An Introduction to Agent-based Modeling and Simulation

Dr. Emiliano Casalicchio
casalicchio@ing.uniroma2.it

Download @
www.emilianocasalicchio.eu
(talks & seminars section)

Outline

- Part1: An introduction to Agent-based Modeling and Simulation (ABMS)
  - Motivation
  - What is an agent
  - The need for ABMS
  - Background on ABMS
  - Why and when ABMS
- Part 2:
  - ABMS applications
  - How to do ABMS
- Part 3:
  - Electricity market, supply chain example
  - ABMS in Workflows and BP re-engineering

Bibliography

- Charles M. Macal, Michael J. North, **TUTORIAL ON AGENT-BASED MODELING AND SIMULATION,** *Proceedings of the 2006 Winter Simulation Conference*
- Charles M. Macal, Michael J. North, **TUTORIAL ON AGENT-BASED MODELING AND SIMULATION PART 2: HOW TO MODEL WITH AGENTS,** *Proceedings of the 2006 Winter Simulation Conference*
- Charles M. Macal, Michael J. North, **Managing Business Complexity: discovery strategic solution with agent-based modeling and simulation,** Oxford University Press, 2007

Motivation

- Systems are even more complex and interdependent
  - Financial and government processes and services depend on IT services; IT services depends on electricity
  - Goods supply chains depend on transportation systems, IT services, electricity, oil distribution, water distribution etc…
- There is the need for new modeling and simulation paradigms that allow to think systems in a different way:
  - **Parts make the whole**

Parts make the whole

- Agent-based modeling and simulation is founded on the notion that:
  - The whole of many systems or organization is greater then the sum of its constituent parts
- To manage such systems the systems or organizations must be understood as collections of interacting components
  - Each of these components has its own rules and responsibilities
  - None of the components completely controls the behavior of the system
  - All the components contribute to the results in a large or small way

Complex Adaptive Systems

- A collection of components with the above characteristics is said to be a
  - Complex Adaptive System (CAS)
- CAS are characterized by emergent behavior:
  - System reaction where the complete results are more then the sum of the individual components outcomes
- Managing a CAS require a good understanding of emergent behavior
- ABMS helps in understanding emergent behavior

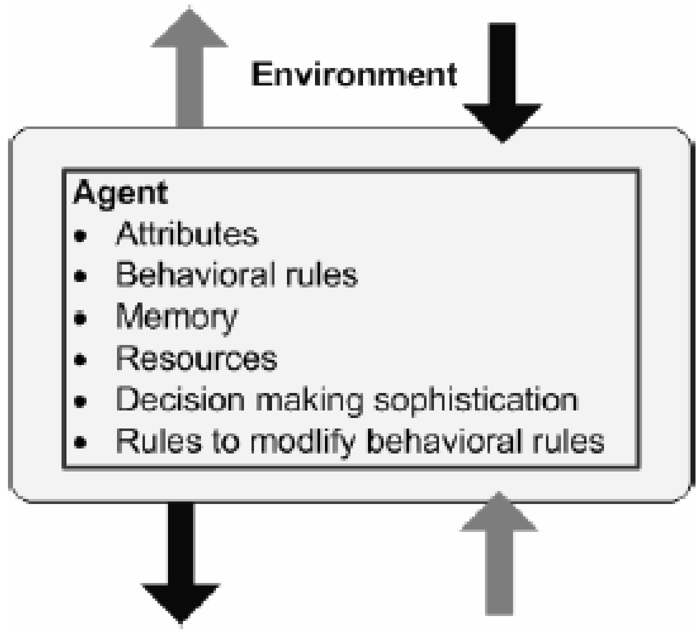
What is an agent ?

What is an agent

- No universal agreement on the precise definition of the term "agent"
  - (Bonabeau 2001) any type of independent component (software, model, individual, etc.); an independent component's behavior can range from primitive reactive decision rules to complex adaptive intelligence.
  - (Mellouli et al. 2003) components with an adaptive behavior; components that can in some sense learn from their environments and change their behaviors in response.
  - (Casti 1997) agents should contain both base-level rules for behavior as well as a higher-level set of "rules to change the rules." The base level rules provide responses to the environment while the "rules to change the rules" provide adaptation.
- The fundamental feature of an agent is **the capability of the component to make independent decisions**.
- This requires **agents to be active rather than purely passive.**

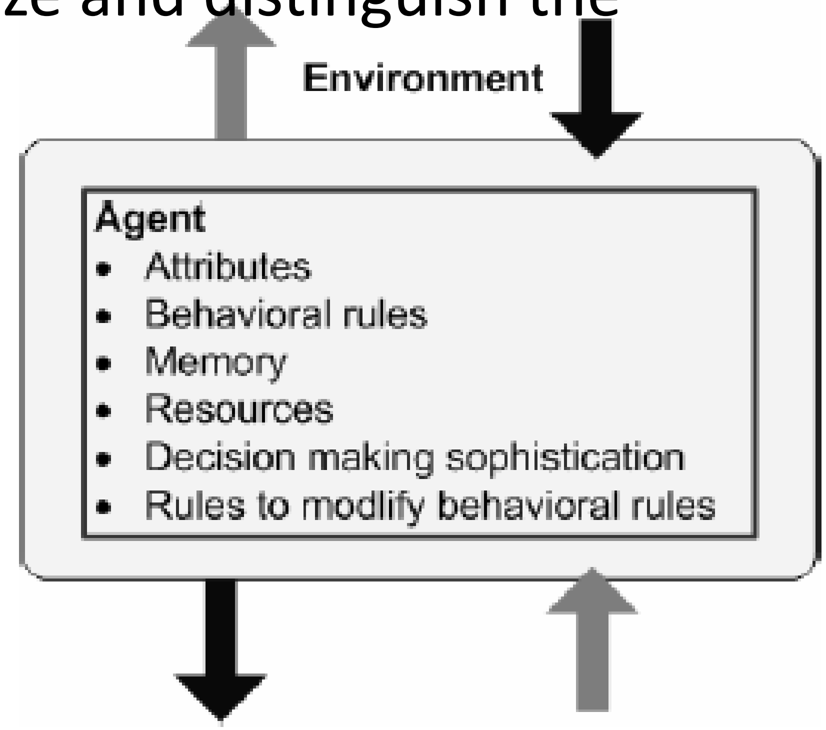
Agents characteristics

- An agent is identifiable (Agents are self-contained)
  - a discrete individual with a set of characteristics and rules governing its behaviors and decision-making capability
  - The discreteness requirement implies that an agent has a boundary and one can easily determine
    - whether something is part of an agent,
    - is not part of an agent,
    - or is a shared characteristic.



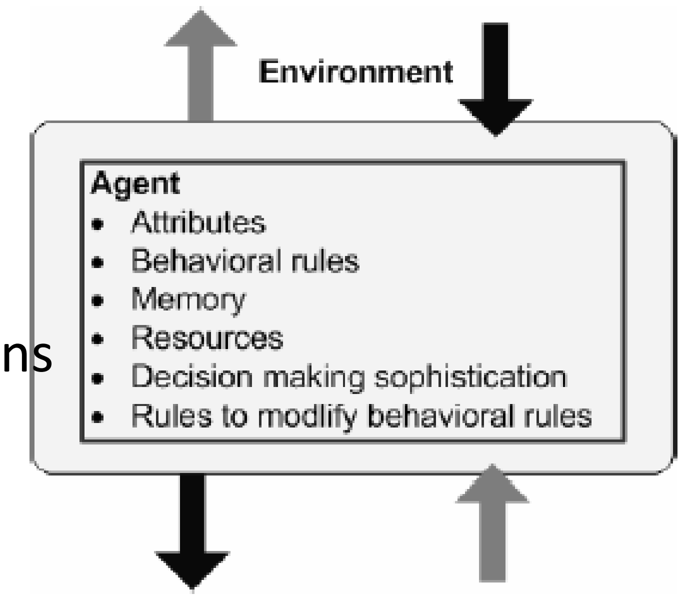
Agent characteristics (cont.)

- An agent is situated, living in an environment with which it interacts with other agents.
  - Agents have protocols for interaction with other agents, such as communication protocols, and the capability to respond to the environment.
  - Agents have the ability to recognize and distinguish the traits of other agents.



Agent characteristics (cont.)

- An agent is goal-directed, having goals to achieve (not necessarily objectives to maximize) with respect to its behaviors
- An agent is autonomous and self-directed
  - An agent can function independently in its environment and in its dealings with other agents, at least over a limited range of situations
- An agent is flexible, and has the ability to learn and adapt its behaviors over time based on experience
  - This requires some form of memory
  - An agent may have rules that modify its rules of behavior



Meta-characteristics of agents

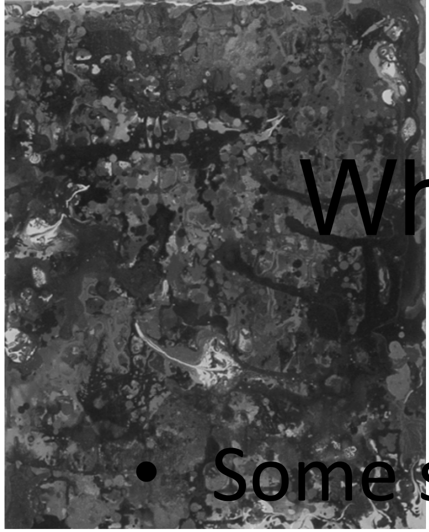
- Agents are diverse, heterogeneous, and dynamic in their attributes and behavioral rules.
- Behavioral rules vary
  - in their sophistication,
  - how much information is considered
  - in the agent decisions (cognitive “load”),
  - the agent’s internal models of the external world including other agents,
  - and the extent of memory of past events the agent retains and uses in its decisions.
- Agents also vary by their attributes and accumulated resources.

The need for ABM: 4 reasons

- The answer is because we live in an increasingly complex world
  - System interdependencies
  - Too much complexity
  - Even more finer level of granularity of data
  - Even more higher computational power

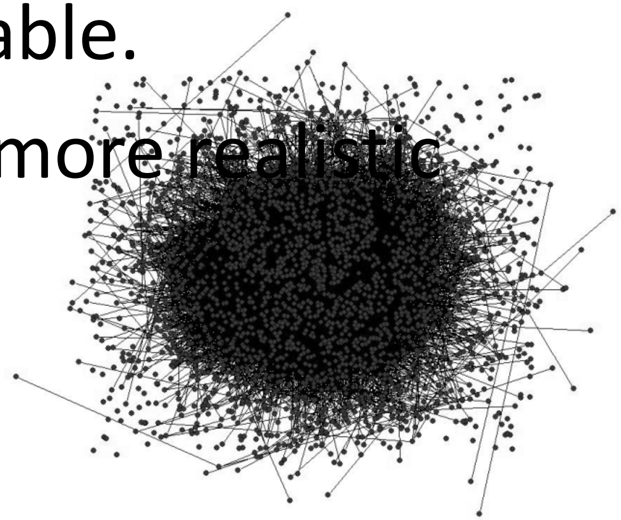
Why ABM: system interdependencies

- The systems that we need to analyze and model are becoming more complex in terms of their interdependencies.
- The traditional modeling tools are not as applicable as they once were.
  - An example application area is the deregulation of the electric power industry.
  - Interdependencies among infrastructures (electric power, natural gas, transportation, petroleum, water, telecommunications, etc.) are becoming the focus public attention as these systems approach their design limits and suffer regular breakdowns.



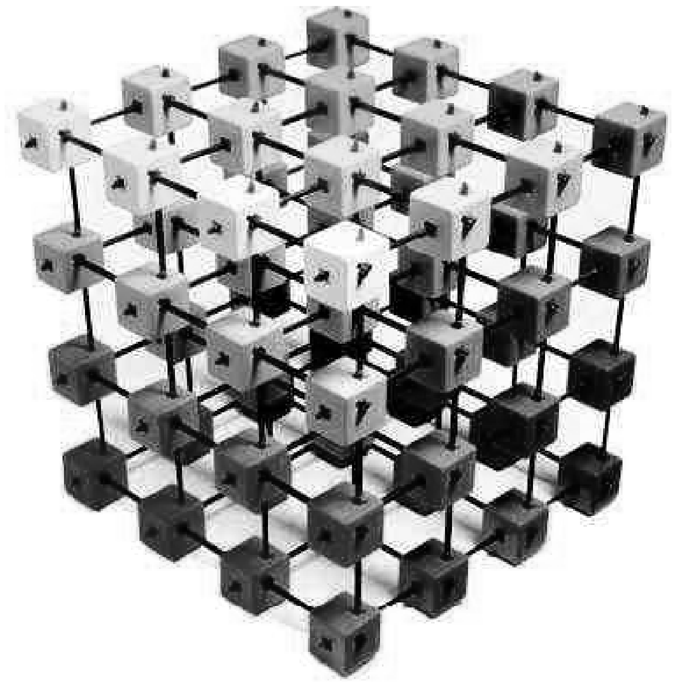
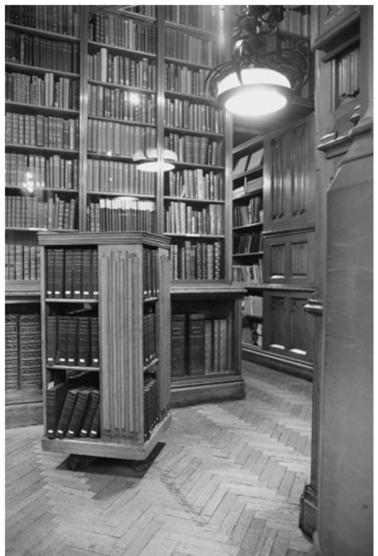
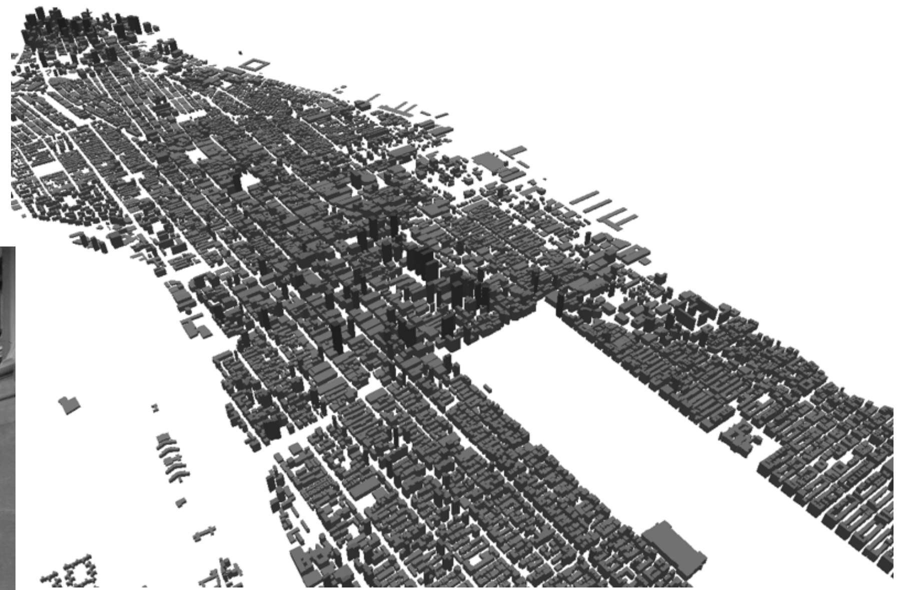
Why ABM: Too much complexity

- Some systems have always been too complex for us to adequately model.
- For example, modeling economic markets has traditionally relied on the notions of perfect markets, homogeneous agents, and long-run equilibrium because these assumptions made the problems analytically and computationally tractable.
- We are beginning to be able to take a more realistic view of these systems through ABMS.



Why ABM: finer level of data granularity

- Data are becoming organized into databases at finer levels of granularity
- Micro-data can now support micro-simulations

Why ABM: higher computational power

- Computational power is advancing rapidly
- We can now compute large-scale micro-simulation models that would not have been plausible just a couple of years ago (2005!!!).

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Backgrounds on ABMS

- ABMS has connections to many other fields including
  - complexity science,
  - systems science,
  - Systems Dynamics,
  - computer science,
  - management science,
  - the social sciences in general, and
  - traditional modeling and simulation

Search “system science” or “system dynamics” on wikipedia

- ABMS draws on these fields for
  - its theoretical foundations,
  - its conceptual world view and philosophy, and
  - for applicable modeling techniques.

Backgrounds on ABMS (cont.)

- ABMS has its direct historical roots in complex adaptive systems (CAS)
  - "systems are built from the ground-up," in contrast to the top-down systems view taken by Systems Dynamics.
- CAS
  - concerns itself with the question of how complex behaviors arise in nature among myopic, autonomous agents.
  - was originally motivated by investigations into adaptation and emergence of biological systems.
  - have the ability to self-organize and dynamically reorganize their components in ways better suited to survive and excel in their environments, and this adaptive ability occurs, remarkably, over an enormous range of scales

Backgrounds on ABMS

- Properties and mechanisms common to all CAS (Holland 1995):
- CAS properties
  - Aggregation: allows groups to form,
  - Nonlinearity: invalidates simple extrapolation,
  - Flows: allow the transfer and transformation of resources and information,
  - Diversity: allows agents to behave differently from one another and often leads to the system property of robustness.
- CAS mechanisms:
  - Tagging: allows agents to be named and recognized,
  - Internal models: allows agents to reason about their worlds,
  - Building blocks: allows components and whole systems to be composed of many levels of simpler components.
- These CAS properties and mechanisms provide a useful framework for designing agent-based models.

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When ABMS

- When there is a natural representation 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 behaviors
- When it is important that agents learn and engage in dynamic strategic behaviors
- 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 is no predictor of the future
- When scaling-up to arbitrary levels is important
- When process structural change needs to be a result of the model, rather than a model input.

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ABMS Applications

- Practical agent-based modeling and simulation is actively being applied in many areas
- modeling agent behavior in the stock market (LeBaron 2002) and supply chains (Fang et al. 2002)
- predicting the spread of epidemics (Huang et al. 2004) and the threat of bio-warfare (Carley 2006),
- modeling the growth and decline of ancient civilizations (Kohler et a. 2005)
- modeling the complexities of the human immune system (Folcik and Orosz 2006),
- and many other areas

Business and Organizations • Manufacturing Operations • Supply chains • Consumer markets • Insurance industry Economics • Artificial financial markets • Trade networks Infrastructure • Electric power markets • Transportation • Hydrogen infrastructure Crowds • Pedestrian movement • Evacuation modeling	Society and Culture • Ancient civilizations • Civil disobedience • Social determinants of terrorism • Organizational networks Military • Command & control • Force-on-force Biology • Population dynamics • Ecological networks • Animal group behavior • Cell behavior and sub cellular processes

ABMS Applications

- ABMS applications range from
  - small, elegant, minimalist models
  - to large-scale decision support systems.
- Minimalist models are based on a set of idealized assumptions, designed to capture only the most salient features of a system.
  - a wide range of assumptions can be varied over a large number of simulations.
- Decision support models tend to be large-scale applications, designed to answer a broad range of real-world policy questions.
  - includes real data
  - has passed some degree of validation testing to establish credibility in their results.

How to do ABMS

- At a general level, one goes about building an agent-based model in much the same way as any other type of model

1. identify the purpose of the model, the questions the model is intended to answer and engage the potential users in the process.
2. systematically analyze the system under study, identifying components and component interactions, relevant data sources, and so on.
3. apply the model and conduct a series of “what-if” experiments by systematically varying parameters and assumptions.
4. understand the robustness of the model and its results by using sensitivity analysis and other techniques.

How to do ABMS: agent prospective vs process-based prospective

- Agent-based modeling brings with it a few unique aspects owing to the fact that ABMS takes the agent perspective, first and foremost, in contrast to the process-based perspective that is the traditional hallmark of simulation modeling.
- Practical ABMS requires one to:
    1. identify the agents and get a theory of agent behavior,
    2. identify the agent relationships and get a theory of agent interaction,
    3. get the requisite agent-related data,
    4. validate the agent behavior models in addition to the model as a whole, and
    5. run the model and analyze the output from the standpoint of linking the micro-scale behaviors of the agents to the macroscale behaviors of the system.

How to do ABMS: not yet mature formalisms

- ABM does not as of yet have a mature set of standard formalisms or procedures for model development and agent representation such as those that are part of Systems Dynamics modeling.
- Other than the implemented software code, there is no scheme for unambiguously representing an agent-based model.
- However, agent modeling documentation schemes along these lines have recently been proposed with the intent of promoting agent model transferability and reproducibility (Grimm et al. 2006).
- Agent-based modeling can benefit from the use of the Unified Modeling Language (UML) for representing models.

How to do ABMS: UML based visual modeling

- UML is a visual modeling language for representing object-oriented (O-O) systems (Booch, Rumbaugh et al. 1998) that is commonly adopted to support agent-based models in both the design and communication phases.
- UML consists of a number of high-structured types of diagrams and graphical elements that are assembled in various ways to represent a model.
- The UML representation is at a high level of abstraction, independent of the model's implementation in the particular O-O programming language used.

How to do ABMS: O-O modeling paradigm

- Most large-scale agent-based modeling toolkits that provide basic agent functionality are based on the object oriented paradigm.
- Agent-based simulation is not the same as object-oriented simulation, but the O-O modeling paradigm is a useful basis for agent modeling, since an agent can be considered a self-directed object with the capability to autonomously choose actions based on the agent's situation.
- The O-O paradigm is natural for agent modeling, with its use of object classes as agent templates and object methods to represent agent behaviors. O-O modeling takes a data-driven rather than a process-driven perspective.
- One way to begin the modeling process is to define abstract data types and objects.

How to do ABMS: 5 general steps

1. *Agents: Identify the agent types and other objects* (classes) along with their attributes.
2. *Environment: Define the environment the agents* will live in and interact with.
3. *Agent Methods: Specify the methods by which* agent attributes are updated in response to either agent-to-agent interactions or agent interactions with the environment.
4. *Agent Interactions: Add the methods that control* which agents interact, when they interact, and how they interact during the simulation.
5. *Implementation: Implement the agent model in* computational software.

How to do ABMS: discovering agents

- Identifying agents, accurately specifying their behaviors, and appropriately representing agent interactions are the keys to developing useful agent models.
  - Agents are generally the decision-makers in a system. These include traditional decision-makers, such as managers, as well as nontraditional decision-makers, such as complex computer systems that have their own behaviors.
- One needs a theory of agent behavior.
  - normative model in which agents attempt to optimize and use this model as a starting point for developing a simpler and more descriptive heuristic model of behavior.
  - behavioral model if applicable behavioral theory is available (e.g. consumer shopping behavior).

How to do ABMS: more…

- Discovery agents
  - Identifying agents, accurately specifying their behaviors, and appropriately representing agent interactions
  - Agents are generally the decision-makers in a system.
    - traditional decision-makers, such as managers
    - nontraditional decision-makers, such as complex computer systems that have their own behaviors
- ABMS life cycle
  - Developing an agent-based simulation is part of the more general model software development process.
  - Desktop ABMS
  - Large-scale ABMS
- ABMS toolkit
  - **Repast (North et al. 2006)**, Swarm (SDG 2006; Minar et al. 1996), NetLogo (NetLogo 2006) and MASON (GMU 2006)

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