Complexity in Economics: Empirical Evidence, Theoretical Models and Policy Implications

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Outline

- What Economics is All About…
  - Explaining emergence of order from disorder
- How Does Economic Theory Explain That?
  - Building Blocks of Mainstream Economic Models
- The Economy as a Complex System?
  - Exploring empirical and experimental evidence
- Modeling the Economy like a Complex System?
  - Methodology, Examples, and Policy Implications
- Concluding Remarks

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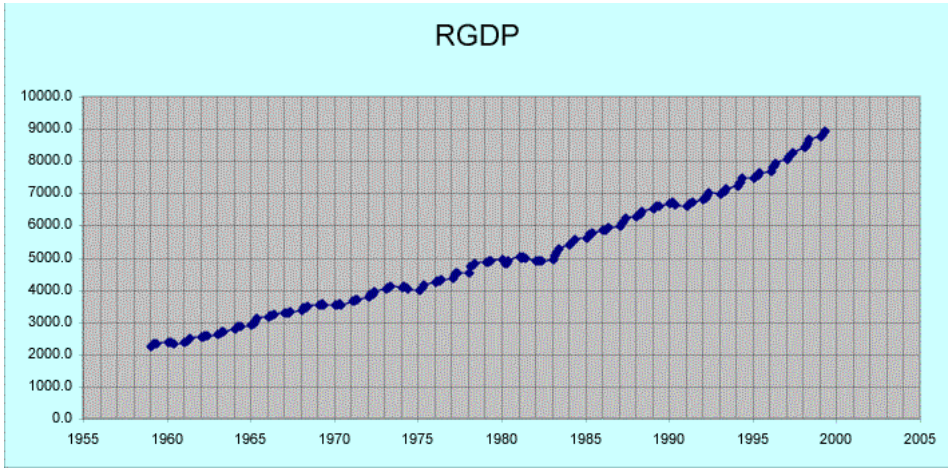
Order from Disorder

- Main Theme in Economics and Social Sciences
  - Explaining emergence of macroeconomic order from microeconomic disorder
  - Disorder: Self-Interested Interacting Agents
  - Order: Some “Stable” and “Persistent” Observed Behavior
  - “*The purpose of science is to find meaningful simplicity in the midst of disorderly complexity*” (Herbert Simon)
- Examples:
  - How do market prices and interest rates emerge?
  - How do GNP, unemployment, consumption, investment move together along economic cycles?
  - How do some technological standards manage to dominate a market?
  - How do cooperative patterns persistently emerge despite self-interested behavior?

Order from Disorder

Macro Level



Feedback to Micro Level

Micro Level

- Firms competing in turbulent markets
- Undertaking strategic decisions (output, investments, marketing, R&D, innovation, etc.)

Standard Approach of Economic Theory

- Build Simple Models to Explain a Messy World
  - Paradigm: Positivist, Instrumentalist and Minimalist
    - Newtonian Paradigm
  - Mathematics and Analytically Solvable Models
    - Models like map of an unknown territory

- The Neoclassical Approach
  - Explaining how do markets work
    - General Equilibrium Theory
    - Game-Theoretic Models
  - Explaining Macroeconomic Dynamics (Growth, etc.)
    - Micro-founded Macroeconomics Models

Mainstream Theory: Building Blocks (1/2)

- Individual Agents as Fully Rational Individuals
  - No computational and memory bounds
  - They know the model of the world
  - They are perfectly rational and know that others are like them
  - No learning takes place: they already know almost all they need

- Interactions
  - Any exchange of information, knowledge, goods, etc. occurring among individuals
  - General Equilibrium Theory & Macroeconomics Models
    - Agents are autonomous, no interaction takes place
  - Game-Theoretic Models
    - Agents interact with everyone else

Mainstream Theory: Building Blocks (2/2)

- Diversity
  - Agents are assumed to be homogeneous
  - Heterogeneity does not add anything new
  - Average Behavior = Behavior of the Average
  - Linearity of Underlying World

- Time and Aggregate Outcomes
  - Economy viewed as being always in equilibrium, where all micro and macro forces compensate
  - Time dimension is not crucial
    - Agents able to decide once and for all their future
  - Static Models instead of Truly Dynamic Models

… but in recent years…

- Many natural and social systems are “complex”
- To understand “complex” systems we need the right models
- Model based on neoclassical simplifying assumptions may not be suited to analyze “complex systems”

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What is a Complex System?

- As many as 45 definitions of it !!
  - The two that I like best:

> "*A system that involves numerous interacting agents whose aggregate behaviors are to be understood. Such aggregate activity is nonlinear, hence it cannot simply be derived from summation of individual components behavior*."
>
> Jerome Singer

> "*A system that can be analyzed into many components having relatively many relations among them, so that the behavior of each component depends on the behavior of others.*"
>
> Herbert Simon

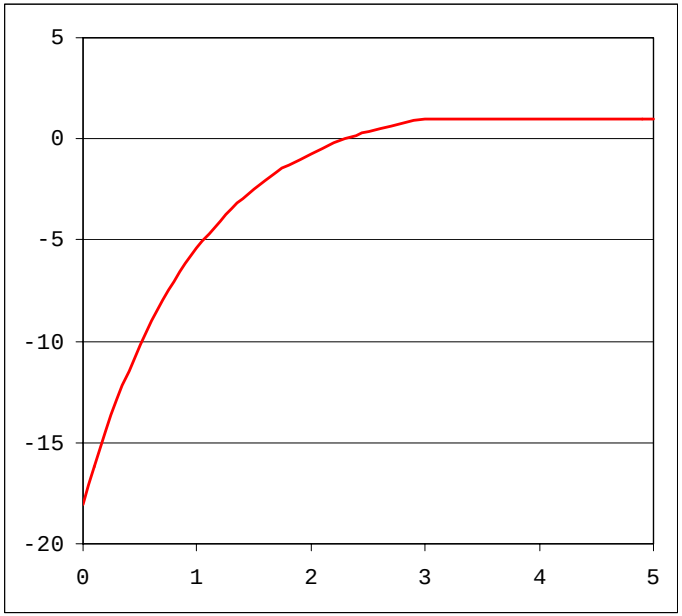
Main Features of a Complex System

- Many micro entities
  - Relatively Simple and Routinized Behaviors
- Heterogeneity
  - Entities are structurally and behaviorally different
  - Possibly Hierarchically Organized
- Interactions
  - Entities locally exchange information
  - Aggregate behaviors may have little to do with micro ones
- Time and Dynamics
  - Systems may or may not be in equilibrium
  - Persistent evolution due to endogenous change

Complexity and Dynamic Systems

- Long-run Behavior of Dynamic Systems

Simplicity

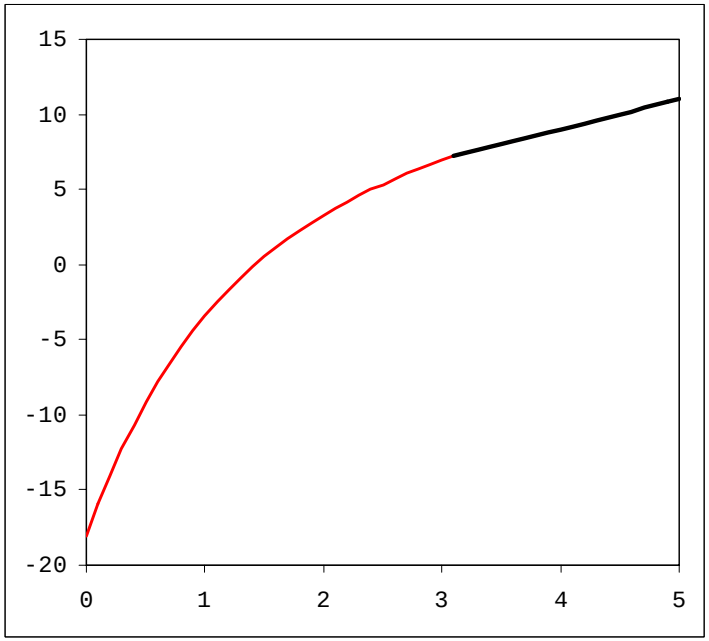


Steady-State 1

Complexity and Dynamic Systems

- Long-run Behavior of Dynamic Systems

Simplicity

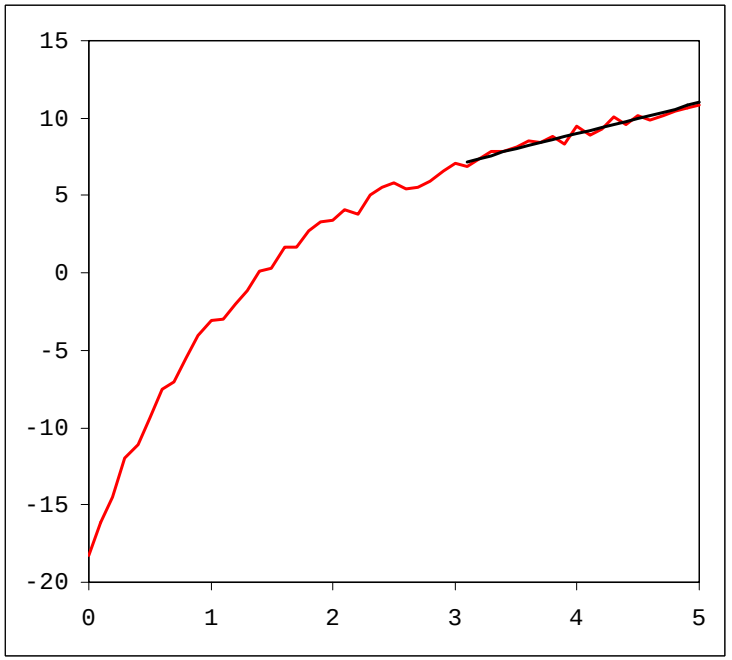


Steady-State 2

Complexity and Dynamic Systems

- Long-run Behavior of Dynamic Systems

Simplicity

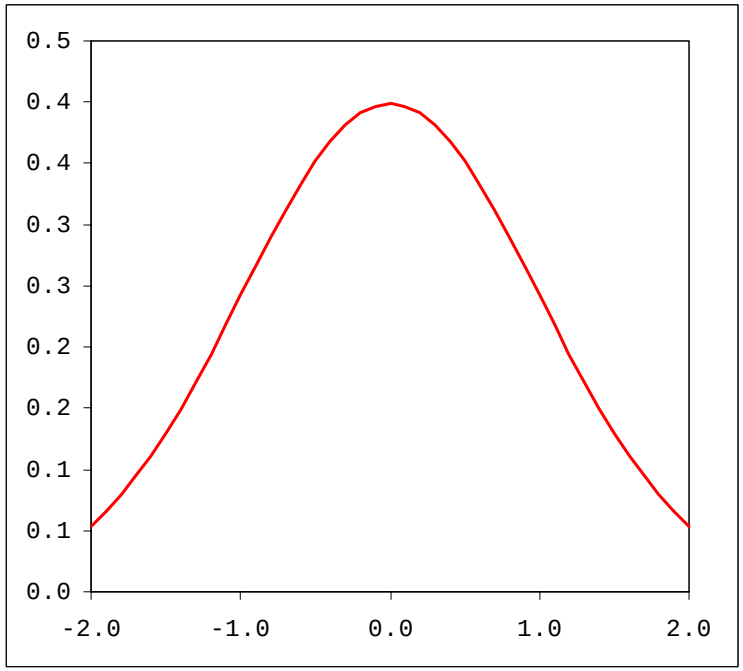


Ergodic Distribution

Complexity and Dynamic Systems

- Long-run Behavior of Dynamic Systems

Simplicity



Ergodic Distribution

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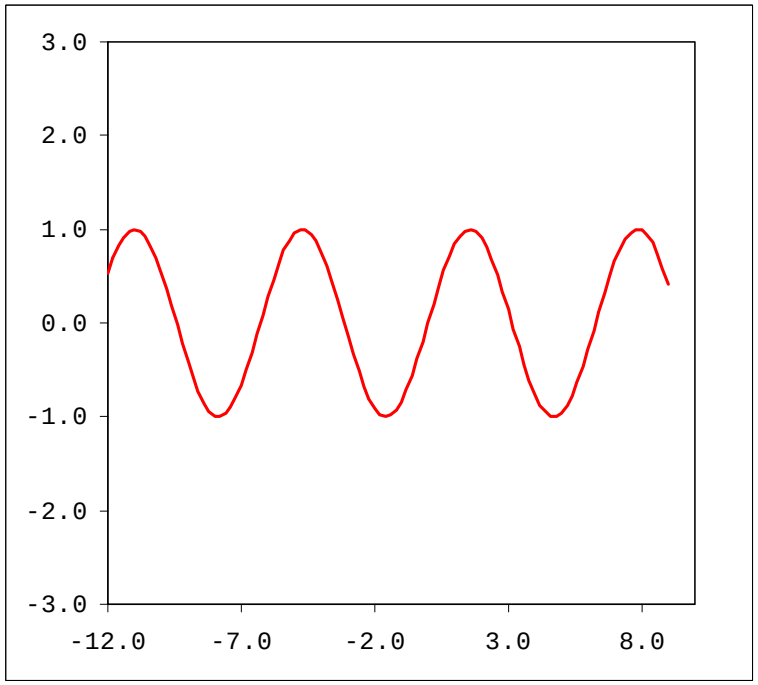
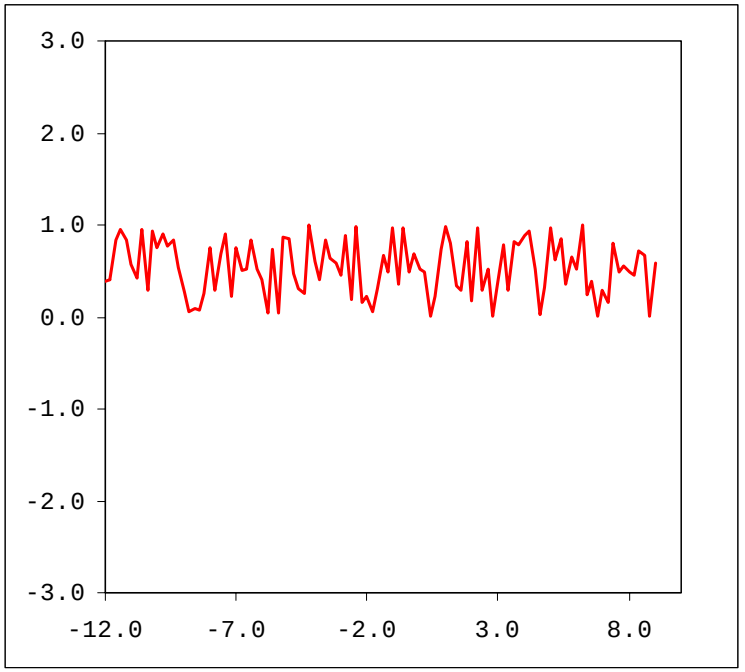


Cycles

Complexity and Dynamic Systems

- Long-run Behavior of Dynamic Systems

Disordered

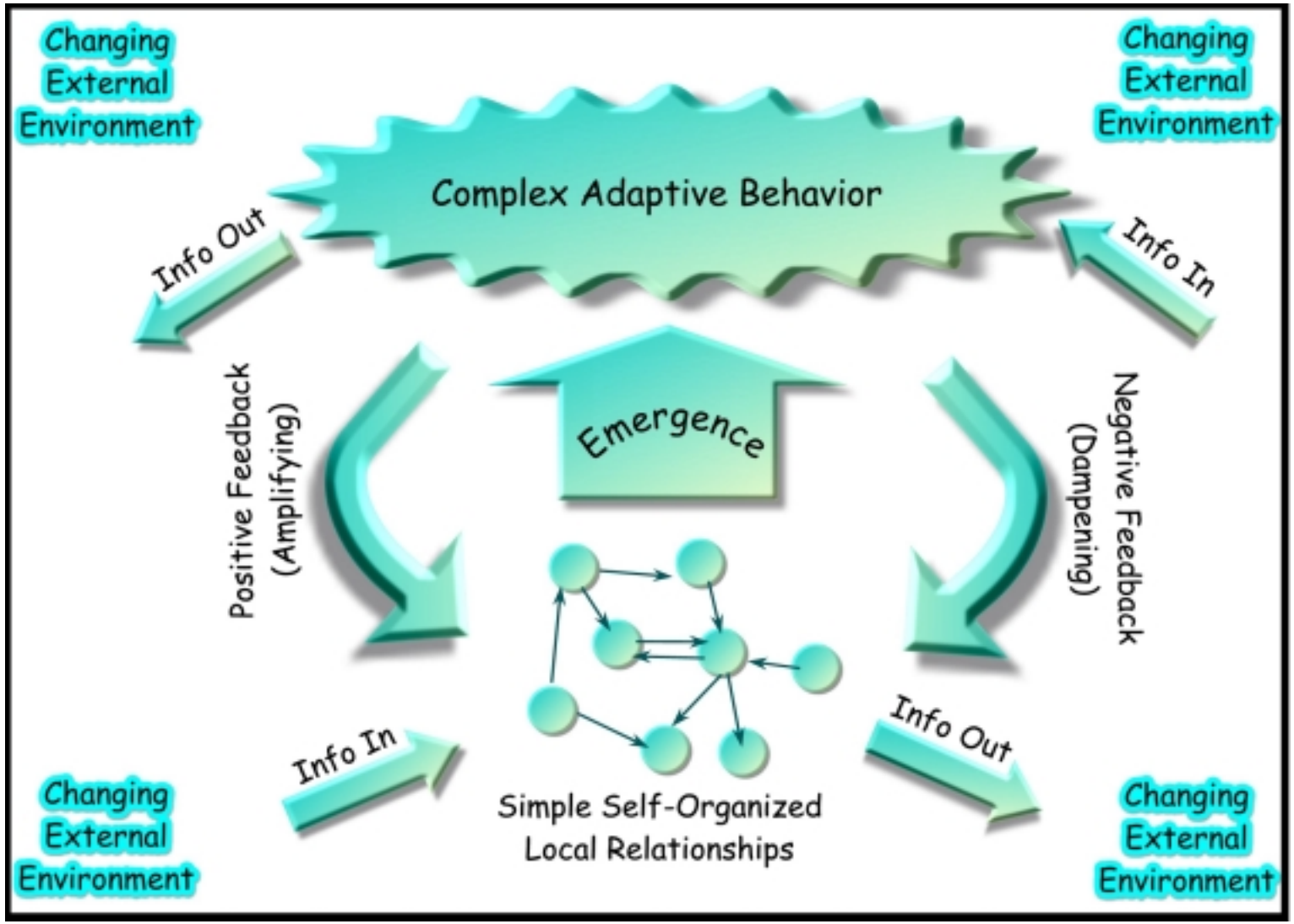


Randomness or Chaos

Complexity and Dynamic Systems

- Complex Systems are Characterized by:
  - Complex Adaptive Behavior (Life?)
  - “Order without Simplicity”
- Trade-Off between Randomness and Simplicity
  - Emergent Properties
    - Meta-stable properties that persist for a period of time sufficiently long with respect to the time-scale of the process
  - Self-organized patterns
    - Complex systems tend to auto-organize and converge to self-sustaining “complex adaptive behavior”

Main Features of a Complex System



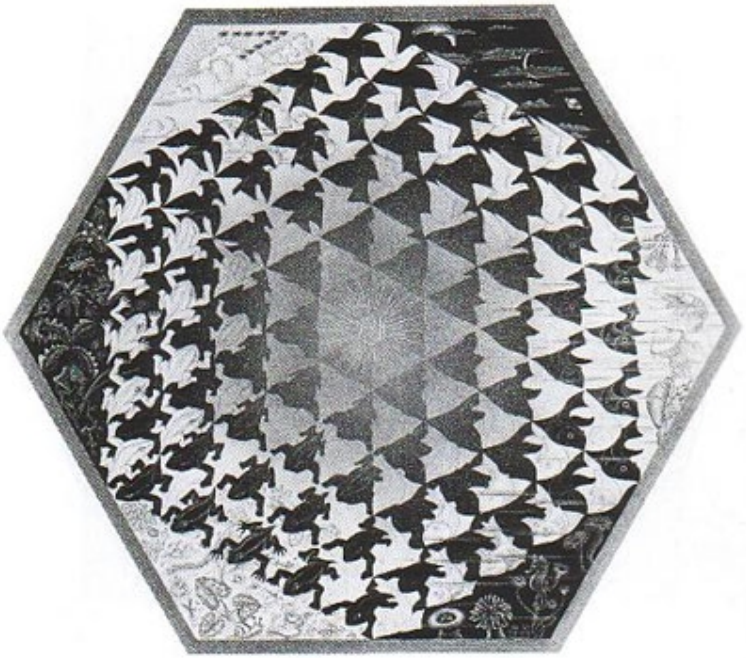
Art and Complex Systems

- Klee, Duchamp, Magritte, Escher,…

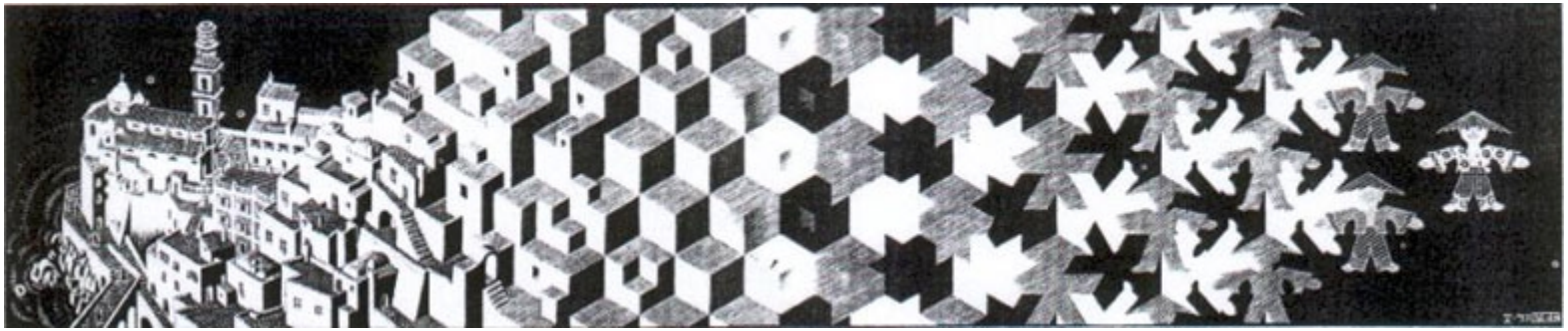
Paul Klee, Red fugue, 1921

Art and Complex Systems

M. C. Escher, E15, 1938



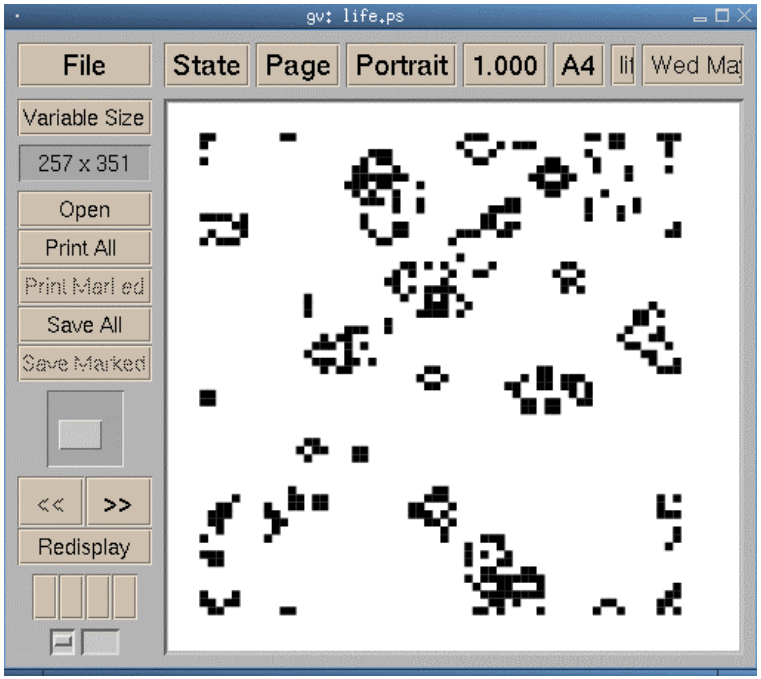
M. C. Escher, Verbum, 1942



M. C. Escher, Metamorphosis, late 1930s

Examples of Complex Systems

- Natural Environments
  - Insect Colonies (Ants, Termites, Bees)
- Artificial Environments
  - Computer Simulations, Information Networks



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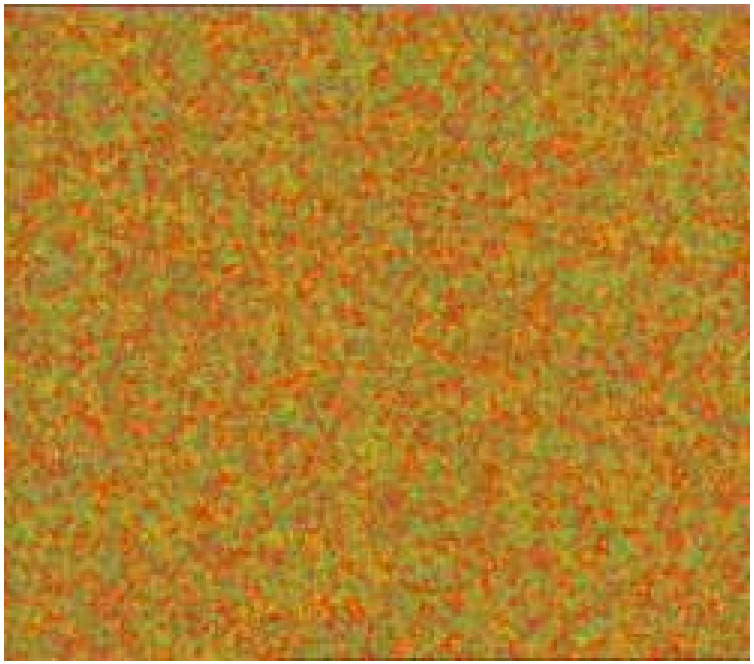

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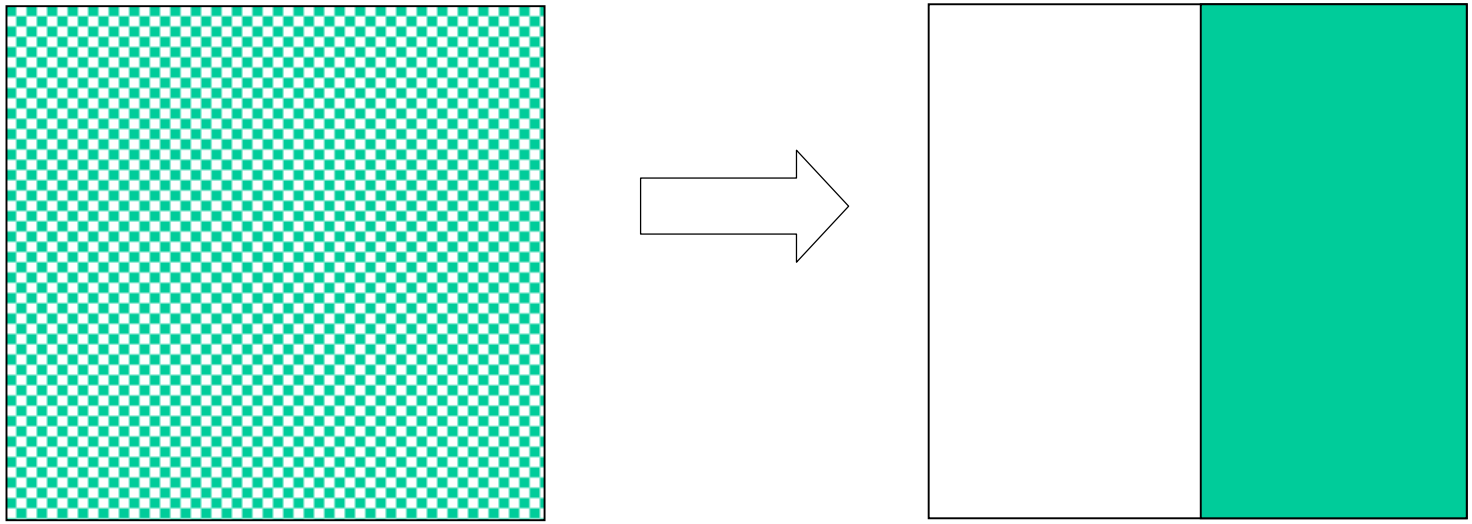


Examples of Complex Systems

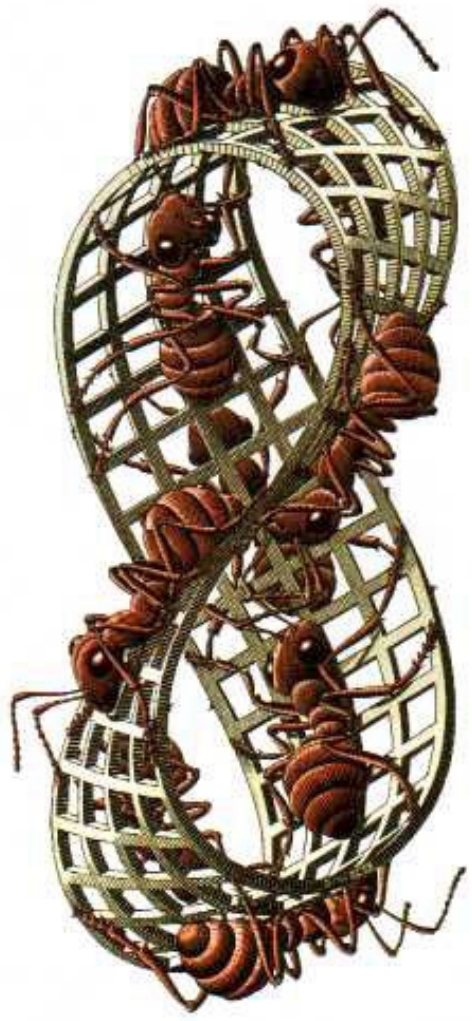
- Natural Environments
  - Insect Colonies (Ants, Bees)
- Artificial Environments
  - Computer Simulations, Information Networks
  - Schelling Segregation Models
- “Real” Social and Economic Environments
  - Societies
  - Markets
  - Industries
  - Countries
  - World Economy

… therefore …

- Many natural systems are “complex”
- Simple “artificial worlds” can easily explain features of “complex systems”
- Can we use simple artificial models to explain also what happens in social systems as Schelling suggests?

Two Crucial Questions to be Answered… (1/2)

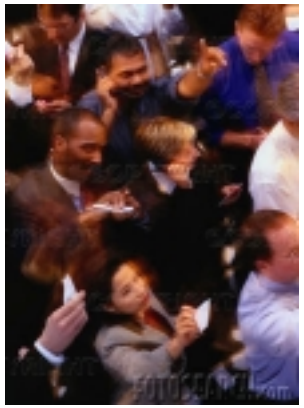
- Are humans like ants?
  - Natural-Artificial vs. Human Systems
  - Are human societies really characterized by CS features?
    - Do economic agents behave in simple and routinized ways?
    - Are economies and market characterized by non-trivial interactions?
    - Are economic agents so persistently heterogeneous?

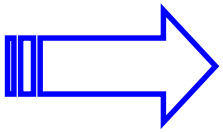


M. C. Escher, Moebius band II, 1963

Two Crucial Questions to be Answered… (2/2)

- Complex Systems and Real-World?
  - What is the value-added in modeling economies as complex systems?
  - Can we explain the real-world around us better than what mainstream models have been able to do?





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Features of a Complex System (1)

- Many micro entities ?
  - Relatively Simple and Routinized Behaviors
- Experimental Evidence: Cognitive Psychology
  - Kahneman, Tversky, Thaler
- People are not rational
  - Inherent difficulty in dealing with uncertainty and probability
    - Risky Environment
  - Persistent cognitive biases
    - Frame- and Context-Dependence
  - Adaptive (Trial & Error) and Simple Behavioral Rules
    - Problem decomposition (Rubik's Cube)
    - Powerful, Simple and Routinized Rules (Heuristics)

Real-World Behavior vs. Rationality: Example 1

- Problem A: You have been given 1.000 Euros
  - Choose between
    - **A1: Win** 1000 Euros with 50% probability (zero otherwise)
    - **A2: Win** 500 Euros with certainty
- Problem B: You have been given 2.000 Euros
  - Choose between
    - **B1: Loose** 1000 Euros with 50% probability (zero otherwise)
    - **B2: Loose** 500 Euros with certainty
- Rational Choice
  - In both case your expected position is 1.500 Euros
  - All depends on whether you are risk-averse or not
    - **If you choose A1 (A2), you must choose B1 (B2)**

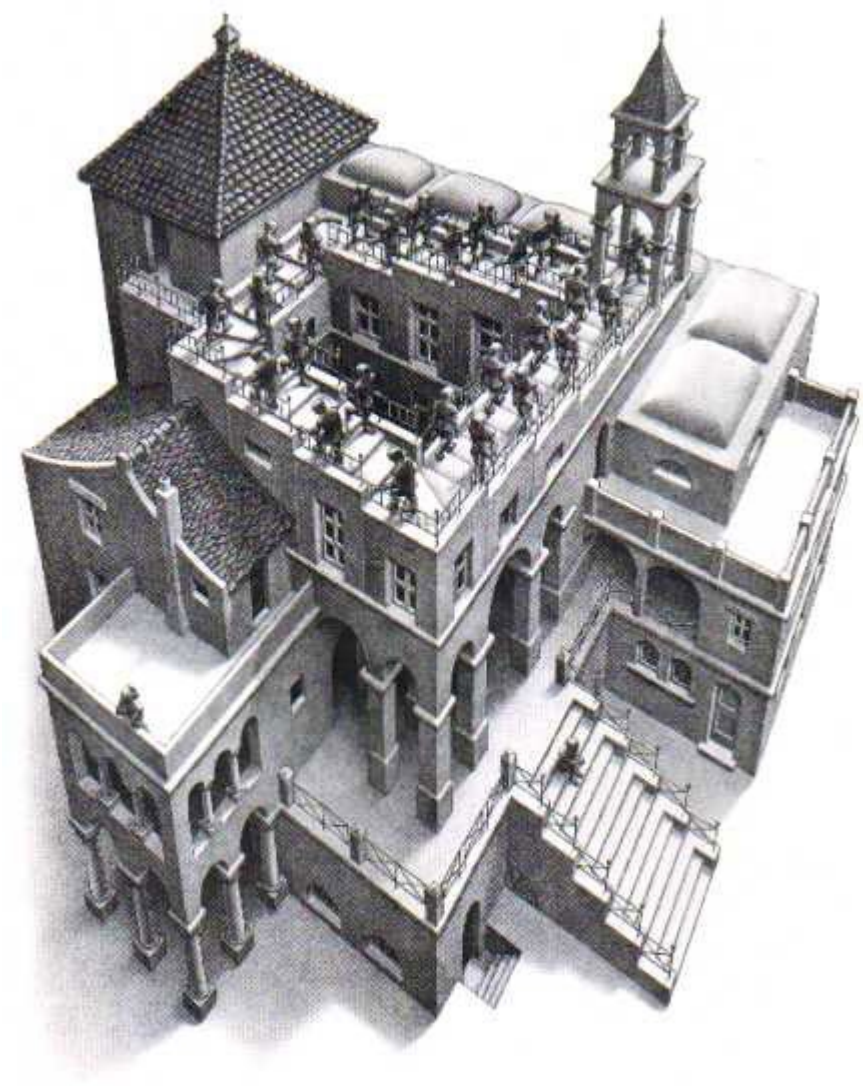
Real-World Behavior vs. Rationality: Example 1

- Laboratory Experimental Evidence
  - Statistically significant majority of subjects
    - Choose A2 and B1!
- What does it mean?
  - Gains are perceived differently from losses
    - Agents are risk-lovers for losses and risk-averse for gains
  - The structure of the problem affects choices (framing)
    - Structurally-similar problems (A & B) are treated differently
- … and there is much more than that
  - Almost all axioms of rational choice are always disregarded…
  - Preferences, if known by the agents themselves, are typically far from having all “smoothness” properties assumed in theory

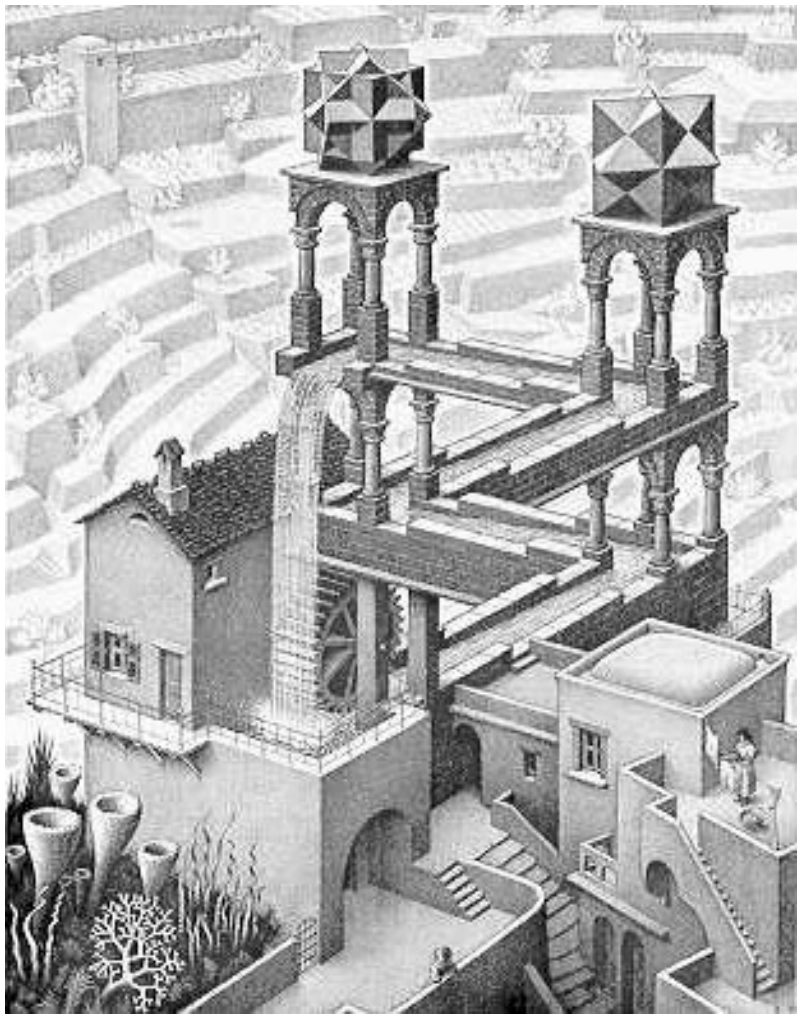
Real-World Behavior vs. Rationality: Example 2

- Dealing with probability
  - Humans “genetically” unable to correctly deal with “risk”
- The (in)famous 3-Doors Monty Hall Problem
  - Three doors
  - Behind one of them a **car**, behind others a **goat**
  - Monty Hall knows where the **car** is
  - You Choose a door without opening it
  - Monty Hall opens one of the remaining two
    - He always opens a door with a goat behind
  - Now you are asked
    - Do you want to **stay** or do you want to **switch** ?
  - Problem is
    - Which strategy (**stay**, **switch**) is the most rewarding?

Mental Biases and Impossible Objects…



M. C. Escher, Ascending and Descending, 1960

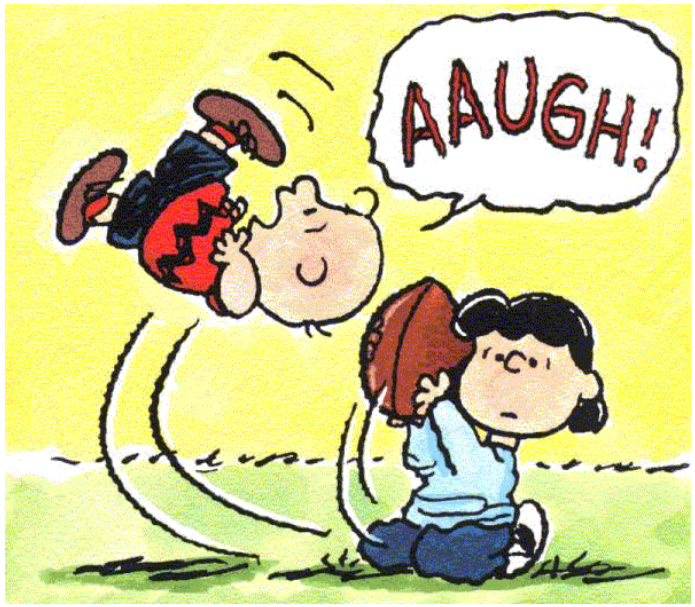


M. C. Escher, Waterfall, 1961

Real-World Behavior vs. Rationality: Example 3

- Expectations
  - Human beings form expectations about others' behaviors
    - Competitors, Buyers, Sellers, etc.
  - Experimental evidence shows that expectations are adaptive
    - Imperfect knowledge of the past helps in predicting the future…

- Standard Models
  - Rational Expectations
  - Consistency of Expectations in Equilibrium
  - Expectation Loop
  - Charlie Brown and Lucy
    - "I know that she knows that I know…"



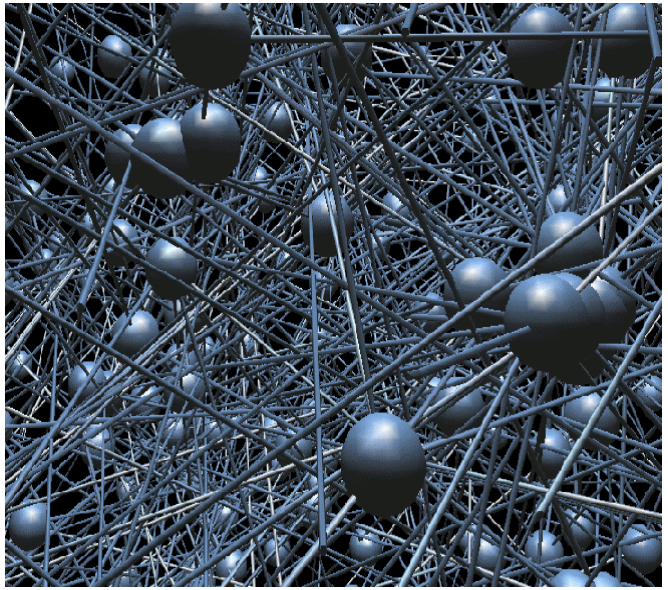
Real-World Behavior vs. Rationality: Summing Up

From: Dosi, Marengo and Fagiolo (2005), "Learning in Evolutionary Environments", In Dopfer, K. (ed.), *The Evolutionary Foundations of Economics*, Cambdridge, Cambridge University Press.		Substantive Uncertainty: Certainty	Substantive Uncertainty: "Weak" Uncertainty (risk)	Substantive Uncertainty: "Strong" Uncertainty
Procedural Uncertainty	Certainty	Trivial maximization problems	Lotteries and standard decisions under uncertainty	
	With **Finite** Decision trees	Puzzles like the Rubik Cube	Game-Theoretic and Economic Choices in Stationary Environments	
	With **Infinite** Decision trees	Proving theorems. Developing Innovations given known principles…	Non-recursively Computable Games (Chess)	**Adaptation and innovation in evolutionary environments**

Features of a Complex System (2)

- Empirical evidence shows that
  - People exchange **locally** information, knowledge, goods…
    - Output, Capital, Labor Markets…
    - Technological spillovers and knowledge flows
    - … and many other situations…

- Interaction Structures as non-trivial networks
  - Empirical studies on
    - Who owns who, boards of directors, …
    - Patent citations, collaboration citations, …
    - R&D joint-ventures, knowledge spillovers, …
    - Air transportation

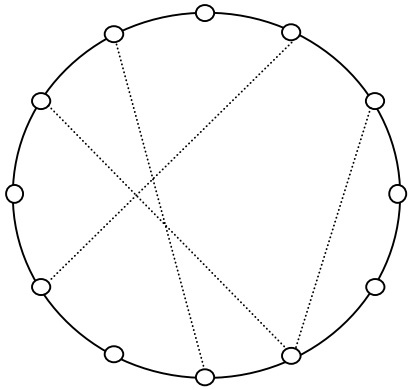


3D View of Network of Friendship of a Large Group of People in Canberra, Australia

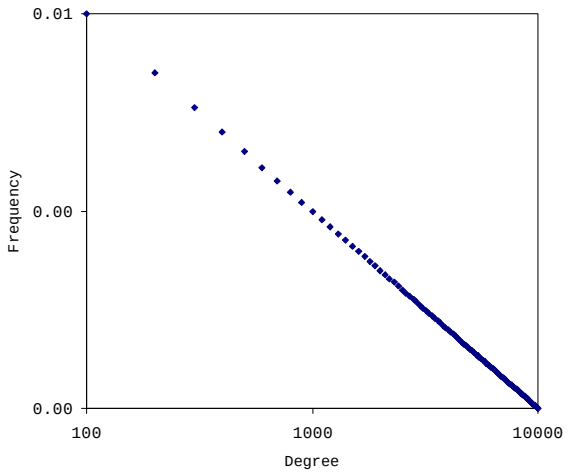
Interactions and Networks: Small-Worlds

- Six Degrees of Separation
  - Many networks are characterized by:
    - Many local ties: agents mostly interact with their neighbors
    - Few long-distance ties: agents have some friends living far away
- Milgram's Experiment: Is it a small world?
  - How long is the shortest path connecting unacquainted people?
    - Letters gave to hundred people in Boston, MA and Omaha, NE
    - Letters to be sent to XY, who works (but not lives) in Boston
    - Rule:
      - Letter can be actually sent to a person whom you know personally
      - If you know XY then you can send the letter directly to him
- How many letters from Nebraska to Boston?
  - On average, only 6 !!
  - Despite clustering, anyone in the planet is reachable in 6 steps!

Interactions and Networks: Scale-Free

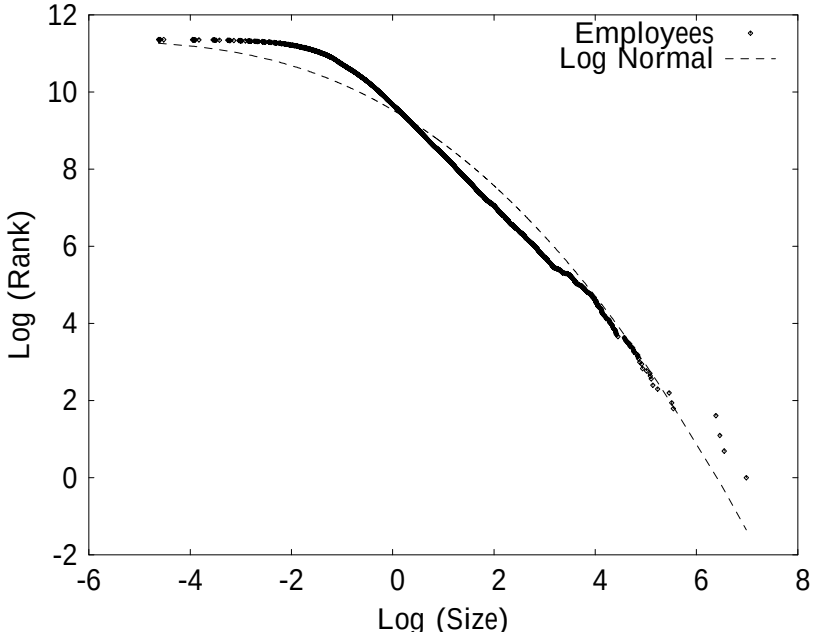


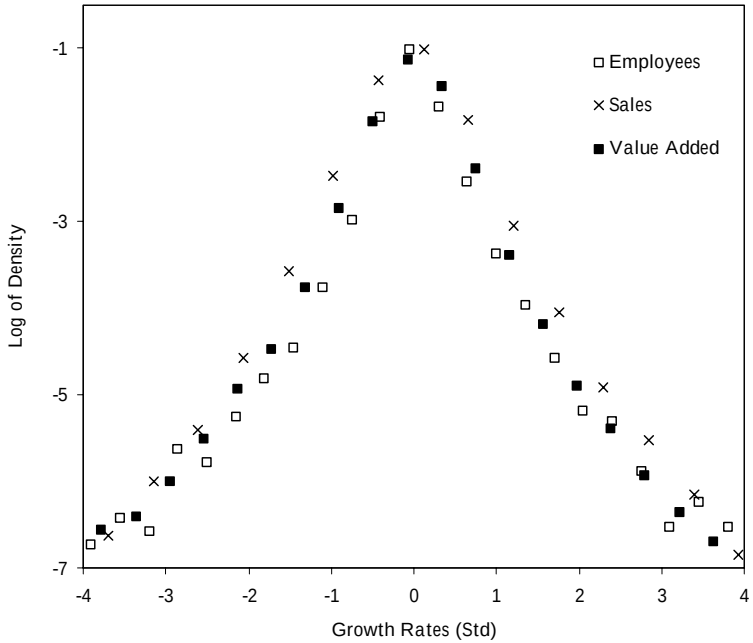
- Small-Worlds
  - High clustering: lots of local connections
  - Low path length: easy to reach distant nodes
- Scale-Free Networks
  - Few nodes with many links (hubs), many nodes with few links
  - Rich get richer… who has many links will receive more links
- Pareto Degree Distribution
  - Physical Internet Network, WWW Link structure
  - Boars of directors, citation, etc.



Features of a Complex System (3)

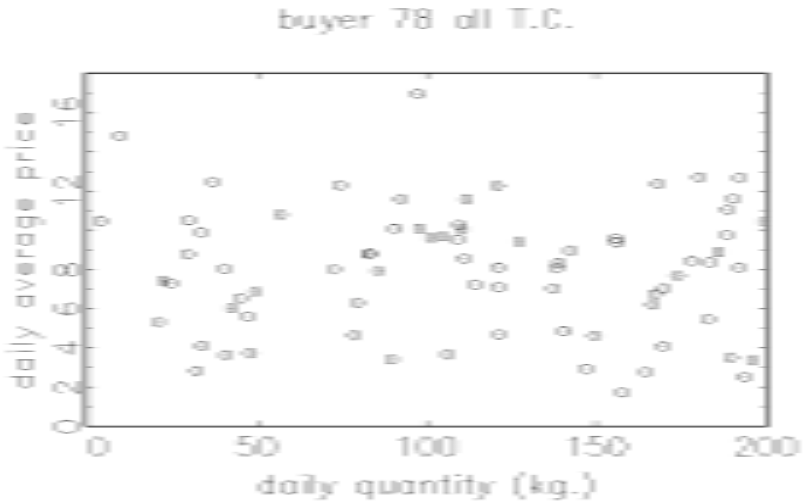
- Persistently heterogeneous economic agents?
  - Empirical Evidence:
    - Consumers: Wealth, Income, …, Cognitive repertoires
    - Firms: Size, Growth Rates, Productivity, …
    - Markets: Prices, Rules, Institutions, …

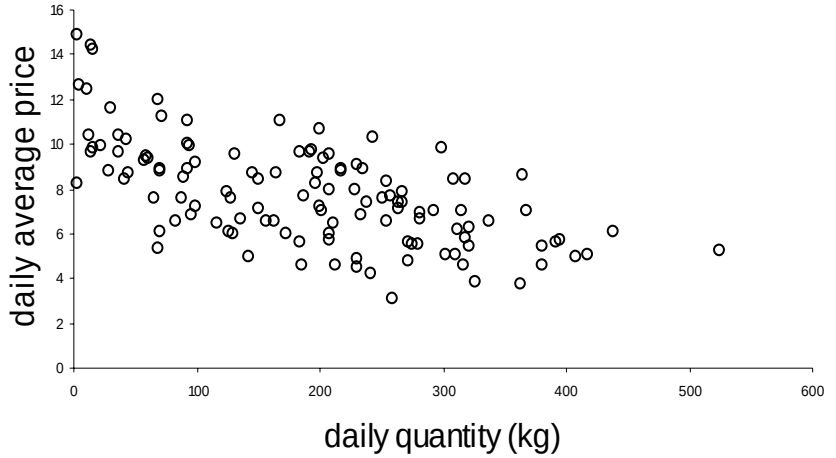




Heterogeneity, Interactions, and Aggregation

- Is aggregate behavior more than the sum of its parts?
  - Do non-linearities in behaviors and interactions lead to aggregate behaviors that are structurally different from individual ones?





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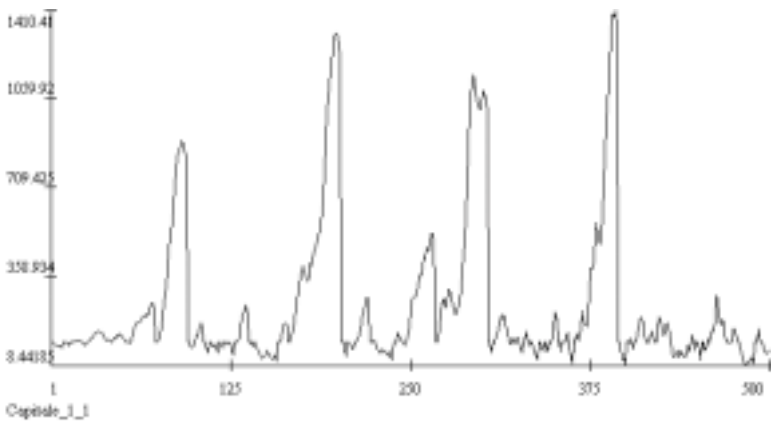

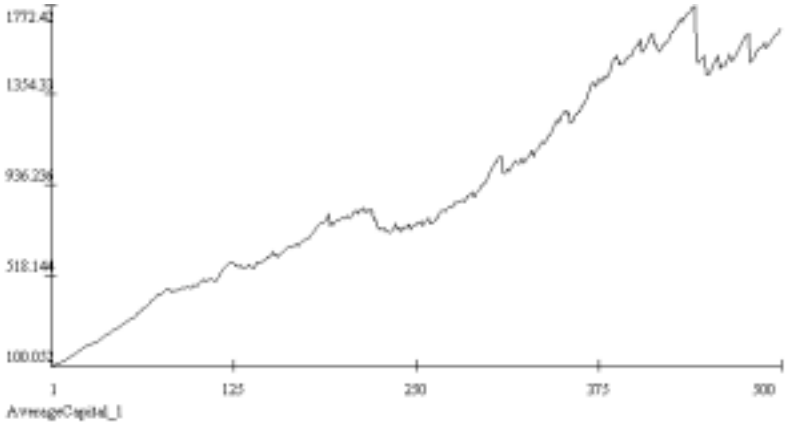

Back to Our Two Crucial Questions…

- Are human societies really characterized by CS features?
  - Plenty of evidence in favor of a positive answer…

- Complex Systems and Real-World?
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Agent-Based Economic Models

- Ingredients for a Recipe…
  - **Bottom-up** (agent-based) Philosophy (Tesfatsion, 1997)
  - Agents live in **complex systems** evolving through time (Kirman, 1998)
  - Agents are (or might be) **heterogeneous** in almost all their characteristics
  - Environment is too complex: **“hyper-rationality” not viable** (Dosi et al., 1996)
  - Agents behave as **boundedly rational** entities with adaptive expectations
  - **“True” dynamics**: Systems are typically non-reversible
  - Agents **interact directly**, interaction networks may change over time (Fagiolo, 1998)
  - Endogenous and persistent **novelty** (technological change): open-ended spaces
  - **Selection**-based market mechanisms (Nelson & Winter, 1982)

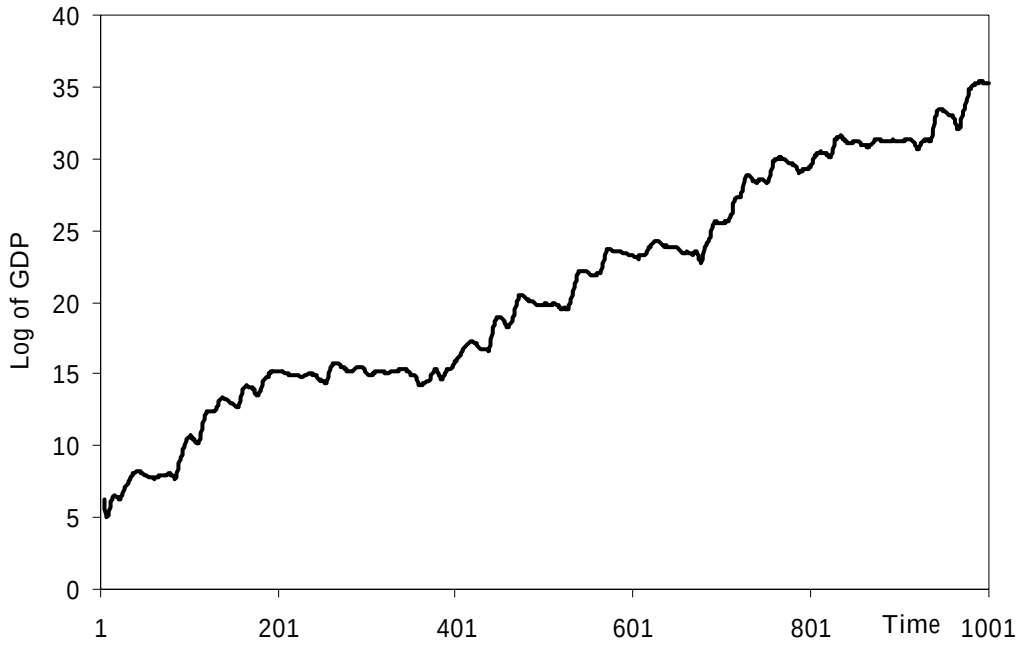
An Example: Modeling Economic Growth

- The “Islands” Model: Fagiolo & Dosi (2003)

Technological Space	Notionally Unbounded Sea
Technology	Island (i.e. a ‘mine’)
Output	Homogeneous Good
Firms	Stylized Entrepreneurs
Production	Mining (Extracting the Good)
Technological Search	Exploration of the Sea
Innovation	Discovering a new island
Technological Diffusion	Spreading information from islands
Imitation	Traveling between already known islands
Tech. Differences	Distance between Islands

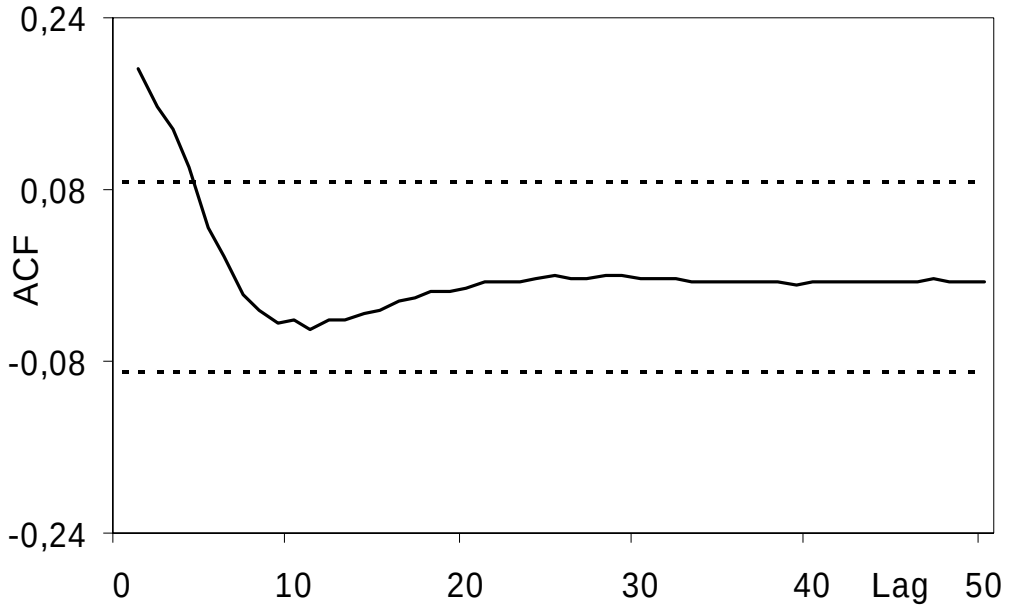
An Example: Modeling Economic Growth

- Reproducing Real-World GNP Time-Series…



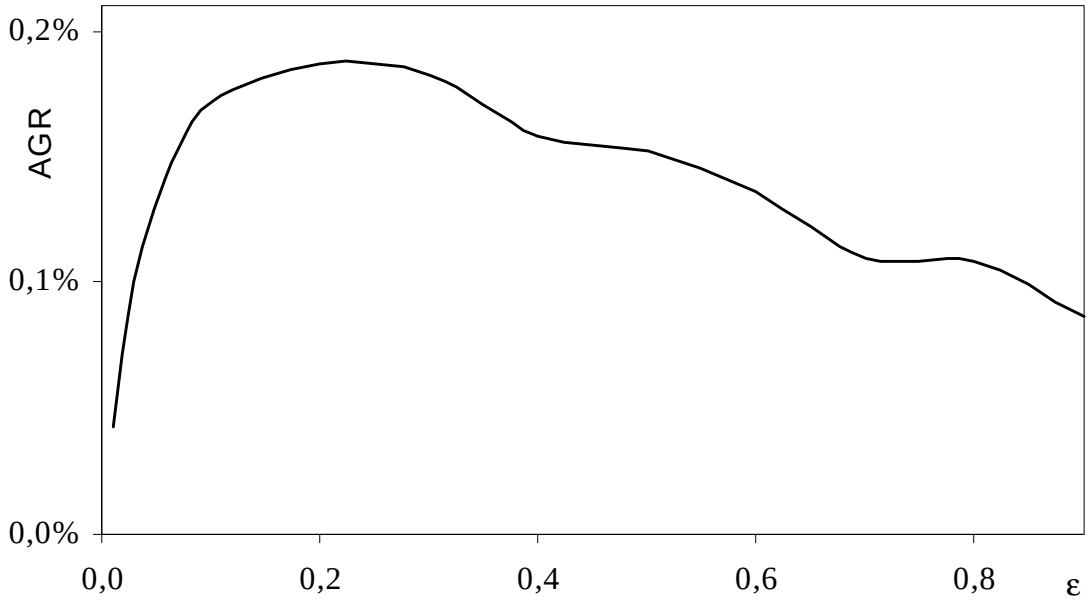
An Example: Modeling Economic Growth

- … with the right statistical properties



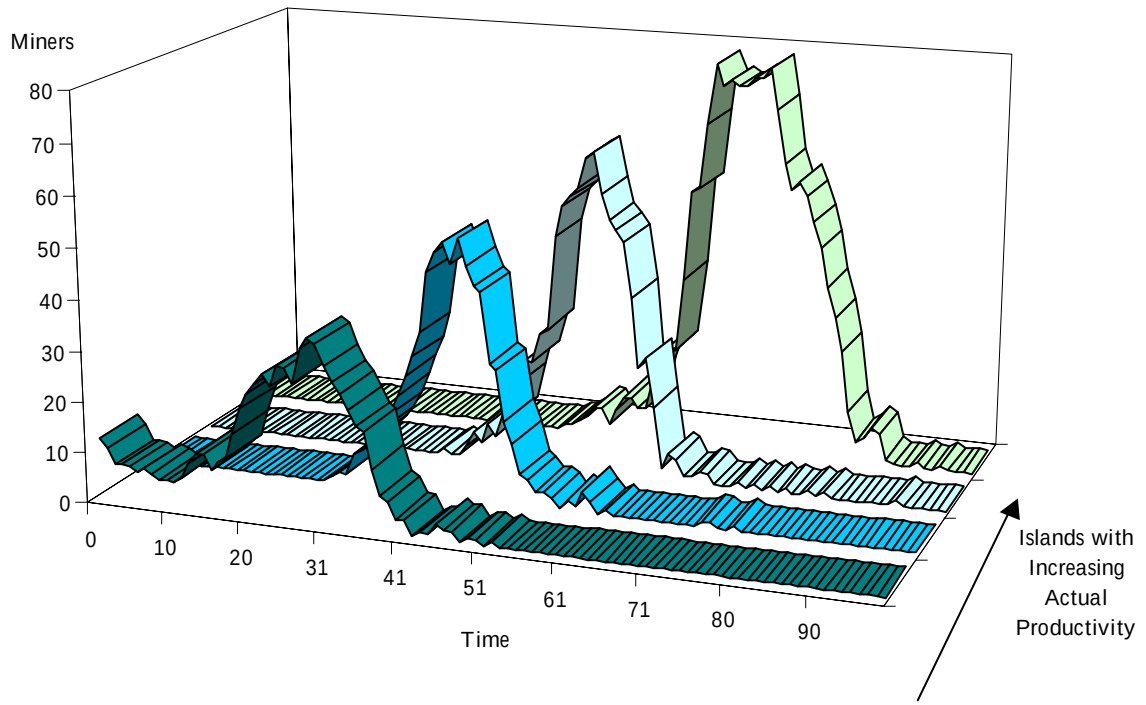
An Example: Modeling Economic Growth

- Growth as an Exploitation-Exploration Trade-Off



An Example: Modeling Economic Growth

- Reproducing S-Shaped Diffusion Curves



An Example: Modeling Economic Growth

- Showing that irrationality is necessary for growth

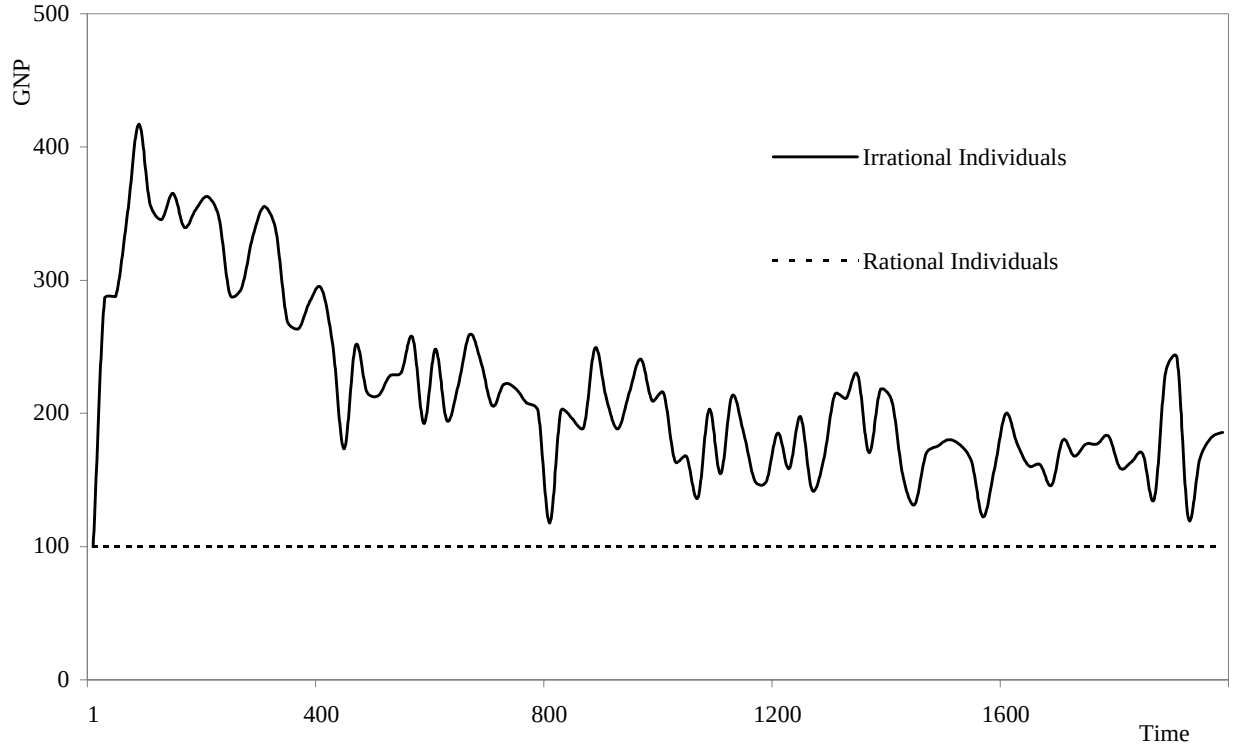


Figure 13
Individual vs. Collective Rationality: A Simple Example
Parameter Setup: $s*=100$, $N=100$, $\varepsilon=0.05$, $\varphi=0$, $\lambda=5$, $\pi=0.15$, $\rho=\infty$, $\alpha=1$

Outline

- What Economics is All About…
  - Explaining emergence of order from disorder
- How Does Economic Theory Explain That?
  - Building Blocks of Mainstream Economic Models
- The Economy as a Complex System?
  - Exploring empirical and experimental evidence
- Modeling the Economy like a Complex System?
  - Methodology, Examples, and Policy Implications
- Concluding Remarks
  - A lot of work (but also of fun) still ahead…