Agent-Based Modeling and Simulation

Models, Agent-based Models and the Modeling Cycle

Dr. Alejandro Guerra-Hernández

Instituto de Investigaciones en Inteligencia Artificial
Universidad Veracruzana
Campus Sur, Calle Paseo Lote II, Sección Segunda No 112,
Nuevo Xalapa, Xalapa, Ver., México 91097

mailto:aguerra@uv.mx
https://www.uv.mx/personal/aguerra/abms

Doctorado en Inteligencia Artificial 2024

Universidad Veracruzana

Credits

- These slides are based on the book of Railsback and Grimm [14], chapter 1.
- Any difference with this source is my responsibility.
-
-

Universidad Veracruzana

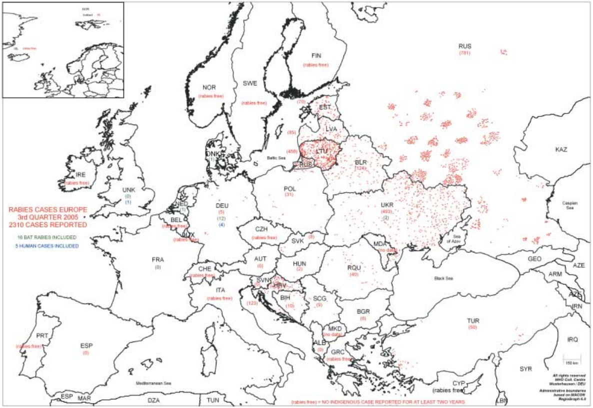
Rabies in Europe

- Rabies is a viral disease that kills great numbers of wild mammals and can spread to domestic animals and people.
- In Europe, rabies is transmitted mainly by red fox.
- When an outbreak starts in a previously rabies-free region, it spreads in traveling waves: alternating areas of high and low infection rates.
- Rabies can be eradicated from large areas, and new outbreaks can be controlled, by immunizing foxes.
- Which is extremely expensive and works only if new outbreaks are detected and contained.

Universidad Veracruzana

Rabies in central Europe

- Confirmed cases in 2005, second quarter [5].



Universidad Veracruzana

Cost-Effectiveness

- What percentage of wild foxes need to be vaccinated to eliminate rabies from an area? and
- What is the best strategy for responding to outbreaks?

Universidad Veracruzana

Classical Solution

- Differential equation models of the European rabies problem predicted that 70% of the fox population must be vaccinated to eliminate rabies.
- Managers planned to respond to new outbreaks using a belt vaccination strategy: not vaccinating the outbreak location itself but a belt around it, the width of which was usually determined by the limited emergency supply of vaccine.

Universidad Veracruzana

New Approaches

- Jeltsch et al. [9] developed a simple agent-based model (ABM) that represented fox families in stationary home ranges and migration of young foxes, accurately simulating the spread of rabies over both space and time.
- Eisinger et al. [6] and Eisinger and Thulke [5] modified the ABM to evaluate how the distribution of vaccination baits over space affects rabies control: Eradication could be achieved with a vaccination rate 10% lower.
- The reason: Spread of rabies emerges from local infectious contacts that actually facilitate eradication. The belt vaccination strategy for outbreaks would fail more often than an alternative local compact treatment circle.

Universidad Veracruzana

Common Features of These Problems

- ABM can find new, better solutions to many problems important to our environment, health, and economy.
- The common feature of these problems is that:
  - They occur in systems composed of autonomous agents
  - that interact with each other and their environment,
  - differ from each other and over space and time, and
  - have behaviors that are often very important to how the system works.

Universidad Veracruzana

Learning Objectives

- What models are, and what modeling is –Why do we build models anyway?
- The modeling cycle, the iterative process of designing, implementing, and analyzing models and using them to solve scientific problems.
- What agent-based models are –How are ABMs different from other kinds of model, and why would you use them?

Universidad Veracruzana

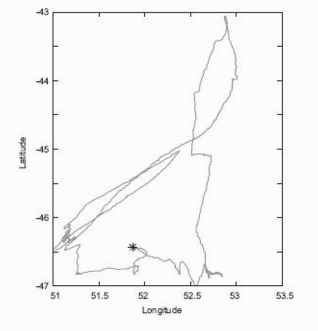
Ideas

- A model is a purposeful representation of some real system [16].
- Models are used to solve problems or answer questions about a system or a class of systems.
- To formulate a model means to design its assumptions and algorithms.
- The problem/question serve as a filter: all those aspects of the real system considered irrelevant or insufficiently important for answering this question are filtered out (ignored or represented only in a very simplified way).

Universidad Veracruzana

Example: Searching for mushrooms

- Did you ever search for mushrooms in a forest?
- Did you ask yourself what the best search strategy might be?
- Intuitive strategies, such as scanning an area in wide sweeps but, upon finding a mushroom, turning to smaller-scale sweeps because you know that mushrooms occur in clusters.



Universidad Veracruzana

Common features

- Their sensing radius is limited –they can only detect what they seek when they are close to it– so they must move. And,
- Often the items searched for are not distributed randomly or regularly but in clusters, so search behavior should be adaptive: it should change once an item is found.

Universidad Veracruzana

Why would we want a model?

- Because even for this simple problem we are not able to develop quantitative mental models.
- Intuitively we find a search strategy which works quite well, but then we see others who use different strategies and find more mushrooms.
- Are they just luckier, or are their strategies better?

Universidad Veracruzana

Purpose

- We need a clearly formulated purpose before formulating a model.
- With the purpose “What search strategy maximizes the number of mushrooms found in a certain time?” we know that:
  - Trees and vegetation can be ignored; we only need to take into account that mushrooms are distributed in clusters. Also, other heterogeneity in the forest can be ignored, e.g., topography or soil type-they might affect searching a little, but not enough to affect the general answer to our question.
  - The mushroom hunter will be represented in a very simplified way: just a moving “point” that has a certain sensing radius and keeps track of how many mushrooms it has found and perhaps how long it has been since it found the last one.

Universidad Veracruzana

A model

- Clusters of items.
- An individual agent that searches for the items.
- A strategy: If it finds a search item, it switches to smaller scale movement, but if the time since it found the last item exceeds a threshold, it switches back to straight movement to increase its chances of detecting another cluster of items.

Universidad Veracruzana

Which factors are important?

- This searching problem is so simple that we have good idea of what processes and behaviors are important for modeling it.
- How in general can we know whether certain factors are important with regard to the question addressed with a model? We can't!
- We have to formulate, implement, and analyze a model: using mathematics and computer logic to rigorously explore the consequences of our simplifying assumptions.
- Our first formulation of a model must be based on our preliminary understanding of how the system works, what the important elements and processes are, and so on.

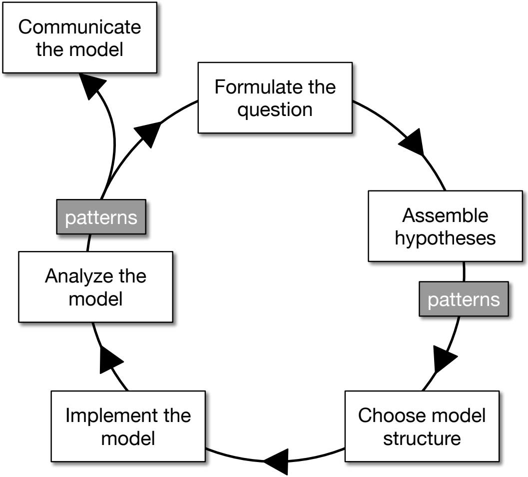
Universidad Veracruzana

Evaluation

- Because the assumptions in the first version of a model are experimental, we have to test whether they are appropriate and useful.
- We need criteria for whether the model can be considered a good representation of the real system. These criteria are based on patterns or regularities that let us identify and characterize the real system.
- Example: Stock market models should produce the kinds of volatility and trends in prices we see in real markets (stylized facts [2]).
- Often we find that the first version of a model is too simple, lacks important processes and structures, or is simply inconsistent. We thus go back and revise our simplifying assumptions.

Universidad Veracruzana

The Iterating Modeling Cycle



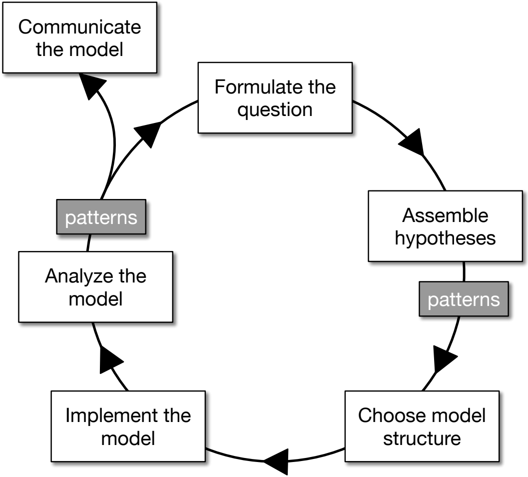
Universidad Veracruzana

Formulate the Question

- We need to start with a very clear research question because this question then serves as compass and filter for designing a model.
- Often, formulating a clear and productive question is by itself a major task because a clear question requires a clear focus. For complex systems, getting focused can be difficult.
- Very often, even our questions are only experimental and later we might need to reformulate the question, perhaps because it turned out to be not clear enough, or too simple, or too complex.
- Example: What search strategy maximizes the rate of finding items if they are distributed in clusters?

Universidad Veracruzana

The Iterating Modeling Cycle



Universidad Veracruzana

Assemble hypotheses

- Agent-based modeling is “naive” [3] in the sense that we are not trying to aggregate agents and what they are doing in some abstract variables like abundance, biomass, overall wealth, demographic rates, or nutrient fluxes.
- Instead, we naively and directly represent the agents and their behavior.
- Is it possible to answer our question using a more aggregated and thus simpler model?
- Usually we have to formulate many hypotheses for what processes and structures are essential to the question or problem we address.

Universidad Veracruzana

Approaches

- We can start top-down:
  - What factors have a strong influence on the phenomena of interest?
  - Are these factors independent or interacting?
  - Are they affected by other important factors?
- We might draw so-called influence diagrams, or flow charts, or just caricatures of our system and question.
- But whatever technique we prefer, this task has to combine existing knowledge and understanding, a “brainstorming” phase in which we wildly hypothesize, and, most importantly, a simplification phase.

Universidad Veracruzana

Simplification

- We have to force ourselves to simplify as much as we can, or even more.
- The modeling cycle must be started with the most simple model possible, because we want to develop understanding gradually, while iterating through the cycle.
- A common mistake of beginners is to throw too much into the first model version –usually arguing that all these factors are well known and can't possibly be ignored.
- Just our preliminary understanding of a system is not sufficient for deciding whether things are more or less important for a model. Remember the purpose.

Universidad Veracruzana

Advice

- So, it is wise to have a model implemented as soon as possible, even if it is ridiculously simple.
- But the simpler the model is, the easier it is to implement and analyze, and the sooner we are productive.
- The real productive phase in a modeling project starts when we get the modeling cycle running: assumptions - implementation - analyses - interpretation - revised assumptions, and so on.
- Finally, see pattern-oriented modeling.

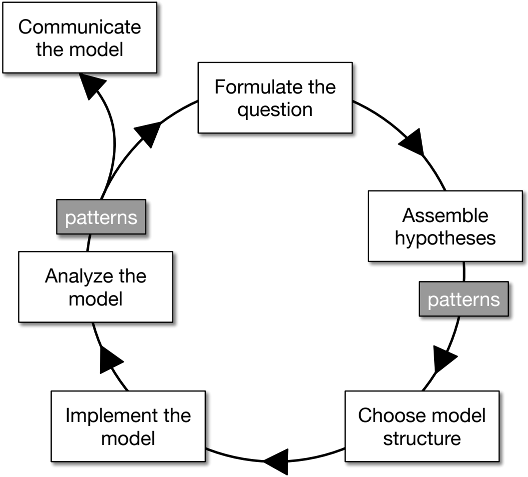
Universidad Veracruzana

Example

- The essential process is switching between relatively straight large-scale “scanning” movement and small-scale searching, depending on how long it has been since the hunter last found an item.

Universidad Veracruzana

The Iterating Modeling Cycle



Choose Model Structure

- It is time to sit down and think through our model in detail.
- Produce a written formulation of the model.
- Producing and updating this formulation is essential for the entire modeling process, including delivery to our "clients" (our thesis committee, journal reviewers, research sponsors, etc.).
- It includes:
  - scales
  - entities
  - state variables
  - processes, and
  - parameters.

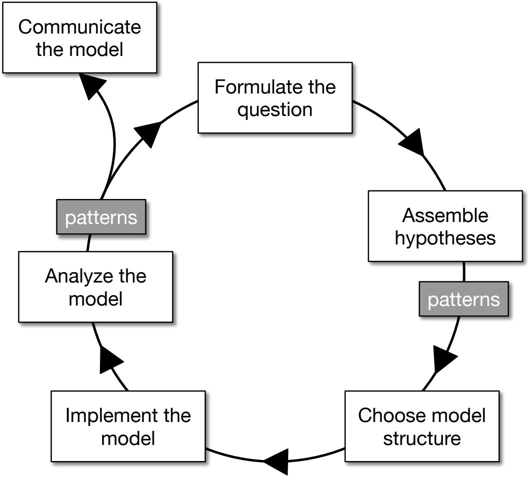
Universidad Veracruzana

Example

- This step, for the Mushroom Hunt model, includes specifying
  - how the space that hunters move through is represented (as square grids with size equal to the area the hunter can search in one time step),
  - what kinds of objects are in the model (one hunter and the items it searches for),
  - the state variables or characteristics of the hunter (the time it has hunted and the number of items it has found, and the time since last finding an item), and
  - exactly how the hunter searches.

Universidad Veracruzana

The Iterating Modeling Cycle



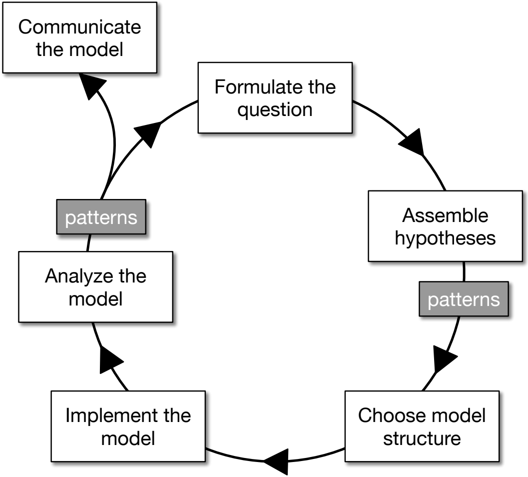
Universidad Veracruzana

Implement the Model

- The most technical part, where we use mathematics and computer programs to translate our verbal model description into an "animated" object [11].
- Why "animated"? Because, in a way, the implemented model has its own, independent dynamics, driven by the internal logic of the model.
- Our assumptions may be wrong or incomplete, but the implementation itself is, barring software mistakes, always right: it allows us to explore, in a logical and rigorous way, the consequences of our assumptions and see whether our initial model looks useful.
- NetLogo.

Universidad Veracruzana

The Iterating Modeling Cycle



Universidad Veracruzana

Analyze the Model

- Analyzing a model and learning from it-is the most time-consuming and demanding task in the cycle.
- Individual-based ecology [7]: we do not just want to see what happens when we create some agents and make up their behaviors –we want to see what agent behaviors can explain and predict important characteristics of real systems.
- Example: we could analyze the model by trying a variety of search algorithms and parameter values to see which produces the highest rate of finding items.

Universidad Veracruzana

Simplification revisited

- Historically, the complexity of scientific models was often limited by mathematical tractability: with differential calculus, we had to keep models simple enough in order to "solve" them. We were often limited to modeling quite simple problems.
- With computer simulation, the limitation of mathematical tractability is removed so we can start addressing problems that require models that include more characteristics of the real systems.
- ABMs are less simplified in one specific and important way: they represent a system's individual components and their behaviors. Instead of describing a system only with variables representing the state of the whole system, we model its individual agents.

Universidad Veracruzana

Agent-Based Models I

- ABMs are thus models where individuals or agents are described as unique and autonomous entities that usually interact with each other and their environment locally.
- Example: Agents may be organisms, humans, businesses, institutions, and any other entity that pursues a certain goal.
- Being unique implies that agents usually are different from each other in such characteristics as size, location, resource reserves, and history.
- Interacting locally means that agents usually do not interact with all other agents but only with their neighbors –in geographic space or in some other kind of "space" such as a network.
- Being autonomous implies that agents act independently of each other and pursue their own objectives.

Universidad Veracruzana

Agent-Based Models II

- Example: Organisms strive to survive and reproduce; traders in the stock market try to make money; businesses have goals such as meeting profit targets and staying in business; regulatory authorities want to enforce laws and provide public well-being.
- Agents therefore use adaptive behavior: they adjust their behavior to the current states of themselves, of other agents, and of their environment.

Universidad Veracruzana

Emergence

- Using ABMs lets us address problems that concern emergence: system dynamics that arise from how the system's individual components interact with and respond to each other and their environment.
- Hence, with ABMs we can study questions of how a system's behavior arises from, and is linked to, the characteristics and behaviors of its individual components.

Universidad Veracruzana

Kinds of Questions I

- How can we manage tropical forests in a sustainable way, maintaining both economic uses and biodiversity levels critical for forests stability properties [8]?
- What causes the complex and seemingly unpredictable dynamics of a stock market? Are market fluctuations caused by dynamic behavior of traders, variation in stock value, or simply the market's trading rules [10, 4]?
- How is development of human tissue regulated by signals from the genome and the extracellular environment and by cellular behaviors such as migration, proliferation, differentiation, and cell death? How do diseases result from abnormalities in this system [13]?

Universidad Veracruzana

Kinds of Questions II

- What drives patterns of land use change during urban sprawl, and how are they affected by the physical environment and by management policies [1, 12]?

Universidad Veracruzana

ABMs Features

- ABMs are different because they are concerned with two (and sometimes more) levels and their interactions: we use them to both look at what happens to the system because of what its individuals do and what happens to the individuals because of what the system does.
- ABMs are also often different from traditional models in being unsimplified in other ways, such as representing how individuals, and the environmental variables that affect them, vary over space, time, or other dimensions. ABMs often include processes that we know to be important but are too complex to include in simpler models.

Universidad Veracruzana

Required skills

- Traditionally differential calculus and statistics, but ABMs modeling required additional skills:
  - A new "language" for thinking about and describing models. We need a standard set of concepts, e.g., emergence, adaptive behavior, interaction, sensing.
  - The software skills to implement models on computers and to observe, test, control, and analyze the models. ABMs are harder to implement than other kinds of models.
  - Strategies for designing and analyzing models. If a model is too complex it quickly becomes too hard to parameterize, validate, or analyze.

Universidad Veracruzana

Summary

- A model is a purposeful simplification of a system for solving a particular problem (or category of problems).
- We use ABMs when we think it is important for a model to include the system's individuals and what they do.
- Modeling is a cycle of: formulating a precise question; assembling hypotheses for key processes and structures; formulating the model by choosing appropriate scales, entities, state variables, processes, and parameters; implementing the model in a computer program; and analyzing, testing, and revising.

Universidad Veracruzana

TRACE

- Understanding this modeling cycle is so important that a recent review of modeling practice [15] concluded that explicitly thinking about and documenting each step in the cycle is the primary way we can improve how models are developed and used.
- Schmolke et al. then proposed a very useful format (TRACE) for documenting the entire cycle of developing, implementing, and analyzing a model:

  `http://cream-itn.eu/trace`

Universidad Veracruzana

References I

[1] DG Brown et al. "Agent-based and analytical modeling to evaluate the effectiveness of greenbelts". In: *Environmental Modelling & Software* 19.12 (2004), pp. 1097–1109.

[2] R Cont. "Empirical properties of asset returns: stylized facts and statistical issues". In: *Quantitative Finance* 1.2001 (2001), pp. 223–236.

[3] D DeAngelis, K Rose, and M Huston. "Individual-oriented approaches to modeling ecological populations and communities". In: *Frontiers in mathematical biology*. Springer, 1994, pp. 390–410.

[4] J Duffy. "Agent-based models and human subject experiments". In: *Handbook of computational economics* 2 (2006), pp. 949–1011.

[5] D Eisinger and HH Thulke. "Spatial pattern formation facilitates eradication of infectious diseases". In: *Journal of Applied Ecology* 45.2 (2008), pp. 415–423.

[6] D Eisinger et al. "Emergency vaccination of rabies under limited resources–combating or containing?" In: *BMC Infectious Diseases* 5.1 (2005), p. 10.

[7] V Grimm and SF Railsback. *Individual-based modeling and ecology. Princeton series in theoretical and computational biology*. Princeton, NJ, USA: Princeton University Press, 2005.

Universidad Veracruzana

References II

[8] M Huth and M Ryan. *Logic in Computer Science: Modelling and Reasoning about Systems*. Cambridge, UK: Cambridge University Press, 2004.

[9] F Jeltsch et al. "Pattern formation triggered by rare events: lessons from the spread of rabies". In: *Proceedings of the Royal Society of London B: Biological Sciences* 264.1381 (1997), pp. 495–503.

[10] B LeBaron. "Empirical regularities from interacting long-and short-memory investors in an agent-based stock market". In: *IEEE Intelligent Systems transactions on evolutionary computation* 5.5 (2001), pp. 442–455.

[11] AJ Lotka. *Elements of Physical Biology*. Baltimore, MD, USA: Williams & Wilkins Company, 1925.

[12] DC Parker et al. "Multi-agent systems for the simulation of land-use and land-cover change: a review". In: *Annals of the association of American Geographers* 93.2 (2003), pp. 314–337.

[13] SM Peirce, EJ Van Gieson, and TC Skalak. "Multicellular simulation predicts microvascular patterning and in silico tissue assembly". In: *The FASEB journal* 18.6 (2004), pp. 731–733.

Universidad Veracruzana

References III

[14] SF Railsback and V Grimm. *Agent-Based and Individual-Based Modeling*. Second. Princeton, NJ, USA: Princeton University Press, 2019.

[15] A Schmolke et al. "Ecological models supporting environmental decision making: a strategy for the future". In: *Trends in ecology & evolution* 25.8 (2010), pp. 479–486.

[16] AM Starfield, KA Smith, and AL Bleloch. *How to model it: Problem solving for the computer age*. New York, NY, USA: McGraw-Hill, 1990.

Universidad Veracruzana