Agent-Based Modeling and Simulation

Patterns for Theory Development

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

Credits

- These slides are based on the book of Railsback and Grimm [7], chapter 19.
- Any difference with this source is my responsibility.
-
-

Universidad Veracruzana

The Problem

- As we design a model's structure and formulate its schedule, the overview part of the ODD protocol, we identify which processes we need without bothering yet about how they work.
- Then, to get the modeling cycle going, we start with a very simple, often obviously wrong, representation of the model's processes.
- Example. We often just assume that agents make decisions randomly.
- However, after we have a first implementation of the entire model, we need to unsimplify and come up with sufficiently realistic and useful representations of key processes.
- How can we do this?

Universidad Veracruzana

Minor and Major Processes

- First of all, we do not want to consider all the processes in a model with the same level of detail.
- ABMs typically include a number of relatively minor processes that can be represented simply or by using sub-models from the literature.
- Results of the model are unlikely to be too sensitive to the details of such sub-models.
- But ABMs also typically have a few processes, in particular agent behaviors, that seem most important.
- Agent behaviors are especially important because they are the reason we use an ABM in the first place and also because we are less likely to find a useful way to represent them in the literature.

Universidad Veracruzana

Questions

- What is the most important agent behavior, and
- How do we identify or invent a good sub-model to represent it?

Universidad Veracruzana

Model Development

- We call this stage of model design theory development.
- A theory being a sub-model for some particular agent behavior that has been tested and proven useful for explaining how the system works in a particular context
- The goal is to find models of key agent behaviors that are simple, but complex enough to produce useful system behaviors.

Universidad Veracruzana

Testing

- How do we test models of agent behavior to know which to accept as theory?
- The answer of course is via pattern-oriented modeling (POM): we accept models of agent behavior as theory when they cause the ABM to reproduce the set of patterns that we chose to characterize the system's dynamics.
- We introduce here the use of ABMs as virtual laboratories where you test and improve submodels for key behaviors.

Universidad Veracruzana

Motivation

- Theory development is the most unique, important, and academically fertile part of agent-based modeling.
- How to model key agent behaviors is obviously fundamental to agent-based simulation, and there are many important discoveries to be made.
- Currently, almost every ABM requires new theory for a new behavior or context, and developing the theory will often be as important as anything else learned in the modeling study.
- This stage of modeling is, more than any other, about basic scientific discovery.

Universidad Veracruzana

Objectives

- Understand the general concept of developing theory by posing alternative hypotheses, conducting controlled experiments to identify the most useful hypothesis, then revising them and conducting more experiments.
- Understand that theory in agent-based science includes models of agent behavior that explain important system behaviors; and that we develop this theory via pattern-oriented testing of hypothesized sub-models.
- Develop experience with this theory development process.

Universidad Veracruzana

Virtual Labs

- We can consider an ABM a virtual laboratory where we test alternative submodels for key behaviors.
- We do so by plugging these alternative sub-models into the ABM and testing how well the ABM then reproduces patterns observed in the real system.
- Through a cycle of testing and refining sub-models, perhaps combined with research on the real system to find additional patterns, we exclude (falsify) unuseful sub-models and home in on useful ones that we can treat as theory.

Universidad Veracruzana

Strong Inference

- Contrasting alternative theories, or hypotheses, is the foundation of what is simply called scientific method.
- Platt [6] rephrased this approach and called it strong inference.
- He wondered why some fields of science move forward so much faster than others. His answer was that progress depended largely on how systematically people used this method.

Universidad Veracruzana

Steps

1. Devising alternative hypotheses;
2. Devising a crucial experiment (or several of them), with alternative possible outcomes, each of which will, as nearly as possible, exclude one or more of the hypotheses;
3. Carrying out the experiment so as to get a clean result;
4. Recycling the procedure, making sub-hypotheses or sequential hypotheses to refine the possibilities that remain, and so on.

Universidad Veracruzana

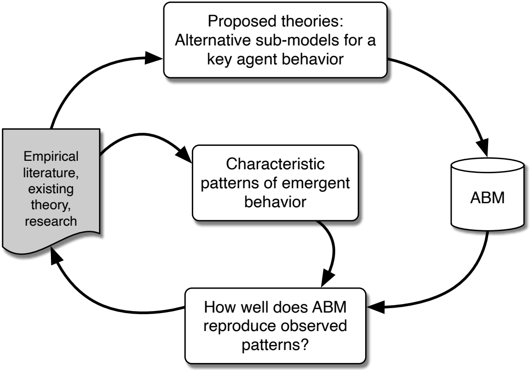
Proposed POM approach

1. Identify alternative sub-models (hypotheses) for the behavior;
2. Implement the alternative sub-models in the ABM, testing the software carefully to get clean results;
3. Test and contrast the alternatives by seeing how well the model reproduces the characteristic patterns, falsifying sub-models that cannot reproduce the patterns; and
4. Repeat the cycle as needed: revise the behavior sub-models, look for (or generate, from experiments on the real system) additional patterns that better resolve differences among alternative submodels, and repeat the tests until a submodel is found that adequately reproduces the characteristic patterns.

Universidad Veracruzana

Graphically

- The approach we use to developing theory for agent behavior is a sub-cycle of the modeling cycle, and closely follows Platt's steps:



Finding Alternative Theories

- Sometimes rules for key behavior have already been proposed by others or identified as the model was conceived.
- However, often it is not at all clear how to model behavior, so we start with both empirical data and existing theory.
- Are there sufficient observations of the real world to develop statistical and stochastic sub-models?
- Is there decision theory for the kinds of agents and decisions being modeled?
- It is always important to understand existing theory as a starting point, and in some fields quite useful kinds of theory can be adapted to ABMs.

Universidad Veracruzana

Behavioral Sciences

- Many scientific fields include a sub-discipline focused on the behavior of individuals.
- Example. Cognitive psychology, behavioral ecology.
- They include theory for how individuals make complex decisions that include trade-offs among competing objectives.
- Example. How people or businesses choose among investments that provide different expected payoffs and risks.
- Example. How animals select among alternative strategies (for foraging, mating, etc.) that affect both growth and survival.

Universidad Veracruzana

Optimization

- This classical individual-level theory often uses optimization: if we assume that an agent knows the future payoffs and risks associated with each alternative behavior, it can mathematically calculate the behaviors that maximize an objective such as net income or reproductive output.
- Optimization approaches have been very successful at producing realistically complex behaviors, so this kind of theory is very appealing for ABMs.
- But agents cannot know the future payoffs and risks of alternative behaviors, or sometimes even the alternatives available, because those future conditions depend on how all the other agents behave.

Universidad Veracruzana

Goal

- Your goal is not to reproduce all behaviors that your agents are known to exhibit! If you try to do so, you will never finish.
- Instead, remember that you seek theory that is just realistic enough to reproduce the patterns of interest, and make sure you have a clear limit on what patterns you need to reproduce.

Universidad Veracruzana

Null Theories

- You should always start with null theories, that is, theories that do not use any specific mechanism or assumption.
- Typical null theories are to just assume that agents make decisions randomly, and (the opposite) to assume agents always do exactly the same thing.
- Why start with null theories?
  - It allows you to develop and test the rest of the ABM before focusing on behavior sub-models.
  - It helps you learn how sensitive the output of the ABM is to how you represent the key behavior.

Universidad Veracruzana

Expected Results

- You might find that some key patterns emerge robustly even without detailed behavior; then you will have learned that the behavior in fact is not key to explaining the patterns; or
- You might learn that some important patterns are not reproduced, showing that the theory development exercise is in fact important.

Universidad Veracruzana

A final methodological comment

- Remember that exploring and testing sub-models independently before you put them into the ABM for pattern-oriented evaluation, is a useful technique.
- Your progress in theory development will be much faster if you implement hypothesized sub-models separately, *e.g.*, in a spreadsheet, and understand them thoroughly before plugging them into the ABM.

Universidad Veracruzana

... and Fish Schooling

- You already have experience doing theory development in section 8.4 (stochasticity).
- We discussed the simulation experiments that Huth and Wissel [4] used to find a model of individual behavior that explains how groups of fish form schools.
- A suggested exercise asks to contrast some alternative sub-models for how animals form schools and flocks.
- This work on fish schools was one of the earliest examples of theory development for ABMs

Universidad Veracruzana

Assumptions

- Individual animals adapt their movement direction and speed to match those of their neighbors, and move toward their neighbors while maintaining a minimum separation distance and avoiding collisions.
- Huth and Wissel [4] identified two alternative assumptions, potential theories, for how fish adapt their movement:
    1. One theory was that fish react to only the nearest other fish;
    2. a second was that fish adapt to the average direction and location of several neighbors.

Universidad Veracruzana

Contrasting alternatives I

- Huth and Wissel simulated them and compared the results to several observed patterns.
- One pattern was simple and qualitative: Did the model fish look like a school of real fish?
- Other patterns were quite quantitative, using measures of how compact and coordinated real fish schools are:
  - the mean distances between fish and their nearest neighbor,
  - the mean angle between a fish's direction and the average direction of all fish, and
  - the root mean square distance from each fish to the school's centroid.

Universidad Veracruzana

Contrasting alternatives II

- The theory that fish adapt to the average of several neighbors reproduced these patterns robustly over a wide range of parameter values.
- The alternative of following one nearest neighbor did not reproduce the patterns and was hence falsified.

Observations

- The experiments of Huth and Wissel considered only the most basic patterns of schooling and focused on fish.
- However, pioneering studies such as theirs started the modeling cycle, and subsequent studies have produced more detailed models, more quantitative data on real animals, and much more refined theory.
- The theory that birds always respond to six or seven neighbors (Ballerini et al. [1]) created a more realistically cohesive model flock than did the alternative that birds respond to all neighbors within a fixed distance.

Universidad Veracruzana

Double-Auction Markets

- Double-auction markets include agents who are either buyers or sellers, with buyers buying goods from those sellers who ask for a price lower than the buyer's value of the good.
- Example. Stock markets.
- They are governed by rules (protocols) that serve purposes such as:
  - Letting buyers know the best available price and sellers know what buyers are willing to pay.
  - Determining the exact price at which trades are made (trades occur only when a buyer is willing to pay more than a seller is asking, so the trading price is between these two values); and
  - Updating this information as trades are executed and participants adjust their prices and willingness to pay.

Universidad Veracruzana

Patterns

- Duffy [2] describes a series of experiments, using both ABMs and real people, to develop theory for how traders decide when to buy or sell.
- The exact theory question is, What assumptions about trader intelligence are sufficient to reproduce patterns observed in double-auction markets operated by real people?
- Double-auction markets have been simulated with ABMs many times, and the obvious theory question is how to represent the elaborate ways that people make trading decisions in sufficient detail so that market models produce realistic dynamics.
- What are realistic dynamics?

Universidad Veracruzana

Human-based Experiments

- A number of empirical experiments have used real people to represent buyers and sellers in game-like artificial markets that are simplified in the same ways that the ABMs are.
- These experiments have identified patterns such as that people rapidly converge on a very efficient solution, the equilibrium price where the number of willing buyers equals the number of willing sellers.

Universidad Veracruzana

Agent-based Experiments I

- Duffy started with a null theory that is extremely simple.
- Gode and Sunder [3] simulated a market with zero-intelligence traders, *i.e.*, traders decided randomly (within very wide bounds) the price at which they would buy or sell.
- Traders could make trades that lose instead of make money. However, the market rules that link the highest offer to buy with the lowest selling price were still in effect.
- As expected, this null theory resulted in wild fluctuation in the market's exchange price.

Universidad Veracruzana

Agent-based Experiments II

- Then Gode and Sunders add the smallest bit of intelligence by constraining the random trades to exclude those that lose money.
- Now, the result was surprising: the simulated market rapidly converged, just as the human market did, on an efficient equilibrium price.
- In fact, these minimal-intelligence trader agents made more total profit than the humans did.

Universidad Veracruzana

Observations I

- One conclusion is that theory for trading decisions in a market ABM might not need to be elaborate at all, because much of the system's behavior emerges instead from the market's elaborate trading rules.
- However, the results of this experiment triggered so much interest that a number of subsequent studies identified additional patterns and tested whether they could be reproduced using minimally intelligent trader behavior.
- At least one of them, the effects of a price ceiling imposed on the market, was reproduced by the minimal-intelligence trading theory.

Universidad Veracruzana

Observations II

- As markets are made more complex and realistic, human traders produce less efficient results but minimal-intelligence agents do far worse.
- And even the original experiment of Gode and Sunder identified one pattern of the human market, low price volatility that was not reproduced by the ABM.
- By using zero-intelligent agents as a baseline, the researcher can ask: what is the minimal additional structure or restrictions on agent behavior that are necessary to achieve a certain goal.

Universidad Veracruzana

Common Resources

- Understanding how people make decisions about harvesting a common resource is important for diverse problems.
- Example. How to manage natural resources, *e.g.*, air quality, public land, water.
- Example. Understanding how cooperative societies first started.
- In these problems, individual people or businesses consume a resource that is shared by many; if individuals maximize their own short-term gain, the common resource is quickly used up.
- Janssen, Radtke, and Lee [5] used an ABM, laboratory experiments, and POM to study how people make one particular kind of common resource decision.

Universidad Veracruzana

Human-based Experiments

- They modeled a laboratory experiment in which human subjects harvested a shared resource in a computer game.
- Players moved an avatar around a resource grid, harvesting tokens that grew on each cell; players were actually paid for each token they harvested.
- To produce negative feedback between harvest rate and resource availability, which makes total harvest much more sensitive to harvest behavior, the time until a cell grew a new token after being harvested was made to increase with the number of neighbor cells that were also harvested.
- People compete on the same grid for the available tokens, experiencing the consequences of each other's decisions.

Universidad Veracruzana

ABM-based Experiments

- The ABM of Janssen et al. then simulated those movements as a way of quantifying the participants' harvest behavior.
- Three patterns that characterized the laboratory experiments with real people.
- The patterns are the range (mean $\pm$ 1 standard deviation) over time of three metrics:
  1. The number of tokens available for harvest,
  2. The inequality of harvest among the participants, and
  3. How often participants changed direction as they moved their avatar through the grid.
- A pattern was assumed to be matched by the ABM if the ABM's results fell within the observed range.

Universidad Veracruzana

Theories I

- Janssen et al. tested alternative theories for how people moved to harvest the tokens. The first two were null theories embodying two extremes:

    1. Making decisions for no reason, *e.g.*, making the avatars to move randomly; and
    2. Always using the same decision, *e.g.*, making them to always move toward one of the nearest tokens.

- The third one included some mechanisms observed in the human experiment:

    - Avatars tend to move toward closer tokens,
    - To avoid tokens that are closer to the avatars of other participants, and
    - To prefer continuing in their current direction.

Universidad Veracruzana

Theories II

- The relative strength and exact effects of these three tendencies were controlled by seven parameters.
- When testing the third theory Janssen et al. ran their model with 33,000 combinations of values for these parameters.

Universidad Veracruzana

Results

- Janssen et al. found that the null theories reproduced only the second observed pattern.
- The third theory reproduced the second pattern under most parameter combinations, and reproduced the other two patterns for only a few parameter combinations.
- Janssen et al. concluded that their second pattern, inequality of harvest, seemed built into the system because it was produced by even the null theories.
- They also concluded that harvesting tokens close to the avatar and moving in a constant direction seem to be particularly important parts of the human behavior.

Universidad Veracruzana

Referencias I

[1] M Ballerini et al. "Interaction ruling animal collective behavior depends on topological rather than metric distance: Evidence from a field study". In: *Proceedings of the National Academy of Sciences* 105.4 (Jan. 2008), 1232–1237. ISSN: 1091-6490. URL: http://dx.doi.org/10.1073/pnas.0711437105.

[2] J Duffy. "Agent-based models and human subject experiments". In: *Handbook of computational economics*. Ed. by L Tesfatsion and KL Judd. Vol. 2. Amsterdam, the Netherlands: North-Holland, 2006. Chap. 19, pp. 949–1011.

[3] DK Gode and S Sunder. "Allocative efficiency of markets with zero-intelligence traders: Market as a partial substitute for individual rationality". In: *Journal of political economy* 101.1 (1993), p. 119.

[4] A Huth and C Wissel. "The simulation of the movement of fish schools". In: *Journal of Theoretical Biology* 156.3 (1992), pp. 365–385.

[5] MA Janssen, NP Radtke, and A Lee. "Pattern-Oriented Modeling of Commons Dilemma Experiments". In: *Adaptive Behavior* 17.6 (Sept. 2009), 508–523. ISSN: 1741-2633. URL: http://dx.doi.org/10.1177/1059712309342488.

[6] JR Platt. "Strong Inference: Certain systematic methods of scientific thinking may produce much more rapid progress than others.". In: *Science* 146.3642 (Oct. 1964), 347–353. ISSN: 1095-9203. URL: http://dx.doi.org/10.1126/science.146.3642.347.

Universidad Veracruzana

Referencias II

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

Universidad Veracruzana