Agent-based modeling in finance

Mark D. Flood

Department of Finance

University of Maryland

Center for Latin American Monetary Studies (CEMLA)

Course on Financial Stability

Mexico City, 19 September 2019

Historical context for agent-based economics

Classical and neo-classical building blocks

- Early macroeconomics focuses on coarse aggregates
  - GDP, savings, investment, money supply, etc.
  - Price level, aggregate output, IS-LM
  - Unique Arrow-Debreu price vector
- Rational (homogeneous) behavior
  - Common information sets (e.g., public prices, economic aggregates)
  - Constrained maximization of utility or profits

Microfoundations of exchange

- Heterogeneity
  - Diversity of beliefs, idiosyncratic information sets
  - Principal-agent problems, networks, distributed control
  - Decentralized markets, diversity of prices, limits to arbitrate
- Alternatives to strictly rational behavior
  - Noise traders, bounded rationality, behavioral economics
  - Game theory, strategic interaction, feedback dynamics

Origins

Biology

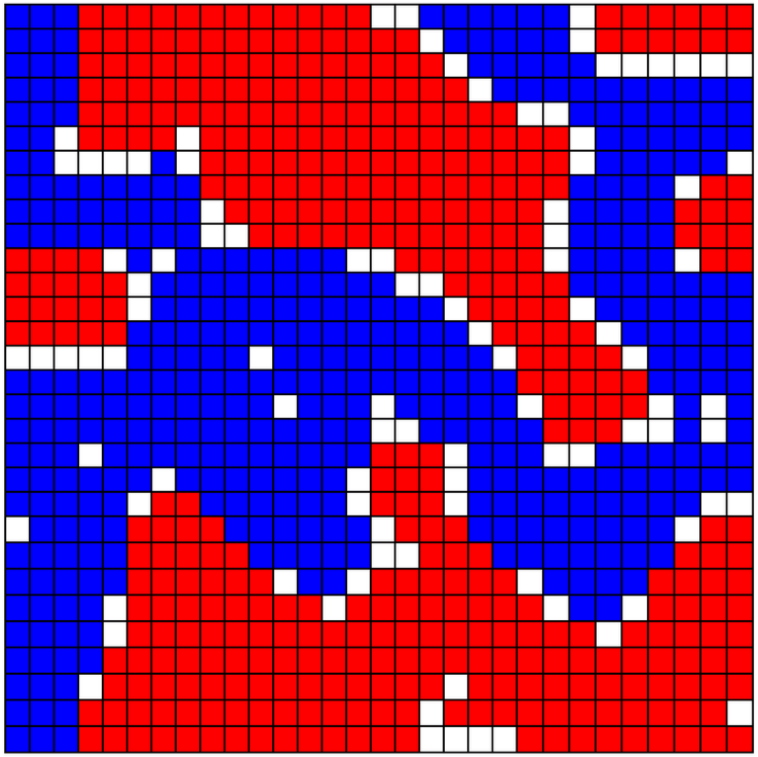
- **Self-replicating automata**
  - **John von Neumann**
- **Game of Life**
  - **John Conway**

Economics

- **Satisficing decision model**
  - **Richard Cyert, James March, and Herbert Simon**
- **Tipping point model**
  - **Tom Schelling**

Computer science

- **Artificial intelligence (AI)**
- **Robotics**
- **Object-oriented programming**

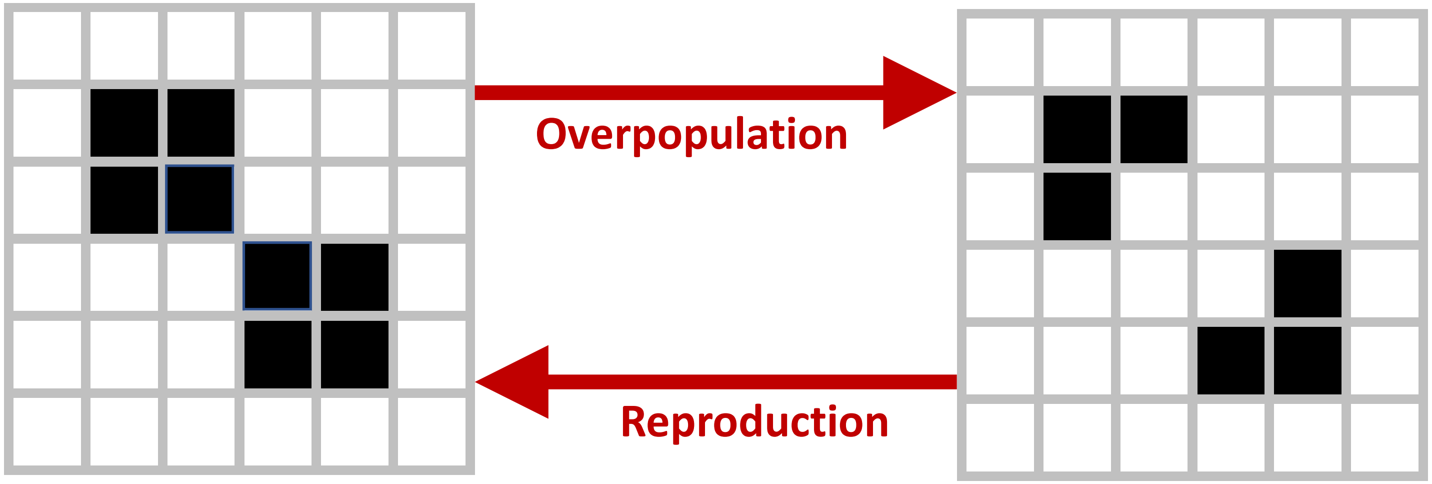


Schelling's endogenous segregation (tipping point model)

Image source: bookdown.org

Example - Conway's Game of Life

- Dynamics of the "life" state of cells in a grid
- State change depends on the state of neighboring cells
  - **Underpopulation** – Live cell with fewer than 2 live neighbors dies
  - **Survival** – Live cell with 2 or 3 live neighbors survives
  - **Overpopulation** – Live cell with 4+ live neighbors dies
  - **Reproduction** – Dead cell with 3 live neighbors is reborn

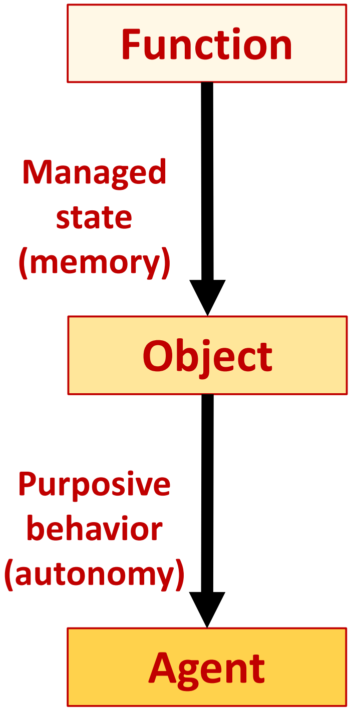


"Beacon" dynamic in the Game of Life

What are agent-based models (ABMs)?

Collection of agents, interacting to generate system behavior

- **Purposive** – preferences, with behavior seeking preferred outcomes
- **(Semi-)autonomous** – internal state and behavioral rules
  - May respond to local or system-wide events and actions
  - Object-oriented programming
- **Interactive** – agents respond to one another
  - Also possibly respond to social/environmental stimuli



Agents' behaviors can range widely

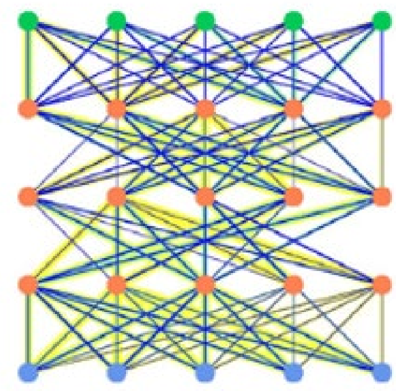
- Zero intelligence traders
  - Budget constraints alone generate meaningful patterns
- Bounded rationality
  - Sophisticated strategies can over-adapt to transient state (brittle)
- Agent learning/adaptive behavior
  - Genetic programming – e.g., Arifovic (1996); Chen and Yeh (2001)

ABMs are not computational economics / finance / game theory

What are ABMs?

System behavior

- **We are typically interested in an ill-defined task**
  - **Example: convert market data to portfolio decisions**
- **Globally optimal, rational behavior is unclear**
  - **May require strong assumptions with weak support**
- **Specify local satisficing behavior instead**
  - **System behavior may be invariant wrt local behavior**



Formal neighborhood

Defines permissible local interactions

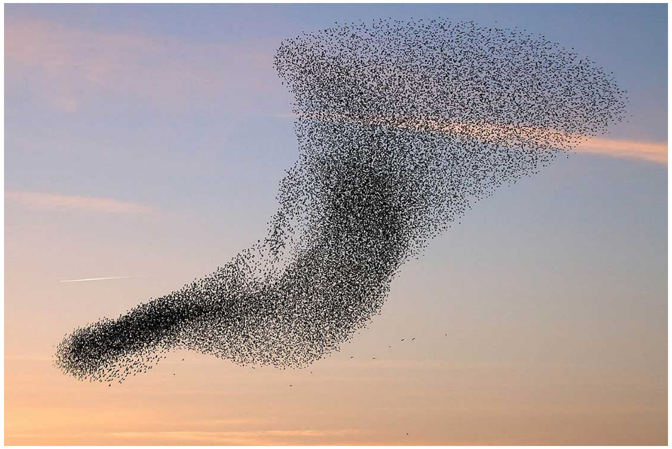
Emergence

- **System properties that are not characteristic of individual agents**
  - **The whole is not the sum of the parts (fallacy of composition)**
  - **Example: invisible hand of market equilibrium**
- **Population dynamics**
  - **New generations of agents can descend from ancestors' interactions**
- **Heterogeneity – *vive la différence***
  - **Parameterize (and experiment over) a distribution of beliefs, strategies, etc.**
  - **Or allow heterogeneity to emerge endogenously**

Complexity

Complex adaptive systems:

- Reproduction including artificial life
- Self-organization and emergence
- Self-organized criticality
- Evolutionary computation



Emergence

- System properties that are not characteristic of individual agents
  - The whole is not the sum of the parts (fallacy of composition)
  - Example: invisible hand of market equilibrium
- Population dynamics
  - New generations of agents can descend from ancestors' interactions
- Heterogeneity – *vive la différence*
  - Parameterize (and experiment over) a distribution of beliefs, strategies, etc.
  - Or allow heterogeneity to emerge endogenously

Image: Maani (2018)

Advantages

Rationality is difficult to justify

- Representative agent models overemphasize model tractability
  - Mathematical aggregation requires restrictive (Procrustean) assumptions
  - Model results as point estimates, not distributions
- ABMs use heuristics and bounded rationality instead
  - Resort to simulation in lieu of closed-form solution
- Formal results on learning and rationality
  - Learning to be rational is computationally NP-hard and game-theoretically impossible
  - Agent automata resolve this through procedural rationality (Simons) – plausible mechanisms for behavior at the agent level

ABMs have different emphases from representative-agent models

- Heterogeneous agents
  - Focus on distribution of behavior instead of average behavior
- Local interactions
  - Microfoundations for learning, information propagation, equilibrium formation
- System dynamics
  - Analysis of paths to equilibrium and nonequilibrium processes

Challenges

Robustness

- **Artefacts of software implementation**
  - **Bugs**
  - **Dependence on parameters**
    - **Parameter sweeps → curse of dimensionality**
- **Dependence on interaction model**
  - **Random versus sequential interaction**
  - **Network topology for interaction neighborhoods**
- **Lack of standards**
  - **Code publication and documentation**
  - **Integration of tools from different software packages / frameworks**
  - **Publication of results**

Estimation / calibration

- **Many calibration techniques available**
- **Challenge afflicts traditional economic theory too**
- **Ecological inference – drawing conclusions about individuals from aggregates**
  - **Manski critique applied to local interactions**

Reduced-form heterogeneous agent models

General structure of HAMs

- **Heterogeneous agents**
  - Often two behavioral categories (e.g., informed vs. noise, or fundamentalist vs. chartist)
  - Typical distinction is between regressive (fundamentalist) and extrapolative (chartist) beliefs
  - Switching of group membership possible
- **Bounded rationality**
  - Frequently using closed-form mathematical solutions – simulation not required

Microfoundations for market anomalies

- **Underpinning for stylized facts about financial markets**
  - Discrete-time models of bubbles and crashes – Brock and Hommes (1997)
  - Continuous-time models of market stability – He and Li (2012)
  - Price/return dynamics of multiple risky assets – Westerhoff (2004)
  - Housing price boom-bust cycles – Bolt, et al. (2019)
  - Securities market microstructure – Chiarella, Iori and Perelló (2009)
- **Price specifications are central**
  - Price changes or simple returns are often the sole input
  - Other factors often ignored – e.g., trading volume, order flow

Chartists and fundamentalists

Basic framework

$$\Delta P_t = \alpha + \beta_\varphi \varphi_t (P_{t-1} - P^*_{t-1}) + \beta_\chi \chi_t \Delta P_{t-1} + \varepsilon_t$$

- **Fundamentalists are "regressive" – focus on (P_{t-1} – P^*)**
  - **Chartists appear in proportion φ**
- **Chartists are extrapolative – follow recent price trends ΔP_{t-1}**
  - **Chartists appear in proportion χ**
- **Switching between types may be possible**
  - **Proportions φ and χ can vary over time**
- **Several parameters control system dynamics**
  - **Structural parameters α, β_φ, β_χ**
  - **Probability distribution for ε**
  - **Additional parameters, for example governing switching**

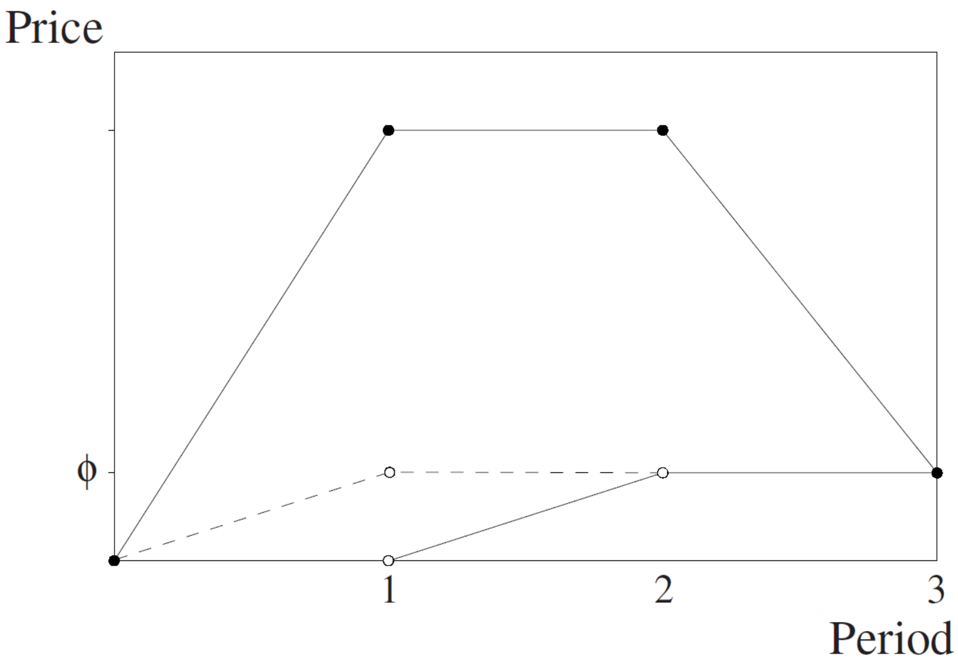
Example: Destabilizing rational speculation

J. B. DeLong, A. Shleifer, L. Summers and R. Waldmann (1990) "Positive feedback investment strategies and destabilizing rational speculation," J. of Finance, 45(2), 379-395.

Two types of traders

- **Rational informed investors**
  - Receive a signal in $\{-\varphi, 0, +\varphi\}$
  - Signal may be noisy
- **Positive feedback traders**
  - No signal
  - Follow the trend

Equilibrium prices and expectations rationality



What is "rationality"?

- Should rational investors adapt to the behavior of trend followers?
- If so, their behavior magnifies the positive feedback

Image: DeLong, et al. (1990)

Example: Volatility clustering

A. Kirman (1991), "Epidemics of opinion and speculative bubbles in financial markets," In M. Taylor (ed.), Money and Financial Markets, Blackwell.

Foreign exchange market

- **Heterogeneous traders**
  - **Optimists expect appreciation**
  - **Pessimists expect depreciation**
- **Traders meet at random**
  - **Probability (1–δ) that trader A converts the beliefs of trader B**

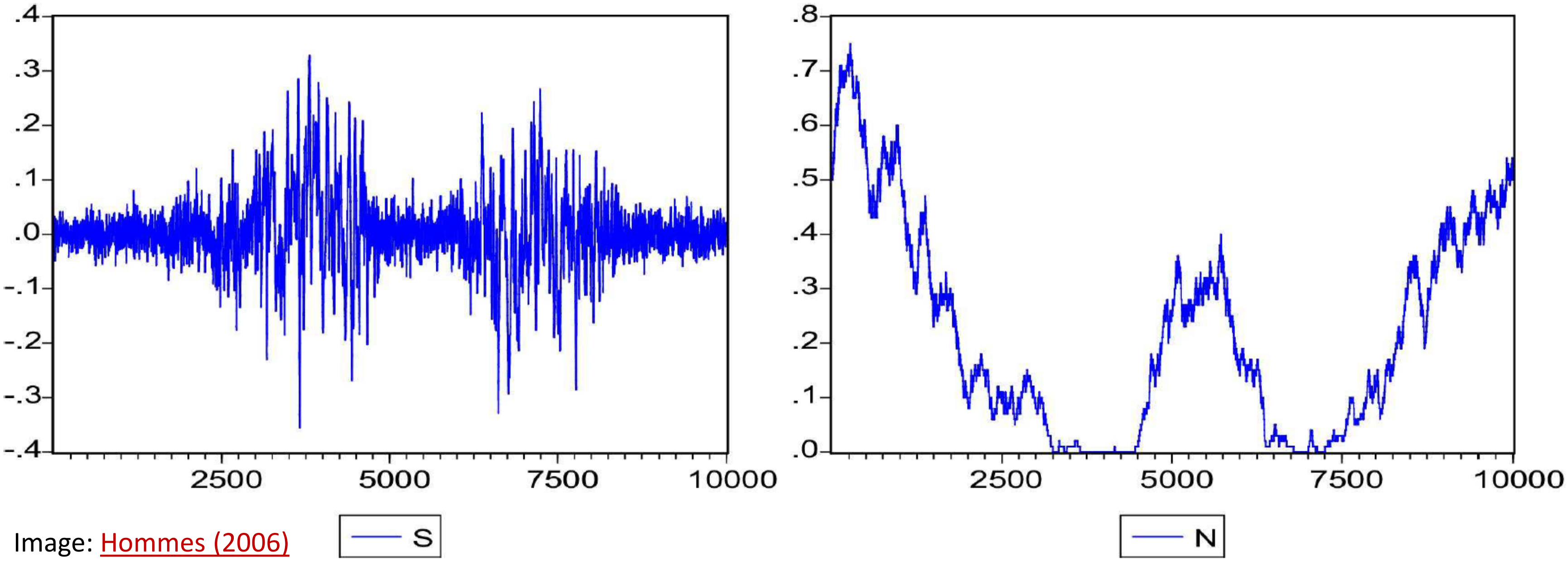


Image: Hommes (2006)

Example: Bank fire sales

R. Cifuentes, G. Ferrucci and H. S. Shin (2005), "Liquidity risk and contagion," *J. of the European Economic Association*, 3(2-3), 556-566.

Interbank lending market

- Many banks with default risk
  - Interbank loans
  - Other marketable assets
- Contagion
  - Default propagation
  - Fire sales of other assets
- Equilibrium
  - Limited liability of equityholders
  - Meet capital requirement or fail
  - Price impact of asset sales
- Structure
  - Interconnections – interbank loans
  - Initial default
  - Iterative propagation

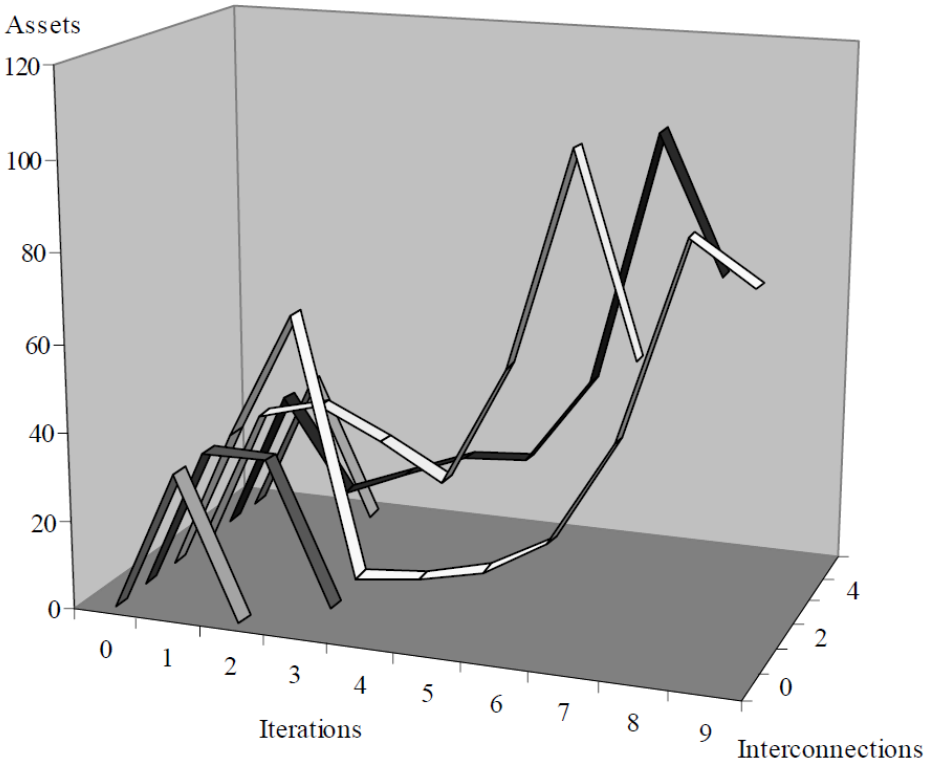


Image: Cifuentes, Ferrucci and Shin (2005)

Model calibration / estimation

Importance of calibration

- **ABMs tend to be heavily parameterized**
  - **Many degrees of freedom = Ability to generate many outcomes**
- **With great power comes great responsibility**
  - **Calibration constrains the model to be realistic**
  - **A statement of how the world works, not how you think about the problem**

Estimation methods

- **Maximum likelihood estimation (MLE)**
- **Method of moments**
  - **Generalized method of moments (GMM)**
  - **Simulated method of moments (SMM)**
- **Latent variables**
  - **State space models**
  - **Particle filtering**
- **Bayesian methods**
  - **Markov Chain Monte Carlo (MCMC)**
  - **Metropolis-Hastings**

Implementation

Object-oriented programming

- Classes (e.g., chartists) with each instance an agent
  - Methods defining behavior
  - Instance variables for agent state and parameters
  - Population of agents as a separate object
- Interaction framework – more classes and objects
  - Neighborhood topology
  - Interaction mechanism (e.g., search, preferential, random)
  - Agent activation and reproduction
- Housekeeping
  - Logging
  - Storing result ensembles
  - User display

Implementation

Agent-based modeling and simulation tools

- Swarm (Objective C, Java)
- NetLogo and StarLogo
- Repast (Java)
- MASON (Java)
- AScape
- MESA (Python)
- HARK (Python)

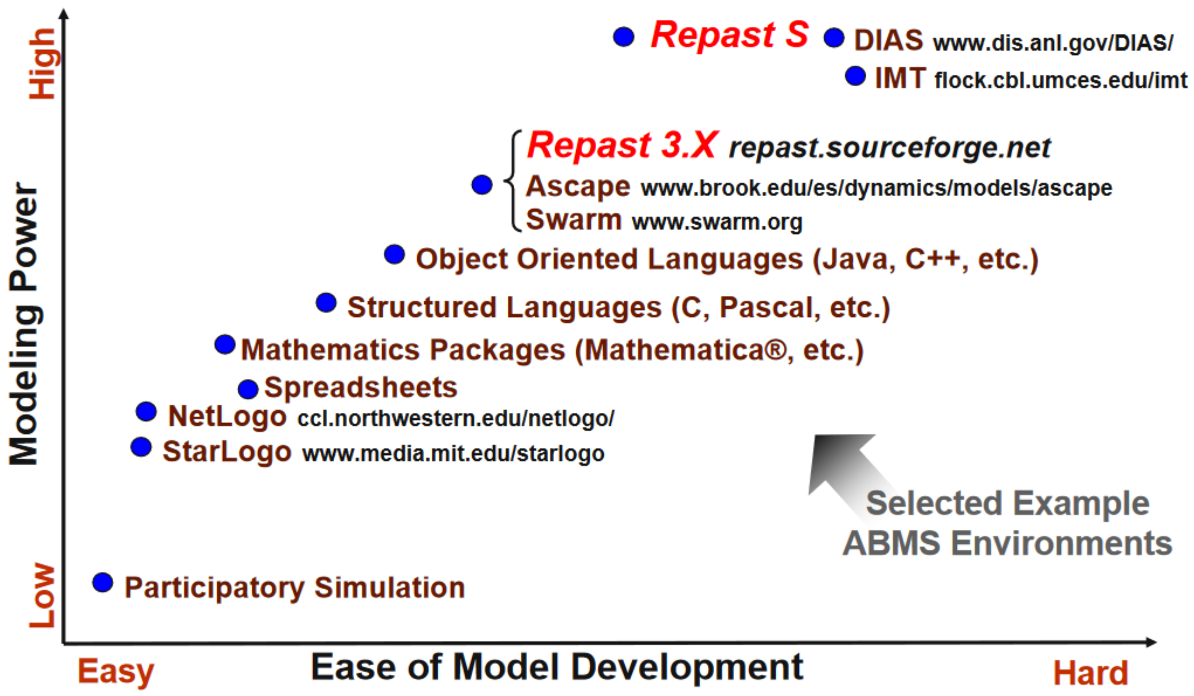


Image: Macal and North (2006)

Reading Suggestions

- R. Bookstaber, (2017), "Agent-based models for financial crises," *Annual Review of Financial Economics*, *9*, 85-100.
- S. Chen (2012), "Varieties of Agents in Agent-Based Computational Economics: A Historical and an Interdisciplinary Perspective," *J. of Economic Dynamics and Control*, 36(1), 1-25.
- J. Epstein and R. Axtell (1998), *Growing Artificial Societies: Social Science from the Bottom Up*, MIT Press.
- G. Fagiolo, M. Guerini, F. Lamperti, A. Moneta and A. Roventini (2017), "Validation of Agent-Based Models in Economics and Finance," Ch. 31 in Beisbart and Saam (eds.), *Computer Simulation Validation*, Springer, 763-787.
- J. D. Farmer and D. Foley (2009), "The economy needs agent-based modelling," *Nature*, 460, 685-86.
- J. Gallegati, A. Palestrini and A. Russo (eds.) (2017) *Introduction to Agent-Based Economics*, Academic Press.
- C. Hommes and B. LeBaron (eds.), (2018), *Handbook of Computational Economics, Vol. 4: Heterogeneous Agent Modeling*, North-Holland.
- B. LeBaron (2001), "A builder's guide to agent-based financial markets," *Quantitative Finance*, 1(2), 254-261.
- A. Liu, M. Paddrik, S. Yang and X. Zhang (2017), "Interbank contagion: An agent-based model approach to endogenously formed networks," *J. of Banking & Finance*, in press.
- M. Wellman (2011), "Trading Agents," *Synthesis Lectures on Artificial Intelligence and Machine Learning*, Morgan and Claypool.
- U. Wilensky and W. Rand (2015), *An Introduction to Agent-based Modeling: Modeling natural, social and engineered complex systems with NetLogo*, MIT Press.

Thanks!