
- Start out small
- Keep only those parts necessary for the theory
- If it is a complex theory focus only on the core
- If a needed component is not in the theory treat it as a parameter don't invent mechanisms
- If you don't know how something changes begin by assuming that it does not
- Build, run a virtual experiment
- Add critical variable

Note: this approach is facilitated by using modular programming and object oriented programming techniques

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What is an Agent Based System?

- Bottom up model – simple model generating complex behavior
- A simulation in which the rules of behavior of agents and the rules of interaction are specified
- An agent-based model consists of:
 - A set of agents (part of the user-defined model)
 - A set of agent relationships (part of the user-defined model)
 - A framework for simulating agent behaviors and interactions (provided by an ABMS toolkit or other implementation)
 - An environment
- Agent-based modeling begins and ends with the agent's perspective

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Agent Based Models

Are not

- An attempt to perfectly reproduce reality (usually)

Are

- Are a tool to gain intuition about the system of interest without needing to know all of the details
- A tool to run “experiments” which cannot be performed in real life
- A tool to generate and test hypotheses about what is occurring
- A tool to refine data collection foci

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What is an Agent?

- Agents are autonomous
 - Decide for themselves whether or not to perform some action
- Agents are capable of flexible behavior
 - Reactive
 - Proactive
 - Social
- Agents provide software designers and developers with a way of structuring applications around autonomous, communicative components
- Multi-agent systems may be multi-threaded
 - Each group have at least one thread of control

I knows it when I sees it


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Agents

- Simulated actor
- A discrete entity with its own behaviors and possibly its own goals, knowledge, emotions, resources
- An agent is a computer system that is capable of flexible autonomous action in dynamic, unpredictable, typically multi-agent domains
- Key features
 - Interaction with others is controlled by agent's perception
 - Providing agents with mental models of others enables self-organization
 - Agents are diverse and heterogeneous

 Examples


- Insects, animals, people, groups, robots

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Agents and Systems

- Internal data representations
 - Memory, transactive memory or state
- Means for modifying the internal data representations
 - Perceptions, Learning, Forgetting, Emotional modulation
- Means for modifying environment
 - Behavior, Actions, Communication
- Agents have connections to each other, and form a system and operate in an environment with feedbacks
- Agents behave autonomously thus they each have their own parameters (data) and behaviors
- Systems change once the agents affect the threshold in a significant way


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Agents as Heterogeneous Autonomous Decision Making Units


- Decision rules vary by agent
 - How many rules?
 - How sophisticated are the rules?
 - How much does the agent need to process ? - Cognitive “load”
 - Does the agent have an internal models of the external world
 - How much memory is employed
- Agents vary by their cognitive capabilities, attributes and available accumulated resources
- Core question is - what is the effect of agent diversity on the system?
 - Do certain types of agents dominate?
 - Does the system evolve toward a stable mix of agent types?
 - How fast does the system evolve?

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Complex Adaptive Systems (CAS)

- Biological systems are **complex adaptive systems (CAS)**. **Complex systems** are composed of many components that interact dynamically so that the system shows spontaneous self-organisation to produce global, emergent structures and behaviours. In biology, the nature of the interactions themselves are often state- or context-dependent so that systems are adaptive. A 'taxonomy of complexity' suggested by (Mitchell, 2003) captures well the complexity found in Biology:
- **Constitutive Complexity:** Organisms display complexity in structure, the whole is made up of numerous parts in non-random organisation.
- **Dynamic Complexity:** Organisms are complex in their functional processes.
- **Evolved Complexity:** Alternative evolutionary solutions adaptive problems, historically contingent.

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Multi-agent systems (MAS)

Topics of research in MAS include:

- beliefs, desires, and intentions (BDI),
- cooperation and coordination,
- organisation,
- communication,
- negotiation,
- distributed problem solving,
- multi-agent learning.
- scientific communities
- dependability and fault-tolerance

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ABM classifications

Do either or both of the following apply in the model?

- 1. The system can be decomposed into subsystems/sub-models e.g. different metabolic pathways, signalling networks.
- 2. The model includes more than one level of description (this can be across both spatial and temporal scales) e.g. some parts of the model given in terms of single molecules while other parts given in terms of concentrations of these same molecules?

System Organisation

- Can entities enter and leave the different subsystems at different times?

Entities and their Behaviour

- 1. Do entities show discontinuous changes in behaviour through their lifetime as part of their development (pre-programmed rule changes) e.g. stops growing after it has reached a certain age?
- 2. Do entities develop new types of behaviour/capabilities in response to certain conditions through its lifetime

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Entity Behaviour: Which of the following affect it at each time step?

- The states of other entities in its neighbourhood or group
- Global state
- Local state (defined spatially)

The Role of Space and Spatio-Temporal Dynamics

1. Are there locally defined state variables that undergo evolution?
2. Do physical-spatial interactions / motion need to be modelled?

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Groups: Groups can be used to relate subsets of agents that interact with each other. The precise nature of the interaction relationships between agents in the same group depend on the model.

Organisational Metaphor with Dynamic Group Structure: In a dynamic group structure, agents can enter and leave groups. Groups can also be dynamic in the sense that they can exist and cease to exist at different times. The Agent-Group-Role formalism is an example of an organisational metaphor that can cope with both dynamic groups and dynamic participation.

Situated agents: Agents are situated in some environment and are located in space. There may be several different ways of representing this environment e.g. discrete grid, continuous space.

Agents with pro-active behavioural rules: Agents have rules that arise from within themselves e.g. rules governing development, random changes. These rules can also interact with reactive rules.

Agents with behavioural rules that are adaptive: Agent rules themselves can change through time.

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Why agent-based modelling?

Traditional mathematical methods (ODE, PDE, statistical approaches):

- can describe macroscopic properties of a system that is already known, but don't explain the origin of those properties. (e.g. rate constants)
- cannot be easily extrapolated to situations where the assumptions behind the equations no longer hold. (e.g. Hooke's law $F = -kx$)
- don't handle discontinuous systems well
- don't handle heterogeneity in populations well

but:

- ABM complements and enhances rather than supplants, traditional approaches

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Why Use Multi-Agent Systems

- Multi-agent systems offer strong models for representing complex and dynamic real-world environments
- Examples: simulation of economies, societies, urban environments and biological environments are typical application areas
- Detailed Model example: Working with Rolls Royce, Lost Wax has developed Aerogility, a multi-agent system to help business managers better understand the complexities of the aerospace aftermarket
- Stylized Model example: Variations of the Schelling segregation model used by the state department to reason about neighborhoods in Iraq

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When do you build and agent based model?

- When there is a natural representation of things as agents
 - When there are decisions and behaviors that can be defined discretely (with boundaries)
 - When it is important that agents adapt and change their behavior
 - When it is important that agents learn and engage in dynamic strategic behavior
 - When it is important that agents have a dynamic relationships with other agents, and agent relationships form and dissolve
 - When it is important that agents form organizations and adaptation and learning are important at the organization level
 - When it is important that agents have a spatial component to their behaviors and interactions
- When the past does not seem to predict the future
- When scaling-up to arbitrary levels is important
- When structural change of process needs to be a result of the model, rather than an input to the model

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Local Interaction is Key

- In a “true” ABS
 - No central authority or controller exists for:
 - How the system operates
 - How the system is modeled
 - How the system/model moves from state to state
 - “Optimization” can be done for the system as a whole
 - Agents can be synchronous or not
 - Agents can be rules or not

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Agent Based Models -

- Generally exhibit
- Self organized criticality

- Go to
- <http://www.tn.tudelft.nl/tn/People/Staff/Thijssen/sandpille.html>

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Mouse Trap

- Mouse Trap – example of nuclear fission
- Mouse Trap – an example of dynamic scheduling and how to do discrete-event simulations using Schedule objects
- A torus is populated with "mousetraps"
- Each trap contains some n number of balls
- A ball is thrown from the "outside" onto the center mousetrap
- The trap triggers and throws its balls into the air
- These balls then trigger other trap, etc.
- The first trap has its trigger method scheduled at 0
- When a mousetrap is triggered it schedules a trigger method on n of its surrounding mousetraps, where n is the number of balls each mousetrap holds.

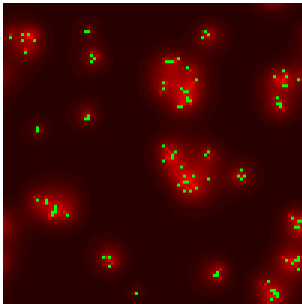
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Heatbugs

- an example of how simple agents acting only on local information can produce complex global behavior
- Each agent is a heatbug
- The world has a spatial property, heat, which diffuses and evaporates over time.
- Green dots represent heatbugs, brighter red represents warmer spots of the world.
- Each heatbug puts out a small amount of heat, and also has a certain ideal temperature it wants to be.
- Simple time stepped model: each time step, the heatbug looks moves to a nearby spot that will make it happier and then puts out a bit of heat
- Isolated heatbugs can't be warm so they tend to cluster together for warmth



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What are multi-agent models ?

- Models composed of multiple agents
- An agent is a model of an actor
 - Humans, WebBots, intelligent databases, avatars, corporate actors
 - Information processing capabilities
 - Goal directed behavior
- Characteristics of models
 - One or more categories of agents
 - Many agents
 - Agents homogenous model, heterogeneous knowledge
- Variations across models
 - Number of agents
 - Representation of physical space and time
 - Task
 - Cognitive realism of agents
 - Representation of networks

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Typical models

- Artificial life (A-Life) models
 - Large numbers of simple rule based agents
 - Move on a grid
 - Agent learning is typically binary
 - Sets of agents evolve
- Structure models
 - Moderate to large number of agents
 - Agents are combination of equations & rules
 - Communicate through networks
 - Agents may learn
 - May have communication technologies
- Cognitive agent models
 - Few to moderate number of agents
 - Agents are complex rule based agents
 - Agents may learn
 - Knowledge intensive & sometimes physical tasks

Sugarscape

VDT

Orgahead

Construct

MA Soar

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Software Engineering Practice for ABM Development

- Validity, usability, extendibility
- Design and validate to a purpose
- Unexpected results:
 - Error? Or Consequence?
- Multi-level verification:
 - check micro-dynamics
 - Check aggregate results.
- Purposeful Occam's Razor
 - Only as complex as needed for the purpose
- Use standard programs for data analysis
- Document all runs

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Balance

Construct *MA Soar*
Sugarscape *Orgahead* *VDT*
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Two Basic Approaches

- Bottom Up
 - Search for specific agent level-capabilities that result in appropriate interaction at the overall group level
 - Agent-level capabilities include interruption handling, abstraction based planning, trans-active memory
- Top Down
 - Search for specific group-level rules that appropriately constrain the interaction repertoire at the level of the individual agents
 - Group-level rules are norms, conventions, etc.

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General Findings

- Emergent behavior
 - Complex behavior emerges from adaptive actors
 - We need to understand what behavior emerges when and how cognition, networks, technology, and policies constrain and enable what emerges
- Path dependence
 - The path taken affects the outcome
 - Bifurcation points
 - We need to understand how to predict which path to take, how to recover from starting down the wrong path
- Inevitability of change
 - Change is inevitable
 - Examine pattern of change not equilibrium
 - We need to understand how to predict and manage change

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What Aspects of Agency Matter


- Cognitive Architecture
 - Cognitive limitations
 - Social limitations
 - Exact information processing capabilities
 - Learning mechanism
- Knowledge
 - Knowledge of others generates more realistic outcomes
 - Task knowledge
 - Resource knowledge
- Constraints on interaction
 - The exact structure of the network
 - The physical space
 - Order of Interaction, pattern, number


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 **Key Features of Application Domains**

- Inherent Distribution
 - Arise at geographically different locations
 - Arise at different times
 - Are structured into clusters (semantic or organizational)
- Inherent Complexity
 - Too large to be solved by single centralized system
 - Hardware and software limitations
 - Enlarging a centralized system is too costly or time consuming
 - Centralized solution is too brittle
 - Natural components are cognitively limited



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 **Basic Questions**

- How to enable agents to:
 - decompose their goals and tasks
 - Allocate sub-goals and sub-tasks to other agents
 - Synthesize partial results and solutions
- How to enable agents to communicate. What communication protocols to use.
- How to enable agents to represent and reason about actions, plans, and knowledge of other agents in order to appropriately interact with them.
- How to enable agents to determine if they have progressed in their coordination efforts.
- How to enable agents to coordinate and improve coordination.


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Cont.


- How to enable agents to recognize and reconcile disparate information and viewpoints.
- How to engineer and constrain practical multi-agent systems. How to design technology platforms.
- How to effectively balance local computation and communication.
- How to avoid or mitigate harmful overall system behavior.
- How to enable agents to negotiate and contract.
- How to enable agents to form and dissolve organizational structures.

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Cont.

- How to formally describe multi-agent systems and the interaction among agents.
- How to realize “intelligent processes” such as problem solving, planning, decision making, and learning in multi-agent contexts.
- How to collectively enable agents to carry out “intelligent processes”.

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Characteristics of Multi-Agent Environments

- Provide an infrastructure specifying communication and interaction protocols
- Typically open and have no centralized designer
- Contain agents that are autonomous and distributed, and may be self interested or cooperative

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Environment Agent Characteristics

- Knowable
 - To what extent is the environment known to the agent
- Predictable
 - To what extent can it be predicted by the agent
- Controllable
 - To what extent can the agent modify its environment
- Historical
 - Do future states depend on the entire history or only the current state
- Teleological
 - Are parts of it purposeful, i.e. are there other agents
- Real Time
 - Can the environment change while the agent is deliberating

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Communication Protocols

- Enable agents to exchange and understand messages
- Conversation: structured exchange of messages
- Might specify types of messages
 - Propose course of action
 - Accept a course of action
 - Reject a course of action
 - Retract a course of action
 - Disagree with a course of action
 - Counter-propose a course of action
- Might specify language

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Illustrative Cooperation Protocols

- Decompose then distribute tasks
- Task distribution criteria
- Avoid overloading critical resources
- Assign tasks to agents with matching capabilities
- Make an agent with a wide view assign tasks to other agents
- Assign highly interdependent tasks to agents in spatial or semantic proximity. This minimizes communication and synchronizes costs.
- Reassign tasks if necessary for completing urgent tasks.

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Spatial ABMs


- Spatial ABMs put agents in a “spatial” environment
 - Interactions take place in locations
 - Behavior may be defined by location
 - Reynolds, 1999
- Examine global consequences of local interactions in a given space
 - Agent generate emergent behavior due to spatially constrained action
 - Holland, 1999
 - Reynolds, 1999
- Locations may be physical or social

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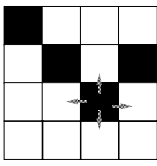
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Interaction Topologies

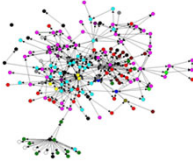
- Agents can move in space (discrete or continuous)
- Cellular automata have agents interacting in local “neighborhoods”
- Agents can be connected by one or more networks
 - static or dynamic
- Agents can move in physical space
 - over Geographical Information Systems (GIS) tilings
 - From one lat-lon to another
- Sometimes *spatial interactions are not important* (“Soup” Model)



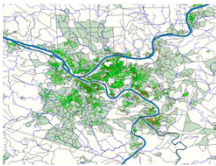
CASOS Euclidean



Grid



Network



GIS

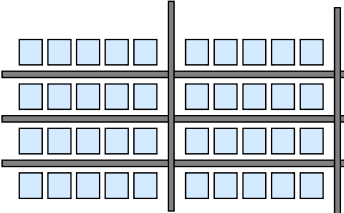
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Latane - City Blocks

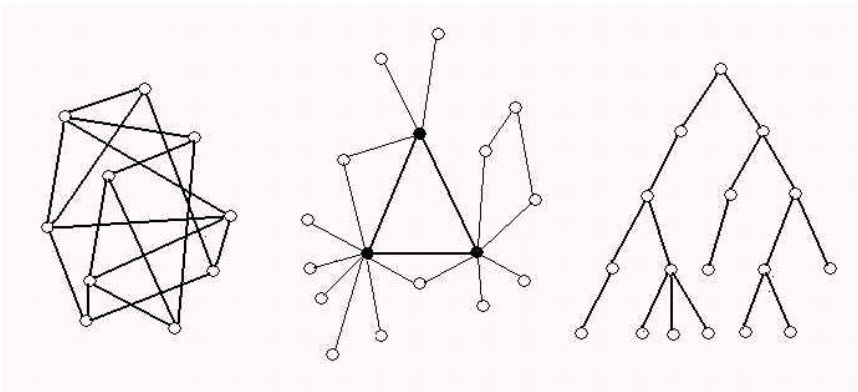
- Cellular Automata
- Opinion formation.
 - Agent has an opinion.
 - Agent's opinion as affected by neighbors.
 - Agent can move or change opinion.
- Movement along grid lines.
- Close off areas as parks, etc.
- Similar to a-life.
 - Distinction is diagonals.



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Different types of Networks (Space)



Random Scale Free Hierarchy

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Small World Networks

Regular Small-world Random

$p = 0$ $p = 1$
Increasing randomness

Small-Worlds by Duncan Watts, 1999

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Validation-In-Parts

Assumptions of Validation Theory are Violated
Cannot Validate by Matching Historical Case (Tuning)
New Approach Needed

Output
Cross-validation
Landscape of possibilities

Process
Utilize lab/field validated processes
SME verification
(Building Block Development)

Input
Instantiation for Real Organization
Stylized Organization
(Data Fusion)

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