Agent-Based Models in Economics: An Overview

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Research Areas

- **Agent-Based Computational Economics (ACE)**
  - Methodology: Empirical validation in ACE models
  - Applications: ACE models and policy

- **Networks**
  - Game-theoretic models of strategic network formation
  - Empirical properties of economic networks

- **Industrial dynamics: models/empirical evidence**
  - Geography of industrial agglomeration
  - Firm size and growth dynamics: the role of financial constraints

- **Statistical properties of micro/macro dynamics**
  - Statistical properties of household consumption patterns
  - Statistical properties of country-output growth
Homepage

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Outline

- Why Agent-Based Models in Economics?
  - Problems with neoclassical models
  - Empirical and experimental findings
  - Philosophical underpinnings

- Building Blocks of Agent-Based Models
  - Classes of assumptions
  - The structure of an agent-based model
  - Analysis of an agent-based model

- Open Issues in Agent-Based Models
  - Interactions with mainstream community
  - Policy Implications
  - Empirical validation

Agent-Based vs. Neoclassical Models

- **Benchmark:** micro-macro (neoclassical) models
  - Endogenous or exogenous micro-founded growth models

- **Based on over-simplifying assumptions**
  - Heterogeneity irrelevant: the “representative individual” hypothesis and its consequences for aggregation
  - Fully-rational agents without computational bounds
  - Equilibrium analysis: empirical observations as equilibria
  - No interactions among agents (other than price-related ones)

- **Why such a set of assumptions?**
  - Need for a sharp relation between assumptions and implications
  - Analytical solutions strongly required
  - Instrumentalist approach à la Friedman
Empirical and Experimental Findings (1/2)

- Persistence of heterogeneity among agents
  - Examples: Firms and industry characteristics
  - Aggregation in theory: average of behaviors different from behavior of the average (Kirman, Lippi)
  - Aggregation in practice: aggregate properties may have nothing to do with individual characteristics (ex: law of demand, see Gallegati, Kirman, etc.)

- Equilibrium analysis?
  - Economy as a complex evolving system
  - Economic observations as equilibria of some kind?
  - Ex: Turbulence in the patterns of industrial dynamics
  - State of the economy as emergent properties: statistical features that last sufficiently long to be observed
Empirical and Experimental Findings (2/2)

- Real-World Economic Agents are not Rational
  - Majority of rationality axioms persistently violated in reality
  - Departures from axioms are systematic
  - Examples: framing, probabilistic judgment and intuition

- Relevance of Interaction Networks
  - Agents form interaction networks to exchange commodities, information, knowledge
  - Real networks have peculiar and persistent properties (small-worlds, scale-free, etc.)
  - Network structure does influence aggregate results (ex: market design)
Evidence vs. Models (1/2)

- Relevance of standard neoclassical models
  - Dick Day: “Can one do good science based on models whose assumptions are clearly at odds with empirical evidence?”

- An old (but still open) philosophical problem
  - Models as abstractions of reality
  - What does “realistic assumptions” really mean?
  - Models as solutions of the trade off between simplicity and usefulness

- Empirical validity of an economic model
  - To what extent is a model able to explain and replicate existing reality (and possibly predict future trends)?
  - Are neoclassical models really good at explaining and replicating stylized facts?
Empirical validity of neoclassical models?
- Industrial dynamics and organization
- Micro-founded models of growth
- Macroeconomic models of investment and output dynamics
- Micro-founded models of labor-market dynamics
- … and so on

Difficulties
- Dynamics and distributions (Paul’s empirical agenda)
- Joint replications of SFs

Exploiting “instrumentalism” at its best
- If the model is not able to replicate stylized facts, assumptions can be freely replaced
- Why not using assumptions “more in line” with empirical evidence?
Agent-Based Models

- A tool to model economies where agents
  - are boundedly rational entities
  - directly interact in non trivial networks
  - might be persistently heterogeneous

- … and
  - State of the economy is not necessary an “equilibrium”

- A bottom-up approach
  - Modeling agents behaviors and their interactions first
  - Statistical analysis of models output
  - Matching with empirical data
ACE/Evolutionary Approaches

- Two competing brands?
  - Sharing almost same ingredients and philosophical underpinnings

- Evolutionary Models
  - Stress on selection-based market mechanisms…
  - … less on tools used

- ACE Models
  - Stress on tool used (OOP)…
  - … focus on open-ended systems where behavioral rules endogenously evolve as well
Main ingredients (to cook an ABM)

- Bottom-up (agent-based) Philosophy (Tesfatsion, 1997)
- Agents live in complex systems evolving through time (Kirman, 1998)
- Agents might be heterogeneous in almost all their characteristics
- “Hyper-rationality” not viable (Dosi et al., 1996)
- Agents as boundedly rational entities with adaptive expectations
- “True” dynamics: Systems are typically non-reversible
- Agents interact directly, networks change over time (Fagiolo, 1997)
- Endogenous and persistent novelty: open-ended spaces
- Selection-based market mechanisms (Nelson & Winter, 1982)
The Structure of Agent-Based Models

• Time \( t = 0, 1, 2, \ldots, (T) \) \ldots Discrete

• Sets of Agents \( I_t = \{1, 2, \ldots, N_t\} \) \ldots Often \( N_t = N \)

• Sets of Micro States \( i \rightarrow x_{i,t} \) \ldots Firm’s output

• Vectors of Micro-Parameters \( i \rightarrow \theta_i \) \ldots Res. Wage

• Vector of Macro-Parameters \( \Theta \in \mathbb{R}^m \) \ldots Opportunities

• Interaction Structures \( G_t \in \mathcal{P} (I_t) \) \ldots Networks

• Micro Decision Rules \( R_{i,t}(\bullet | \bullet) \) \ldots Innovation rule

• Aggregate variables \( X_t = f(x_{1,t}, \ldots, x_{N_t,t}) \) \ldots GNP
Flexibility of ACE/EV Paradigm

- **Micro Decision rules**
  - deterministic (best-replies, routines) → stochastic → algorithmic

- **Dynamics of Micro Decision Rules**
  - fixed → exogenously changing → endogenously adapting

- **Expectations**
  - myopic/adaptive → econometric → AI-based (neural networks)

- **Interactions**
  - global → local
  - symmetric, bilateral → asymmetric, unilateral

- **Dynamics of Interaction Structures**
  - static → exogenously evolving → endogenously evolving
A Large Set of Models…

- Evolutionary-Games (P. Young, Kandori et al., Blume, Ellison…)
- (Local) Interaction Models (Kirman, Weisbuch, Lux, Topol, IPD Models…)
- Endogenous Network Formation (Vega-Redondo, Goyal, Jackson-Watts…)
- Polya-Urn Schemes (Arthur, Dosi, Kaniovski, Lane, …)
- …. 
- …. 
- Industry-Dynamics Models (Nelson + Winter tradition, Paul’s Type II Models)
- Evolutionary Growth Models (Silverberg, Verspagen, Dosi et al., …)
- ACE Models of Market Dynamics (Axtell, Epstein, Tesfatsion, Vriend, …)
The Outcomes of ACE/EV Models

**Micro-Dynamics**
(induced by decision rules, interactions and expectations)

**Macro-Dynamics**
(obtained as aggregation of individual behaviors)

- Stochastic components in decision rules, expectations, interactions imply that the dynamics of micro and macro variables can be described by some (Markovian) stochastic process parametrized by \((\theta_i), \Theta\):

  \[
  (x_{i,t}) \mid (x_{i,t-1}), (x_{i,t-2}), \ldots; (\theta_i), \Theta
  \]

  \[
  X_t \mid (X_{t-1}, X_{t-2}, \ldots; (\theta_i), \Theta)
  \]

- Non-linearities in decision rules, expectations, interactions may imply that it is hard to analytically derive laws of motion, kernel distributions, time-\(t\) probability distributions, etc.
Analysis of Agent-Based Models

- **Analytical tractability?**
  - Analytical solutions only for particular cases
  - Models must often be built and simulated (via computer)
  - Object-oriented programming languages (C++) as natural tools for agent-based models

- **Analyzing the output of agent-based models**
  - Initial conditions for all micro and macro variables of interest
  - Parameterization of the model
  - Model as a “data generation process” for the underlying unknown mechanisms
  - Run of the model: set of time-series (and statistics thereof)
  - Stochastic elements and need for Monte-Carlo analysis
  - Sensitivity analysis vs. parameters and initial conditions
Analysis of Agent-Based Models

Initial Conditions: \((X_{i,0})\)
Micro & Macro Pars: \((\theta_i), \Theta\)

Generate Time-Series through Simulation
\[\{(X_{i,t}), t=1,\ldots,T\}\]
\[\{X_t, t=1,\ldots,T\}\]

Compute a Set of Statistics
\[S=\{s_1, s_2, \ldots\}\]
on micro/macro Time-Series

Repeat M ind. times

Generate Montecarlo Distribution for each Statistics in \(S=\{s_1, s_2, \ldots\}\)

Studying how Montecarlo Distributions of Statistics in \(S=\{s_1, s_2, \ldots\}\) behave as initial conditions, micro and macro parameters change

Statistical Tests for difference between moments
Agent-Based Models: Applications

- **Agglomeration and geographical concentration**

- **Technological adoption**

- **Innovation and endogenous growth**

- **Labor market dynamics**

- **Firms investment and the properties of business cycles**
Remarks (1/2)

- A new way of doing economics?
  - Large community: Ph.D. programs, journals, conferences
  - Still a minority vs. neoclassical economics
  - Two ways of seeing agent-based modeling approach

- ABM as a complementary approach
  - Exploring dimensions difficult to address jointly
  - Grounding behavioral assumptions into empirical/experimental evidence

- ABM as an alternative approach
  - Providing robustly an alternative view of how decentralized economies work
  - ABM replicating reality, generating fresh implications, allow for policy implications and predictions
Remarks (2/2)

- Crucial, open issues
  - Pushing policy and design exercises
  - Fostering empirical validation techniques

- Policy implications and market design
  - Agent-based models as very flexible “laboratory” tools
  - Experimenting with alternative policy designs
  - Testing different market designs: the U.S. experience

- Empirical validation of ABMs
  - Allow for a better and deeper replication of stylized-facts
  - Over-parameterization of agent-based models
  - Developing more powerful calibration techniques
  - A new econometrics of ABMs? Causality and graphical models