Agent-Based Computing in Economics

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Agents and Game Theory

From the Preface to *Games and Economic Behavior* (von Neumann and Morgenstern):

"It is to be expected that mathematical discoveries of a stature comparable to that of the calculus will be needed in order to produce decisive progress in [game theory]…it is unlikely that a mere repetition of the tricks which served us so well in physics will do for social phenomena."

Agent Systems: Origins

- Biology:
  - John von Neumann: self-reproducing automata ('50s)
  - John Conway: game of Life ('60s)
  - Chris Langton: artificial life (late '80s)
- Social science:
  - Simon, March and Cyert: the 'behavioral school' and simulation of few agent systems ('50s and '60s)
  - Tom Schelling: tipping model of segregation (late '60s)
- Computer science:
  - artificial intelligence (AI)
  - robotics
  - distributed AI (DAI)
  - multi-agent systems (MAS)
  - object-oriented programming (OOP)

Constrasting Mindsets

Post WWII:

- *Global* information, *centralized* control
- Math. programming: *scalar* value function
- Firm as *rational* actor
- Neoclassical utility: constrained *maximization*
- Arrow-Debreu markets: *single* price vector
- *Decision* theory
- Conventional *AI*

Now:

- Local info., networks, *distributed* control
- *Diverse* representations: competing world views
- *Many-agent* firms
- Behavioral economics: *multiple* selves
- *Decentralized* markets: heterogeneous prices
- *Game* theory
- DAI and *MAS*

What are Agent Systems?

- Population of individual 'agents' ($10 - 10^7$)
- Each agent has internal states and rules of behavior; implementation as an *object*
- Agents are autonomous or semi-autonomous
- Agents interact with one another and possibly with an environment (local/social interactions)
- Agents are purposive (self-interested, satisficing, utility maximizing locally)
- *Aggregate structure emerges from agent interactions*
- *Subsequent generations of agents emerge from the interactions of their ancestors*

Implementation of Agent-Based Computational Systems

- Each agent is an *object*
  - having *instance variables* (representing internal states)
  - and *methods* (representing behavior repertoire)
- The population of agents is also an object
- There is some *topology of interaction*, e.g., a spatial environment or a social network
- There is a mechanism for *activating* agents
- There are objects for data gathering, storage and display
- Such systems are typically programmed from scratch (e.g., in C/C++) or using higher level systems (e.g., SWARM, AScape, StarLogo, Repast, MASON)

What Agent Systems Are Not

- ‘Computational’ X, where X refers to something from the social sciences, *usually* doesn’t refer to *agents*
  - ‘Computational economics’ means *numerical* analysis of conventional (e.g., rational, equilibrium) models
  - ‘Computational finance’ involves *numerical* solution of stochastic PDEs
  - ‘Computational game theory’ involves numerical determination of equilibrium configurations (e.g., Nash)
  - *Systems dynamics* was once an important computational approach in the social sciences but is *not* agent-based
- Dominant use of agent models is *positive* in orientation, only recently *normative*, i.e., for policy purposes

Advantages of Agent-Based Computation

- *Heterogeneous agents*: replace representative agent, focus on distribution of behavior instead of average behavior
- *Bounded rationality*: essentially impossible to give agents full rationality in non-trivial environments
- *'Local' interactions*: agent-agent interactions mediated by inhomogeneous topology (e.g., graph, social network, space)
- Focus on *dynamics*: paths to equilibrium and non-equilibrium processes
- Each realization a *sufficiency* theorem

Agent Heterogeneity

- ‘Representative’ agent models are an unsatisfactory way to deal with heterogeneity
- Mathematical aggregation can only be accomplished under highly restrictive conditions
- Once aggregated, model results tend to be point estimates, instead of distributions
- *There is no necessity for such assumptions in agent computing*

Bounded Rationality

- To the extent that models use rational agents, they are typically 'substantively' rational, i.e., they do not provide a plausible mechanism by which rational results might be achieved (Simon's 'procedural' rationality)
- Formal results:
  - CS (Fortnow and Wang): learning to be rational is NP-hard
  - Economics (Spear): impossible for agents to learn RatEx
  - Game theory (Foster and Young): impossible to learn to be rational
- *Agent automata are procedurally rational*

Interactions through Social Networks

- Interactions are either indirect (agents interact only with aggregates, i.e., prices) or homogeneous (representative interactions) in much social science modeling
- Recent ‘local interactions’ models in economics utilize idealized graphs
- *Arbitrary interaction graphs (e.g., empirical ones) only analyzable via agent computing*

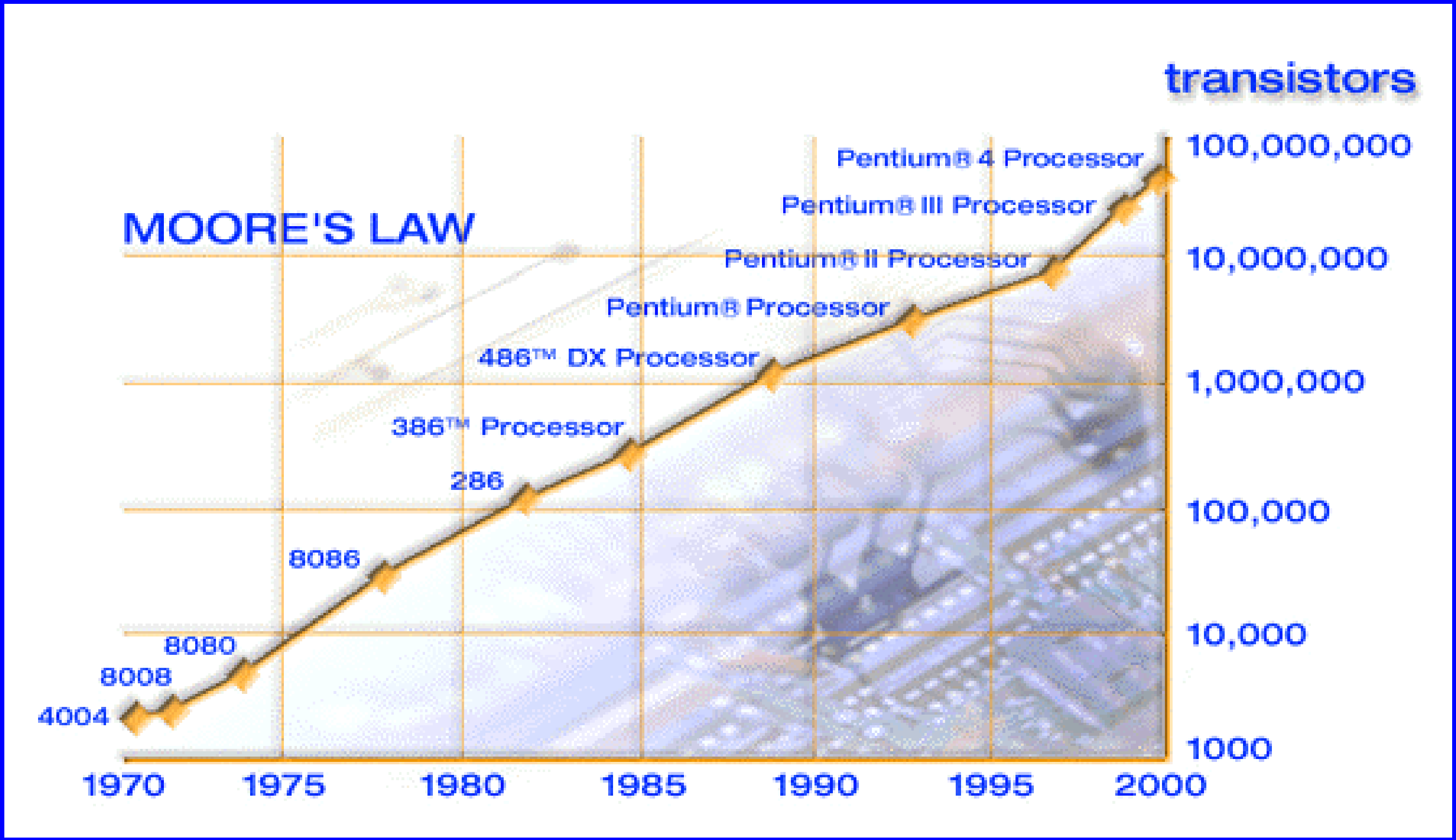
The Emergence of Equilibrium (or not!)

- Equilibrium (Walras, Nash) is proved via Brouwer or Kakutani fixed point theorems
- Constructive proof is through Sperner's lemma
- Papadimitriou [1994] has shown that Sperner is essentially NP-complete
- Contraction maps are sufficient for equilibrium
- *Equilibrium either emerges or not in agent computing*

Disadvantages of Agent-Based Computation

- Robustness of results:
  - Artifacts: spurious correlation resulting from coding peculiarities; to avoid requires careful programming
  - Dependence on parameters: parameter sweeps and the ‘curse of dimensionality’
- No standards exist today:
  - For code availability, documentation
  - Docking with existing models
  - Publication of results

Moore's Law



Applies to system clock, cache size, bus clock, memory, hard disk size

Disadvantage or Advantage?

- Microstructure of interaction matters:
  - Random versus sequential interaction in ‘soup’ (e.g., Axtell *et al*., Gacs, computer scientists)
  - Network topology (e.g., Bell, Page, Watts, sociologists)
  - Preferential activation (e.g., Page)
  - *But this is a problem for equation-based models too!*
- Estimation of models:
  - How to ‘best’ estimate agent models?
  - Manski critique of local interaction models and related
  - Ecological inference
  - *This problem equally severe for agents and conventional models*
- Lack of standardization:
  - ‘Requisite variety’ useful early in evolution
  - *Same problem haunts conventional social science*

Complexity ⊂ Agent Computing

- Important ideas of complex adaptive systems:
  - reproduction, self-reproduction (von Neumann, Buss and Fontana) and artificial life (Alife)
  - self-organization and emergence (Prigogine, ALifers)
  - life on the edge of chaos (Langton)
  - dancing landscapes, N^K models (Kauffman)
  - evolutionary computation (Holland, Mitchell)
  - self-organized criticality, $1/f$ noise (Bak and co-workers)
- Dominant methodology:
  - computation with distributed automata (agents)
  - cellular automata are multi-agent systems on a lattice with nearest neighbor interaction

Example: Genetic Optimization

- Some *combinatorial* optimization problem
- A finite representation, typically *binary* strings
- Global *fitness* function mapping strings into $\mathbf{R}_{+}$
- Global *selection* operator differentially selects individuals for reproduction
- *Mutation* and *cross-over* operators generate new individuals (*global* parameters, i.e., mutation rate, are typical)
- Many, many variants

Agent Computing in the Social Sciences

- **Economics**
  - **<u>Markets</u>: Santa Fe Stock Market (ecologies of trade strategies), Arifovic (cobweb), Albin and Foley, Epstein and Axtell, Bell (bilateral exchange in networks), Youssefmir and Huberman (volatility clustering), Vriend, Kirman and Weisbuch (local prices and learning), Tesfatsion (endogenous networks), Chen and Yeh (role of speculators), Bak *et al*. (correct price statistics), Sellgren (insurance markets), Bruun (spatially-mediated consumption)**
  - **<u>Firms</u>: Bak, Woodford and Schneikman, Miller, Padgett, Axtell, Luna**
  - **<u>Macroeconomics</u>: Bullard, Duffy, Arifovic, Carroll and Allen**
  - **<u>Technology</u>: Teitelbaum, Huberman and Lorch**
  - **<u>Norms</u>: Arthur, Glaeser, Sacerdote and Schneikman, Axtell, Epstein and Young**
- **Politics**
  - **Axelrod, Cederman (behavior of states, cultural processes)**
  - **Kollman, *et al*. (adaptive parties, Tiebout model)**
- **Sociology: Gilbert and co-workers, Macy, Latane, Gaylord**
- **Computational organization theory: e.g., Carley and Prietula**
- **Law: Picker, Wax**
- **Anthropology: e.g., Gumerman *et al*., Kohler *et al.***

Commercial Applications of Agents

- DAI/MAS applications: auction bots, web bots, automated contracting in networks, network debottlenecking…
- Santa Fe 'spin-offs':
  - CASA: Credit scoring, proprietary CitiCorp projects
  - Bios Group->NuTech Solutions: NASDAQ stock market simulation, supply-chain management tools, ResortScape, life insurance model, policy-holder behavior in casualty and property insurance, Southwest Airlines cargo handling optimization
  - Complexica: Insurance World, reinsurance markets
  - Icosystem: Swarm models, risk management tools
  - Emergent Solutions Group of PWC: town model (Treewell, Vermont), broadcast schedule optimization
- DOD applications…

'Big 3' Recent Successes

- Traffic
  - PDE models -> agents
  - Entire Swiss traffic grid on a single laptop
- Policy-relevant epidemiology
  - ODE models to agents
  - Smallpox, SARS, avian flu
- Combat simulation
  - Lanchester ODEs to agents

Few Strategies For Dealing with Large-Scale Systems

- Homogeneous components, heterogeneous behavior: *statistical mechanics*
- Heterogeneous components, homogeneous behavior: *general equilibrium*
- ‘Well-mixed’ systems: *mean field theory*
- ‘Scaleable’ systems: *representative* components and *aggregation*

Need New Methodology for Large-Scale, Complex Systems

- Before we understood the whole by focusing on the parts (reductionism)
- Today we need to focus on the *interactions* between the parts to understand the whole
- We need a new science of the *emergence* of higher-level structure and function
- Need to replace *design* with *evolution*
- Replace *optimization* with *regulation*
- Need to replace *centralized mindset*

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Sufficiency and Necessity of Agents

- So far: agent computing *sufficient* as a methodology for economics
- What of *necessity:*
  - How can we utilize all the hardware we have?
  - CPU speed, memory, storage, bus speed, cache size…
- MAS foundations of economics and social science
- Social science foundations of agent-based systems

Decision Theory ⊂ Game Theory

- Decision theory:
  - Strategic behavior ('games') against possibly dynamic but non-adaptive opponent (Nature)
  - Nature represented stochastically (stationary)
  - Normative (what you 'should' do)
- Game theory:
  - Strategic behavior against strategic opponent
  - Opponent arbitrarily complex
  - Both *normative* and *positive* aspects
    - Weak empirical support for positive predictions

OR ⊂ MAS

- Operations research:
  - Characterize operation with *single* formal representation (mathematical or simulation model)
  - *Extremize* (scalar) value function (e.g., LP, DP) yielding...
  - ...*Normative* prescriptions for operating policies
  - More comfortable with decision theory than game theory
- Multi-agent systems:
  - Each *agent* has an internal representation…
  - …and acts to *improve* its value function
  - Key question: What *emerges* at the societal level?
  - Both *positive* and *normative* aspects
  - Game theory more useful than decision theory

Beyond Optimization…

- More generally, look *beyond* optimization/ OR *focus* to evolutionary heuristics
- In a world dominated by *analysis* and *first order conditions*, we care about the *optimum*
- *Nature* may be more concerned with performance *improvements* than optima (satisficing)…
- …and with *robustness* instead of equilibrium
- Solving for optimality...
  - …may lead to *brittle* solutions
  - …is vestigal from top-down, *centralized* mindset

Example: Mechanism Design

- Within game theory, *mechanism design* yields environments with optimal welfare properties *iff* all agents are rational
- Example: Vickery (second price) auction
- Widely adopted in practice
- Practical problems:
  - Mechanisms can be NP-hard to synthesize
  - Required (rational) behavior of agents may be NP-hard for them to figure out

Mechanism Design: cont'd

- Conceptual problems:
  - Mechanisms not generally robust to non-rational agents (e.g., noise traders in V auction)
  - Humans are not rational:
    - If a human acquires a perfectly rational agent to do her bidding, under quite general conditions she turns it off with probability 1
- Philosophical problem: Why equilibrium (e.g., Nash, Bayes-Nash, some refinement)?

Why Algorithms?

- In the physical sciences, controlled experimentation is pervasive, yielding data
- Data + Algorithms = Programs
- Powerful approach to science:
  – Algorithms created analytically or evolutionarily
  – Analytical ones usually numerical
  – CS: performance of algorithms in general
- Vestigal of Turing machine foundation of CS

Relation between MAS Computer and Social Science

- One strain of MAS computer science:
  - Give agents conventional utility functions, rational behavior
  - Generalize environment to distributed interactions more common to computer systems
  - Use mechanism design to design MAS
- MAS social science:
  - Relax rational behavior in accord with experimental and behavioral results
  - Generalize environment to more realistic topologies
  - Build *positive* models (describing social processes)

MAS are Social Systems

- Active research areas in MAS have direct analogs in social science:
  - communication/speech acts/linguistics
  - social networks
  - strategic behavior
  - learning
  - coalition formation
  - emotions
- Social science an alternative foundation for CS?

Societies of Adaptive Agents

- Individuals constantly *adapt* their behavior to one another to create utility improvements
- Perpetual adaptation is *path* (history) *dependent*, not mixed strategy Nash eq.
- This yields *stationarity* at the macro level, occasionally *punctuated* by new configuration
- Stationary statistics are the *output targets* of microscopic (MAS) models

Non-Elephants

- Ulam: There can be no mathematics of ‘nonlinear dynamics’ in the same sense that there can be no zoology of non-elephants
- Economics of non-elephants:
  - Non-Walrasian markets
  - Non-Coasian firms
  - Non-Keynesian/Monetarist/new classical/ DSGE macro

Summary

- Agent computing is a new technology within computer science
- Agent computing ostensibly provides a foundation for economics and other social sciences
- Several recent successes displacing analytical methods foreshadow other conquests?
- *The future is wide open!*

'Big Picture' Themes

- Agent systems are very general computational systems based on *interactions*
- Interactive systems may constitute an alternative foundation for computer science
- Agents may provide a new *foundation* for the social sciences

Popular Accounts

- T. Kohler *et al.* (2005) "Virtual Archaeology," *Scientific American* (July)
- D. Colander *et al.* (2004) *Conversations with Economists on the Cutting Edge* (University of Michigan Press)
- J. Rauch (2002) "Seeing Around Corners" *The Atlantic Monthly* (April)
- E. Bonabeau (2002) "Predicting the Unpredictable" *Harvard Business Review* (March)
- C. Bourges (2002) "Artificial Societies May Make Policy" *UPI* (May 12)
- M. Crichton (2002) *Prey* Harper-Collins

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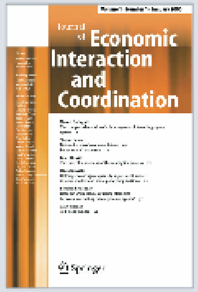

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How Will Things Unfold?

- Analogy to game theory:
  - For 1 generation, game theorists worked in math departments
  - ‘Killer app’ was IO (industrial organization)
- Analogy to experimental economics:
  - For nearly 1 generation, consigned to ‘fringe’
- Each evolutionary with modest revolutionary content
- Agents: evolutionary or revolutionary?