Very Large-Scale Multi-Agent Systems and Emergent Macroeconomics

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Artificial Economics

- New book:
  Artificial Economies of Adaptive Agents: The Multi-Agent Systems Approach to Economics, MIT Press, 2006.
- VIIth Trento Summer School: Agent Computing in Economics
  - Ph.D. students and ass't. prof.s
  - 2-22 July 2006
  - Axel Leijonhufvud, organizer
  - R Axtell and L Tesfatsion, co-directors

Outline

- *Agent computing* in economics and other fields
- *Artificial economies* of adaptive agents
- The macroeconomy, *emergent*
- Architecture of an *artificial macroeconomy*
- Conclusions

Macro from Agents: Background

- Microsimulation (e.g., Orcutt)
  - Small # of households (e.g., 16K memory)
  - No strategic behavior
- *Aspen* model (mid 1990s)
  - Super-computing application (Sandia)
  - Little empirical relevance
- Extant macroeconomics with agents
  - Few agents
  - Maximization of discounted expected utility
- ‘Financial fragility’ models of Gallegati and co-workers
  - Exogenous shocks
  - Firms as agents

Macro from Agents: Project

- Team
  - Agent-based microeconomics
    - Specify component models
  - Macroeconomics
    - C Georges, agent computing
    - A Leijonhufvud, conceptual clarity
    - Brookings economists: output check
  - Computer science
    - Multi-agent systems experts
    - Learning specialists
    - Evolutionary computing pros
- Goals
  - Challenge representative agent macro

Solitary vs Interactive Agents

- Solitary
  - Utility function holds own state and global economic variables
  - Maximization done without regard for others' direct interests ("passable definition of a sociopath" [Aaron, 1994])
  - Seeks global optimum
  - Asocial or anti-social
- Interactive
  - Utility function holds individual state, family, community, societal actions/welfare
  - Seeks own utility improvements, welfare for others (e.g., fairness)
  - Adaptation through interaction
  - Social

Power of Interaction

- Paradigm of *non-interactive* computing:
  - *Data*
  - *Machine* (e.g., Turing machine)
  - Machine turns data into the answer (e.g., *42*) via *algorithm*
- Multi-agent systems: *interactive* computing
  - P Wegner: *systems of interacting agents* at least as powerful as a Turing machine
  - Movement to rework the foundations of computer science from perspective of *interaction*

Against the Nash Program

- An *implicit* assumption of conventional game theory is that social regularities arise from equilibrium at the *agent level*
- Clearly, this is *sufficient*; it is *not necessary*
- Counter-examples: agent-based financial markets and firm formation models
- In a large population, agents perpetually adapt their behavior to one another and their circumstances, yet stationary structures can arise at the social level

Agent Computing in Other Fields

- Computer science: AI → DAI → MAS
- Ecology: decade of work on 'individual-based models' (IBMs)
- Epidemiology: ODE models now agents
- Traffic:
  - Before 1990 <u>all</u> traffic models were CFD analogs realized on vector supercomputers
  - Today agents have displaced these
- Military OR: Complete transition from PDEs to agents over past decade

What is Feasible *Today* with Agent Computing?

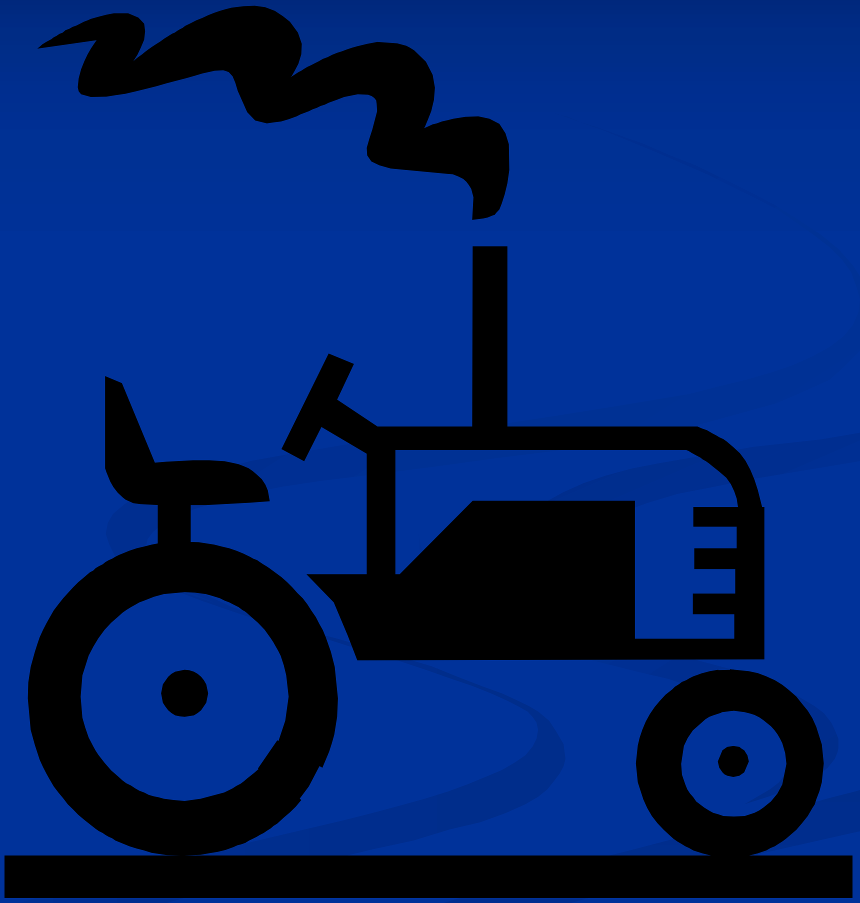
- Simple agents on modern workstation
  - 10^6 - 10^7 agents in C/C++
  - 10^5 - 10^6 agents in Java
- Complex agents on good workstation
  - 10^2 - 10^5 agents in C/C++
  - 10^1 - 10^4 agents in Java
- Bigger numbers on ‘big iron’, the grid
- Main limitation today is software:
  - What behavioral rules do we write for the agents?
  - What rules are sufficient for the emergence of the family, private property, the State?

Agent Computing: The *Future*

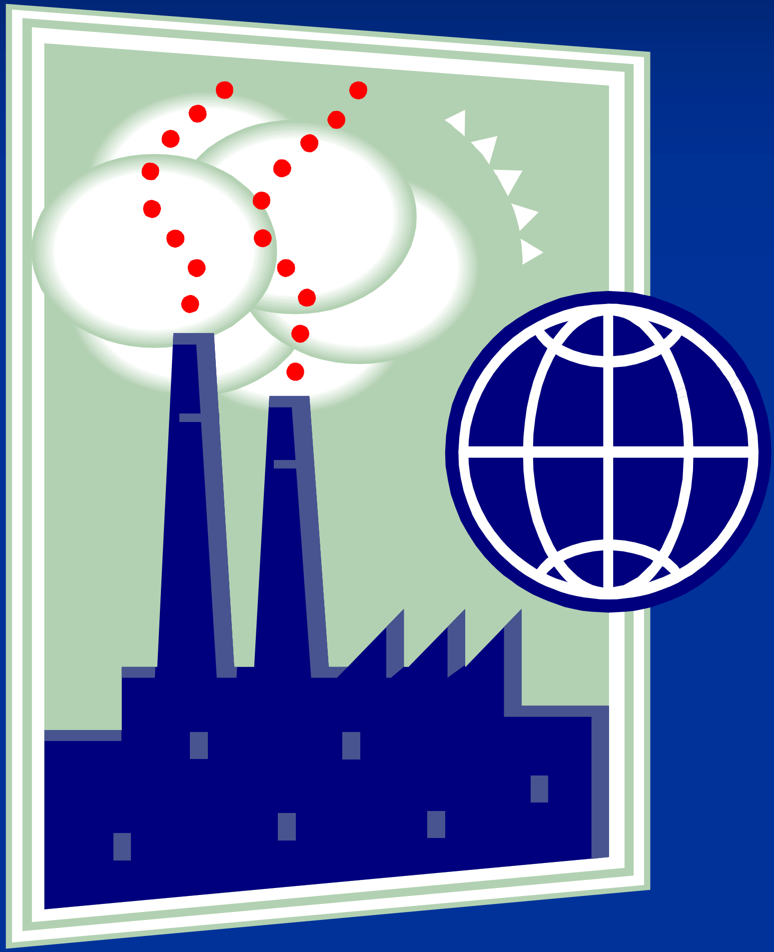
- Agents are the only way for economists to *fully utilize* modern machines
  - Code a few classes of agents and replicate
  - ‘Small-compile time, large run-time’ model
  - No way fill 1 GB RAM with equations!
- Agent models can be considered as *richer specifications* than typical econometrics

Consider a Complex Machine…

- *Reductionist* perspective
- Describe behavior of components *mathematically* (dynamical systems)
- *Aggregate* components to subsystems (e.g., mechanical, electrical, chemical, operational, regulatory)
- Dynamical behavior of each subsystem *very* complex
- Link all subsystems together and there is no *analytical* (i.e., closed form) representation of the whole



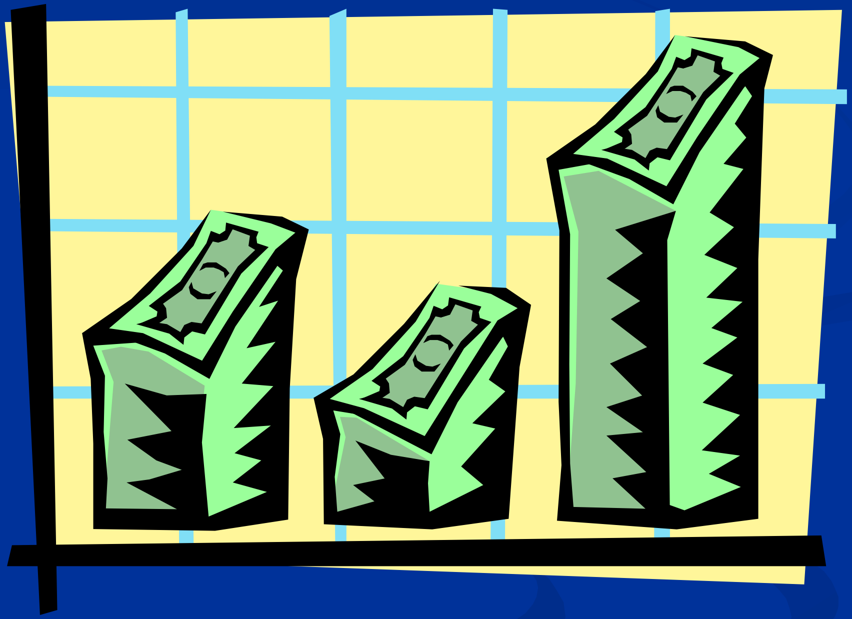
Workarounds…



- Physicists get around this problem via *homogeneity,* then *statistical mechanics*
- Engineers get around problem *pragmatically* via heuristics, rules-of-thumb, computer models, multi-agent organizations
- Macroeconomists use two main abstractions:
  - representative agent/firm
  - aggregate data

Emergent Macroeconomics

- Dynamical models for all components of an economy
- Two flavors:
  - Institutions as agents
  - Individuals as agents (institutions as MAS)
- Explicitly specify inter-actions between agents
- Spin the whole *artificial economy* forward in time; equilibrium *agnosticism*
- Aggregates *emerge*
- Emergent macrovariables influence agent behavior



Philosophy of *Emergence*

- Pragmatic anti-reductionism
- Aggregates and institutions arise from the *interactions* of autonomous agents
- Aggregates may be well-defined at both the individual and social levels, e.g., savings
- Institutions may have behavior not defined at the individual level (e.g., policy-setting ability)
- A macroeconomy is a *complex adaptive system*
  - Difficulties of the ‘representative agent’ are a special case of the philosophers’ “fallacy of division”
  - Related to notions of ‘ecological inference’

Macroeconomics from Micro

- ‘Microfoundations of macro’ is conventionally interpreted as the Walrasian foundations
- Historically, Walrasian model was criticized for being an ‘institution-free’ theory
- Bottom-up/emergent macro has the same aspirations but an alternative methodology:
  - ‘Grow’ macroeconomic aggregates from a heterogeneous population of boundedly rational agents who interact directly with one another, away from equilibrium
  - Along the way ‘grow’ meso-scale institutions
  - Many microspecifications will likely prove sufficient (although today we have none!)

Any *Artificial Economy* must have…

- Artificial Agents…
  - …have preferences, are consumers
  - …earn wages in firms as workers, migrate between firms
  - …own shares of firms
- Artificial Firms…
  - …make products to sell to consumers and firms
  - …pay wages to workers
  - …banks as special case
- Artificial Markets…
  - …for consumption and capital goods, prices emerge
  - …for ownership of firms, share prices emerge
- Certain *institutions* emergent…
  - …money, price level, exchange regimes, etc.
  - …social norms of contracts, work effort and so on
  - …informal social networks

An Artificial Economy

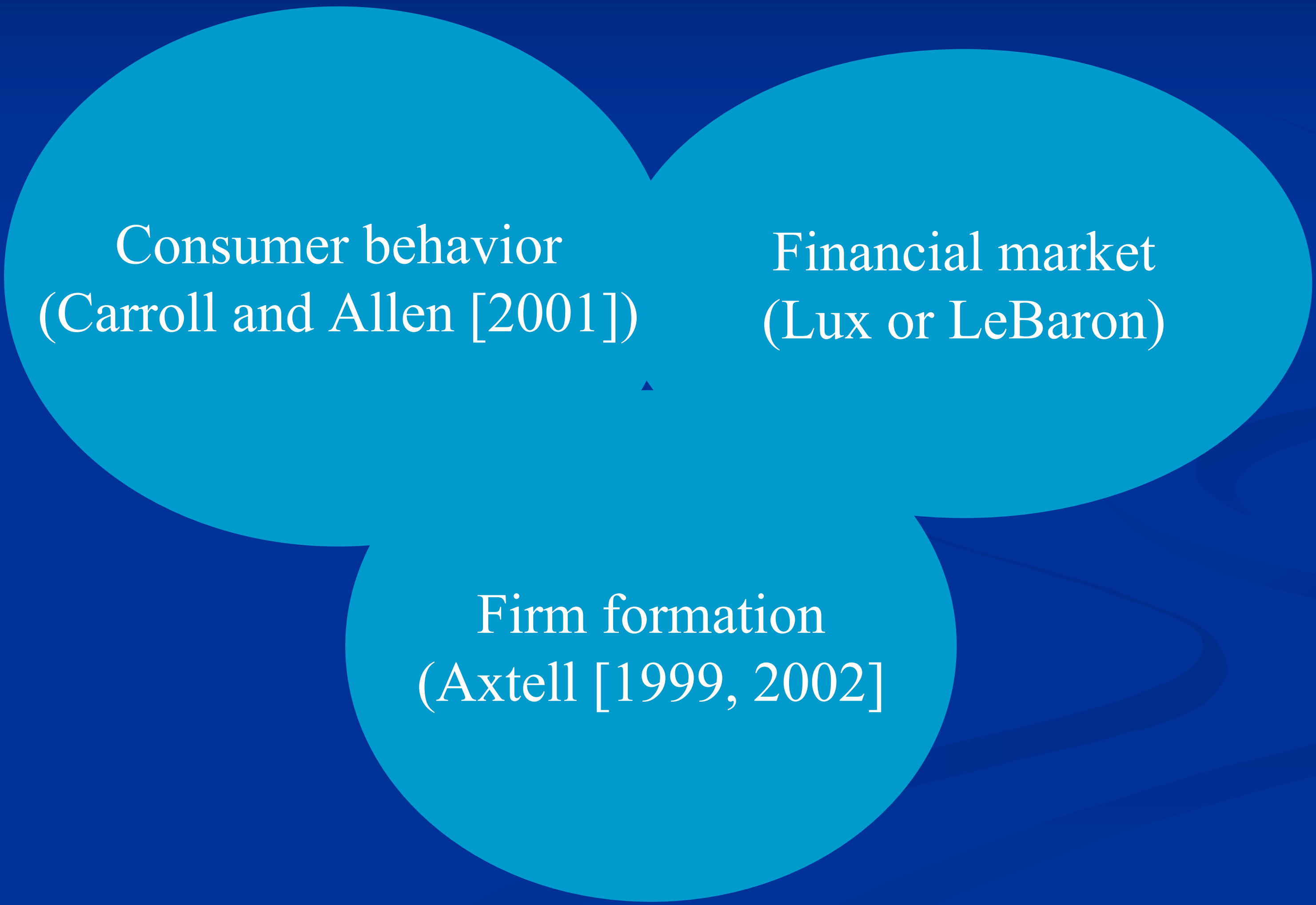
Consumer behavior
(Carroll and Allen [2001])

An Artificial Economy

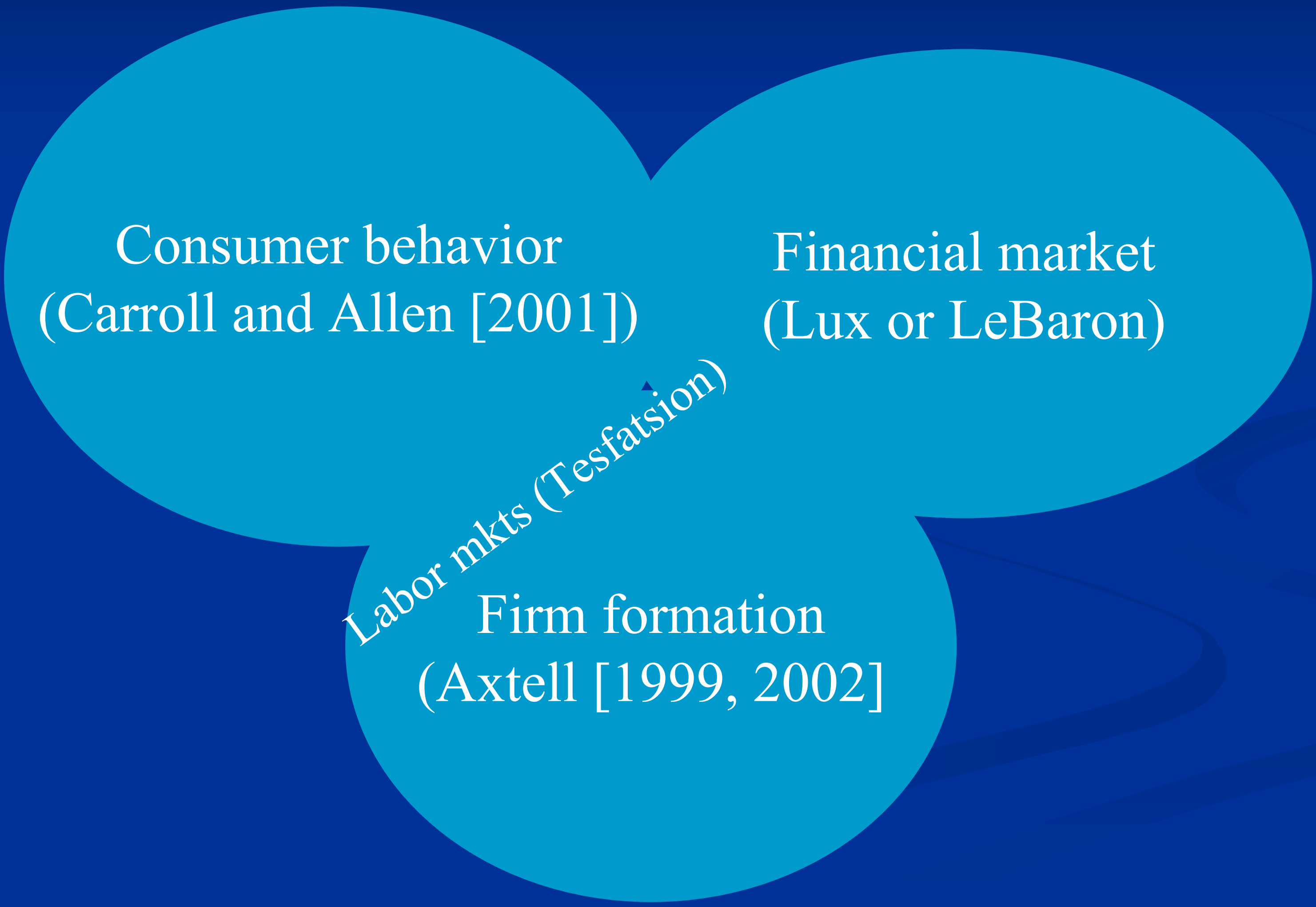
Consumer behavior
(Carroll and Allen [2001])

Firm formation
(Axtell [1999, 2002]

An Artificial Economy



An Artificial Economy



Artificial Agents: Workers and Consumers

- Preferences for consumption goods and leisure, constrained by income, wealth
- Behavioral realism, e.g.
  - non-exponential discounting
  - gain-loss asymmetry
  - varying degrees of risk aversion
- Seek (e.g., grope for) utility improvements through consumption and work choices
- Varying degrees of myopia depending on decision parameters
- Weak empirical targets

Artificial Firms

- Composed of agents
- Each makes a single consumption good
- Increasing returns to scale (effort)
- Some compensation system
- Non-cooperative behavior
- Sales and profits, are determined by market
- Agents migrate between firms when it is utility-improving to do so
- Solid empirical targets

Artificial Markets

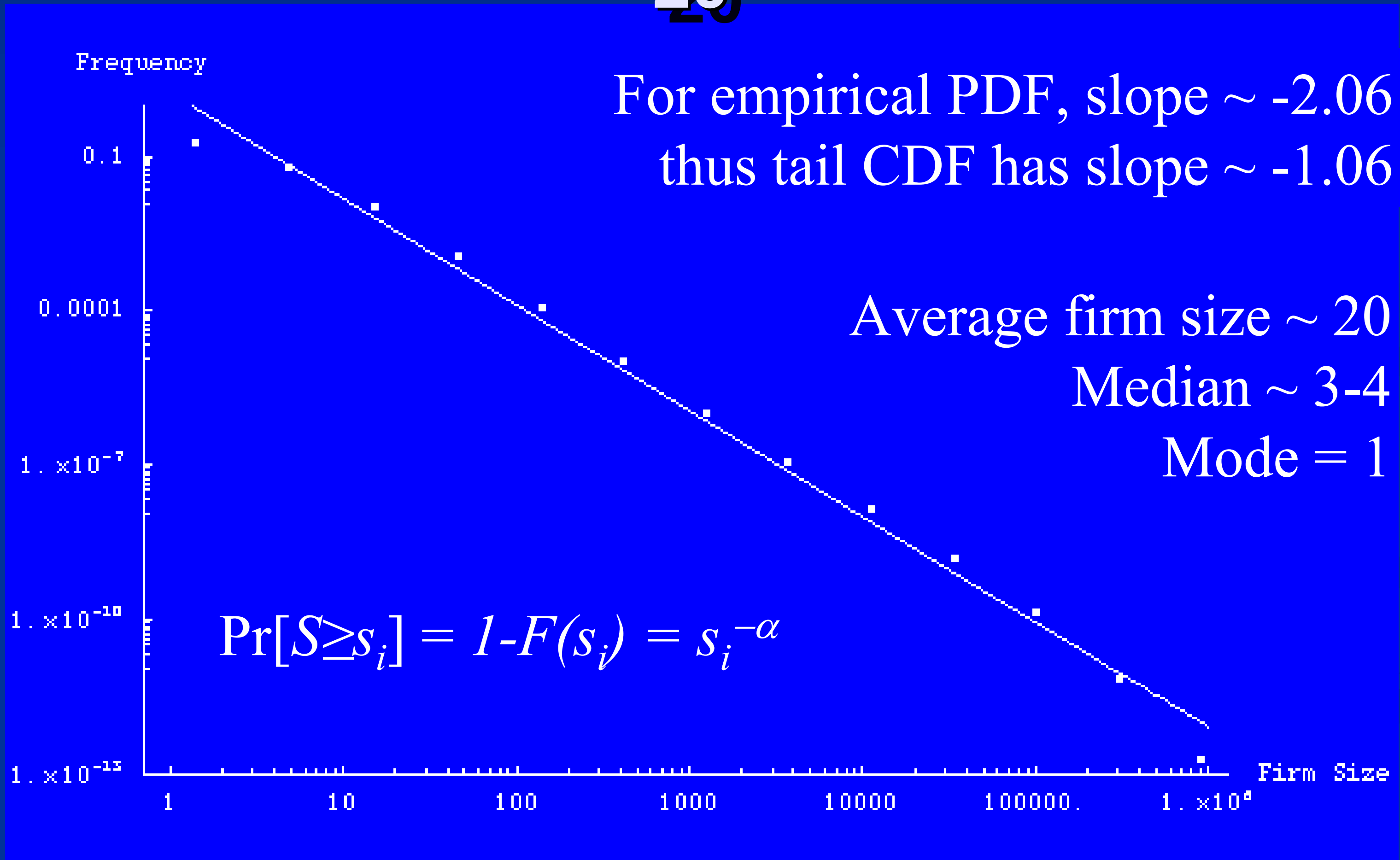
- Consumption, credit and capital goods:
  - Single market
  - Many markets
- Labor ‘market’:
  - Single market with search costs
  - Many markets
- Equity market:
  - Shares of firms bought and sold
  - Price is endogenous
  - Agents purchase shares with savings
    - Must forecast price
    - Must decide what to buy and sell

Typical Set-Up

- 10^7 agents with heterogeneous preferences
- IC: all working as *singletons*
- Run overnight to wipe out initial transient
- Model output:
  - Fluctuating aggregate output, prices, real wages, unemployment rate, share prices
  - Multi-agent firms *emerge*
    - *skew (Pareto) size distribution*
    - *heavy-tailed (Laplace) growth rate distribution*
    - *wage-firm size effect*
  - Stock market dynamics emerge
    - *heavy-tailed SR price fluctuations $\rightarrow$ Gaussian LR*
    - *clustered volatility*

"U.S. Firm Sizes are Zipf Distributed,"

RL Axtell, *Science*, *293* (Sept 7, 2001), pp. 1818-20



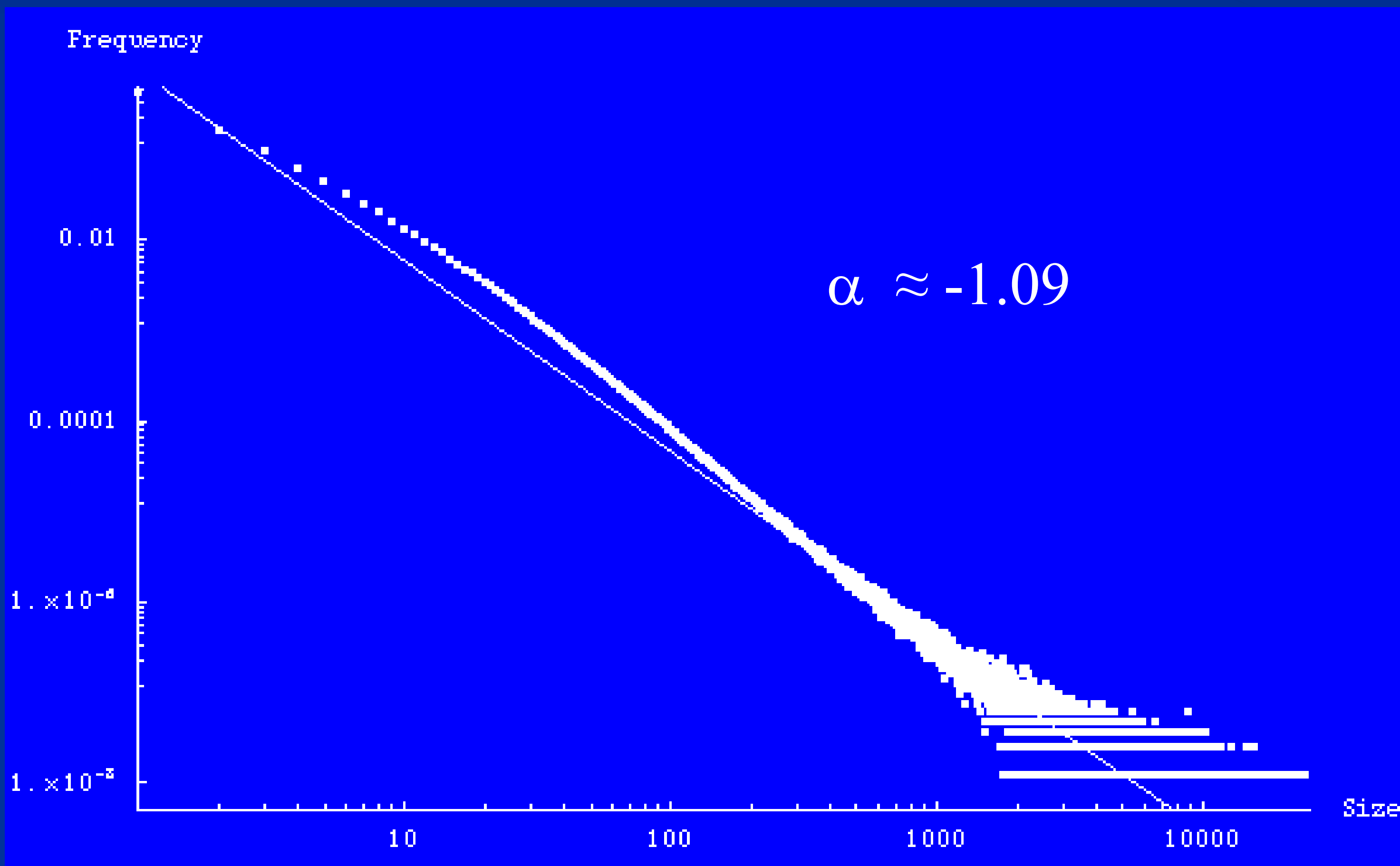
For empirical PDF, slope ~ -2.06
thus tail CDF has slope ~ -1.06

Average firm size ~ 20
Median ~ 3-4
Mode = 1

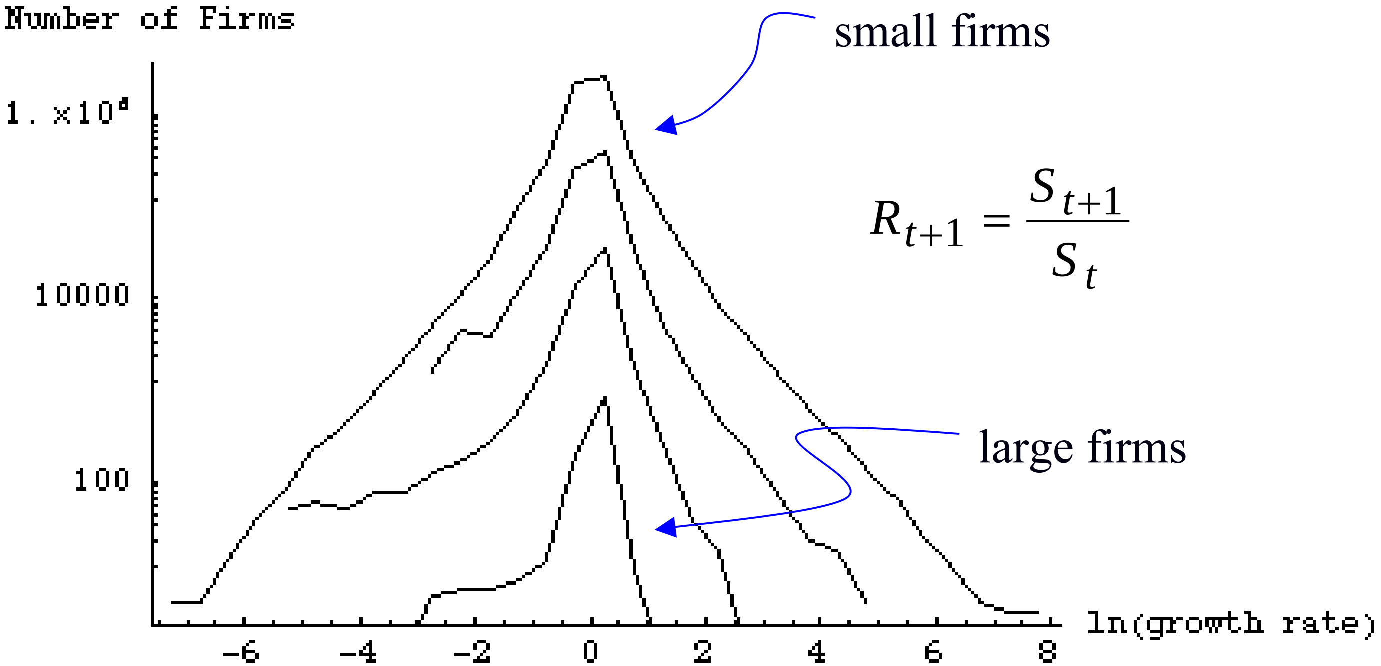
$$\Pr[S \geq s_i] = 1\text{-}F(s_i) = s_i^{-\alpha}$$

Firm Size Distribution in the Model

Firm sizes are Pareto distributed, *f* α *s*$^{-(1+\alpha)}$



"Extremely Heavy-Tailed Firm Growth," Axtell and Teitelbaum, submitted to *Nature*



$$R_{t+1} = \frac{S_{t+1}}{S_t}$$

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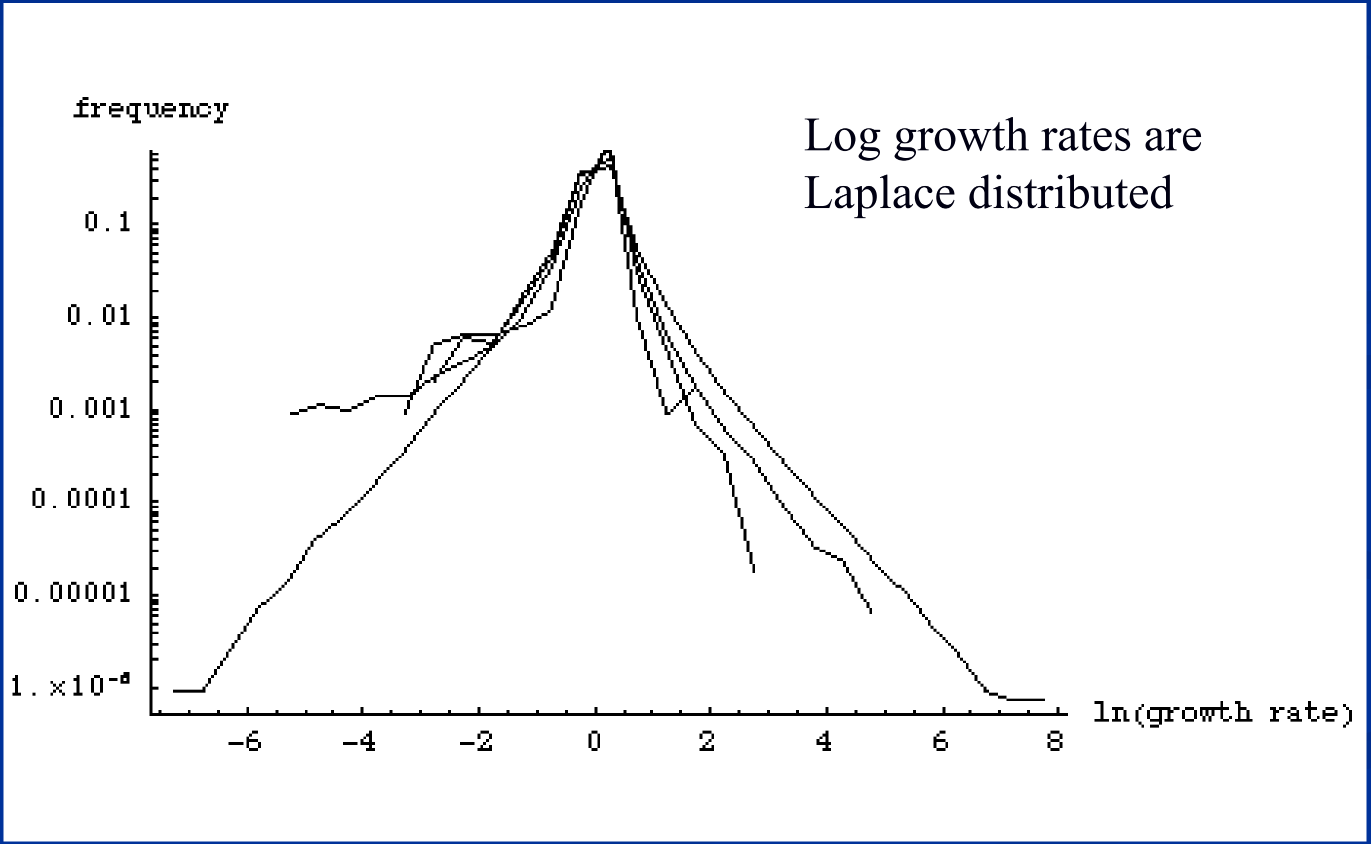

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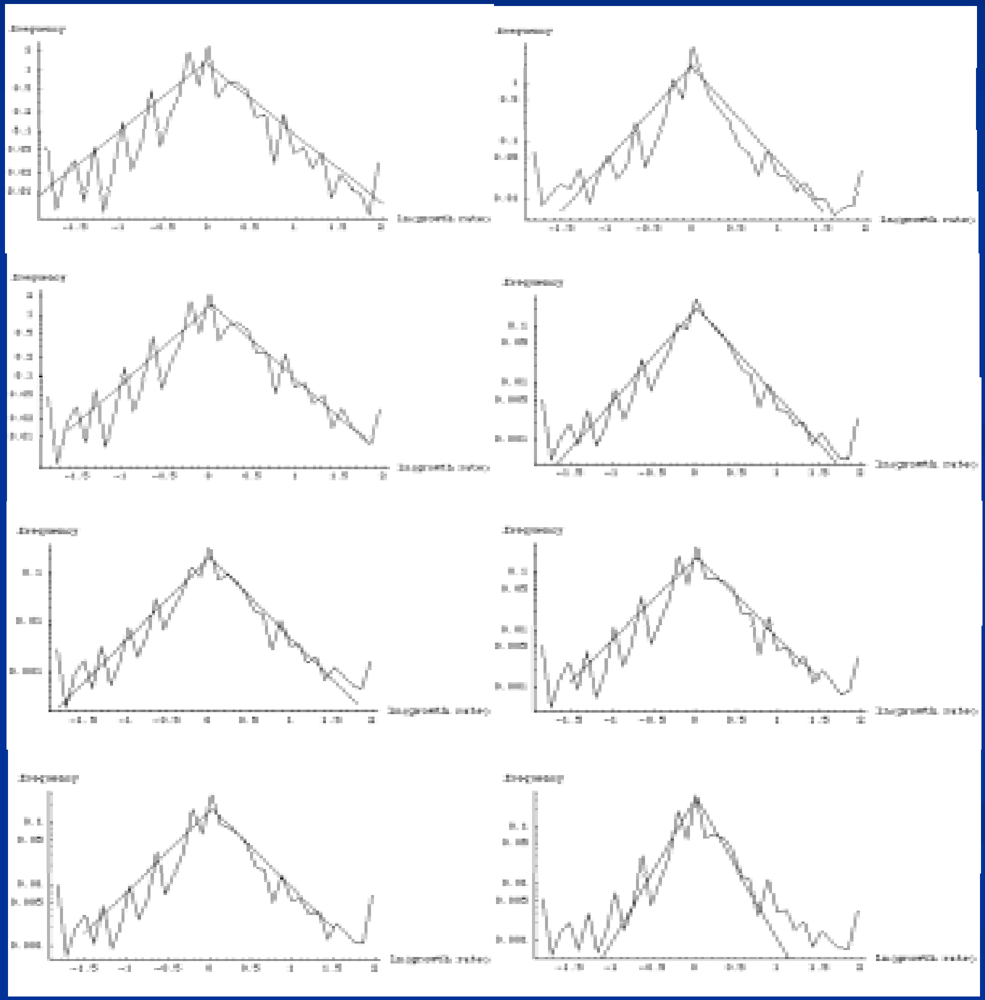
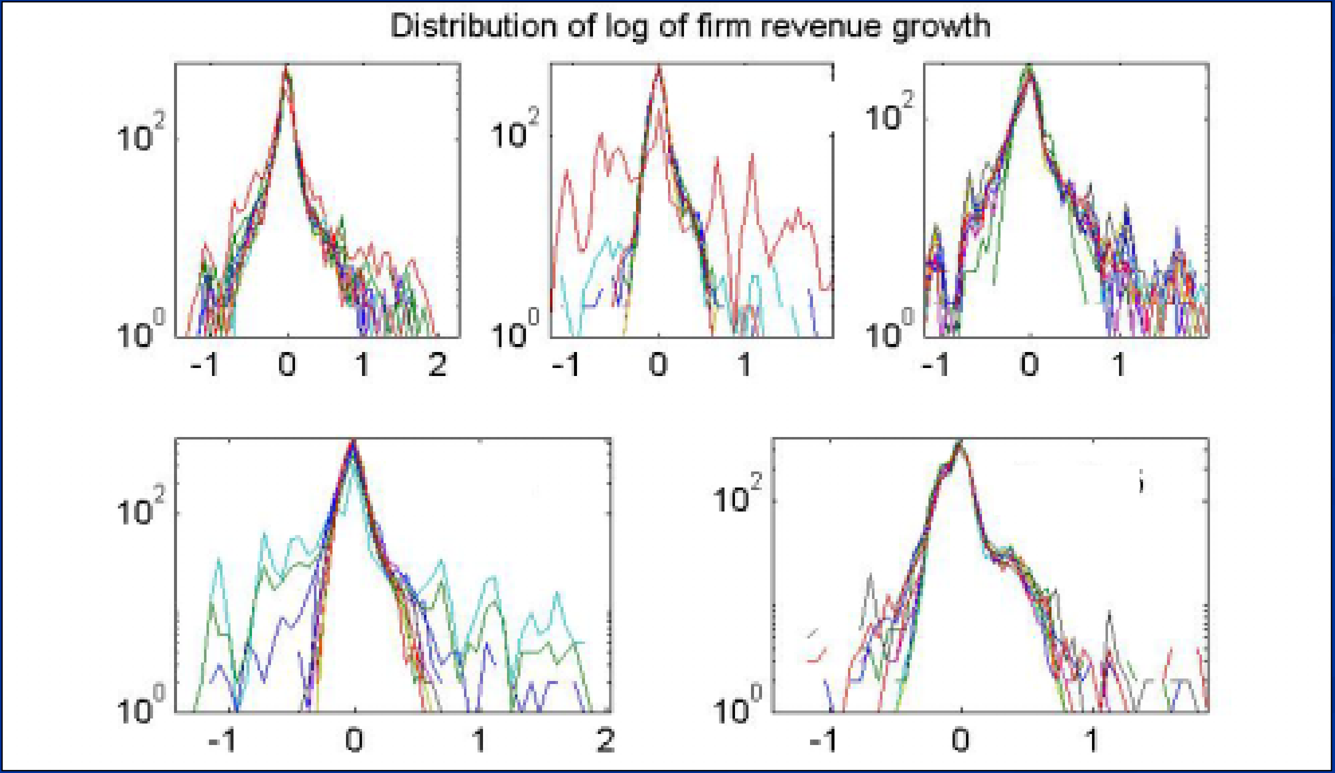


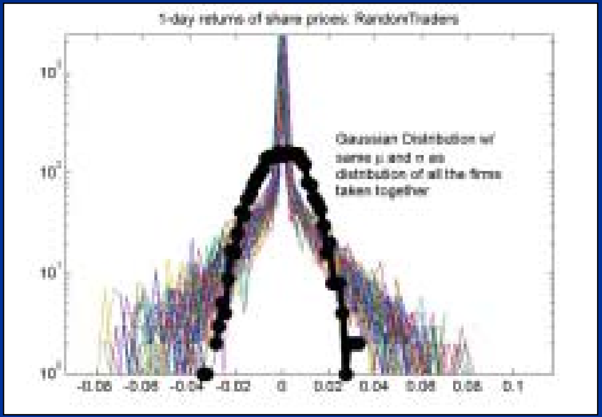
Laplace growth rates in industries

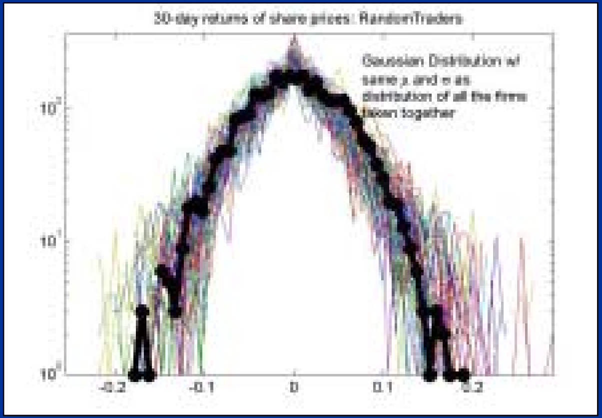
Firm Growth Rate Distribution in the Model

Firm growth rates are Laplace distributed



Firm Share Prices





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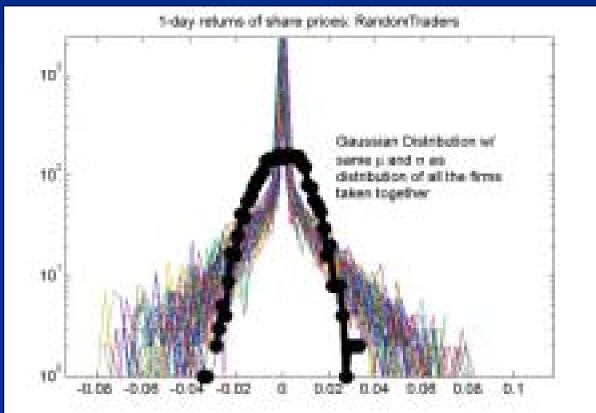

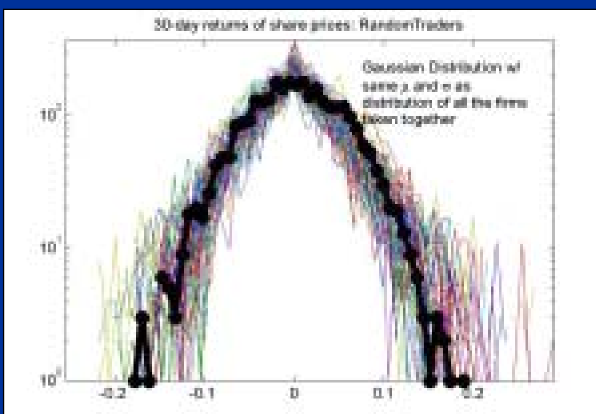

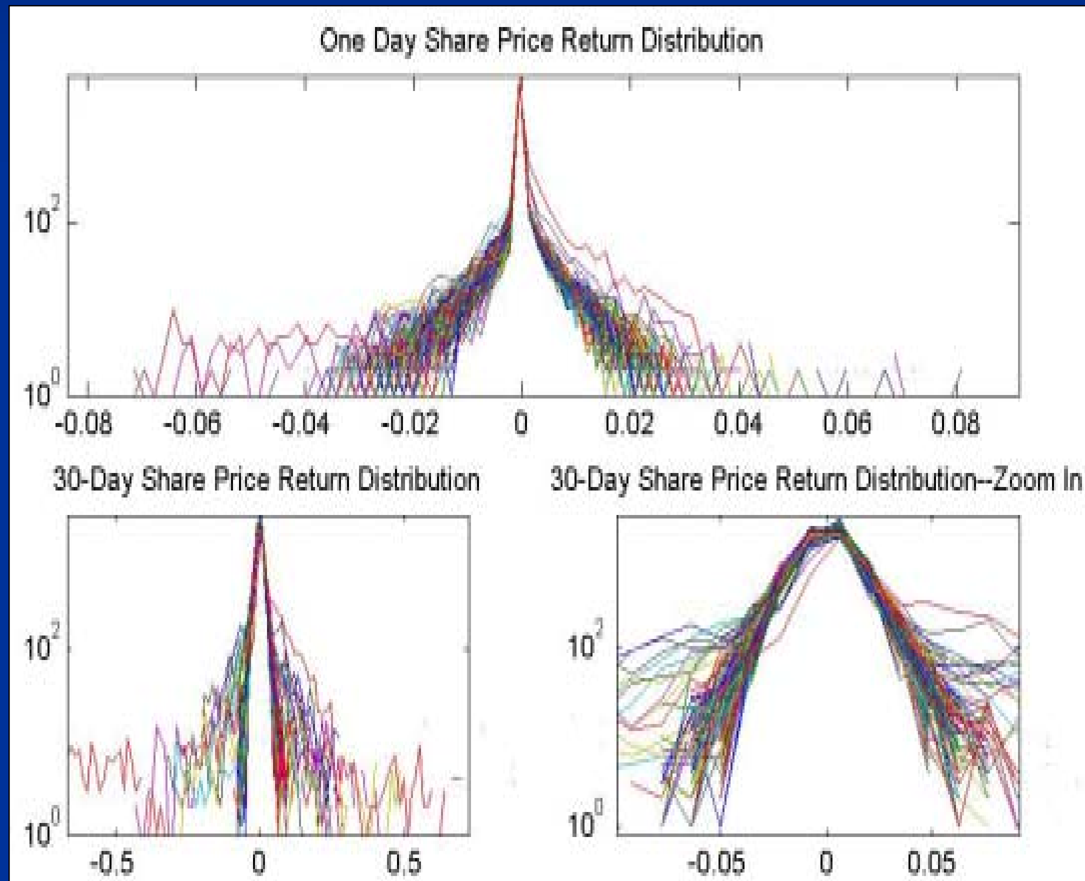

Empirical Artificial Economies

- Many levels:
  - ‘Sniff test’ by ‘old hands’
  - Calibration
  - ‘Estimation by simulation’ in principle
- Econometrics:
  - Agent models can be considered as *richer specifications*
  - Identification may be problematical
- Community of agent-based computational economists has little experience with this to date

Software Development

- Progressively add features, e.g.,
  - Richer specification of the credit market
  - Expand the role of money
- Getting institutions to emerge, e.g.,
  - Emergence of money (à la Howitt and Clower)
- Parallel C++ and Java implementations
- Dissemination:
  - Open portal on the web so outsiders can add their own agents?
  - Pegagogical tool

Main Hurdles

- How to get *realistic institutions* into such a model?
  - Let them emerge…
  - …or build them in?
- Evidence of our *limited knowledge* of how agents form institutions
  - Ostrom: Emergence of *self-governance* institutions
- <u>Hypotheses</u>:
  - Many other heretofore unknown difficulties
  - Satisfactory execution of this research program will take many decades!

Main Casualties of the Artificial Economy Approach to Macro

- *Homogeneity* assumptions
  - Good riddance!
- Agents as *omniscient* utility maximizers
  - Forthcoming marriage of artificial economies to experimental/behavioral economics?
- Economic agents as *solitary* actors
  - Hello sociology
- *Equilibrium*: against the Nash program
- *Representative* anything: micro to macro mediated by institutions
- Theoretically: the *core*

Summary

- *Large-scale* agent models are just feasible today
- Prior work on agent modeling of major components of the economy exists and is sufficiently rich to synthesize into first generation *artificial economy*
- This work will come to fruition over next few years
- A *new way* to do macro!
- Main limitation is how to treat *institutions*

Final Thoughts on Artificial Economies

- *Ontology* of mathematical economics is *maximization*:
  - Given agent methodology, why *maximize?*
  - Are equations outside of agents *legitimate*?
- Firms are multi-agent systems:
  - Why *single* agent firms in agent models?
  - Who can get profit maximization to *emerge*?
- *Sensitivity* analysis:
  - How do results depend on *N*

Exciting Time for Artificial Economies

- Almost everything is an *open problem*:
  - How to 'grow'…
    - …the family
    - …private property
    - …the State
  - How to regulate…
    - *…*a financial market
    - *…*a multi-agent firm (e.g., environment)
    - *…*a macro-economy (i.e., not optimal control!)
- Analogy: Early days of game theory
  - We have reached *the end of the beginning!*