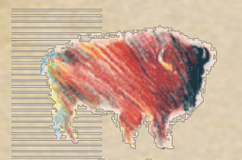
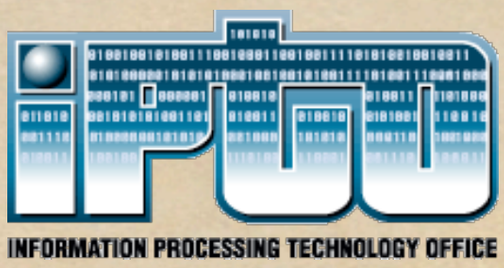
Embodiments of Computation in Cognitive Systems

James P. Crutchfield
www.santafe.edu/~chaos
www.santafe.edu/~dynlearn



Santa Fe Institute
24 October 2003
IPTO Visit



Complexity

Modern Life:

Ever more technological

Ever more interconnected

Ever more diverse

Symptoms:

Increased size and sophistication of systems and processes

Increased interdependence and contingency (globalization, just-in-time)

Increased social & psychological stress, due to lack of knowledge & control

Consequences:

Difficult or impossible to manage and diagnose

Vulnerable to destabilization and catastrophic loss

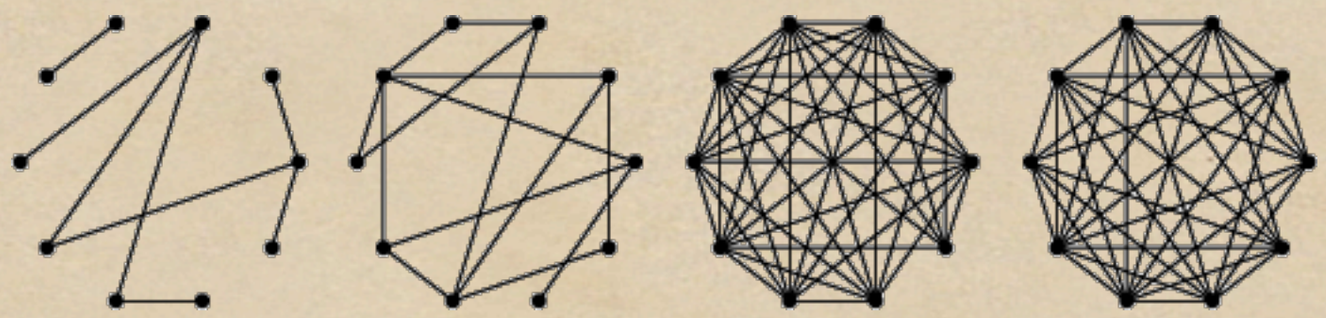
Systems are more complex, but in what sense?

Two definitions

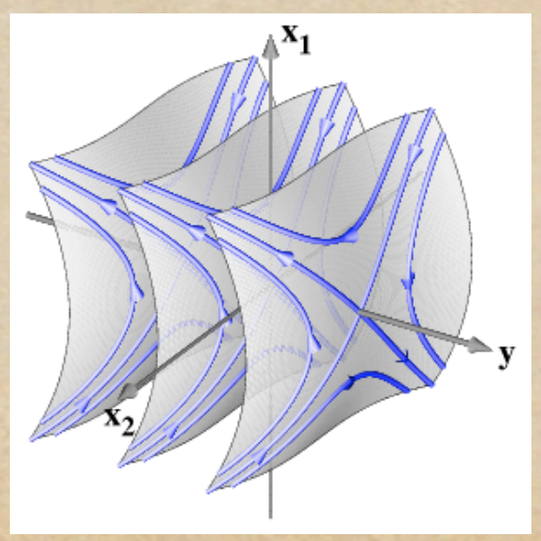
- Complication
- Structure

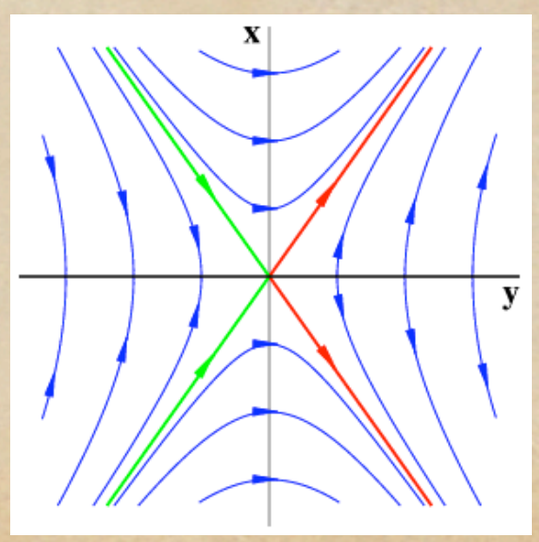
Complication

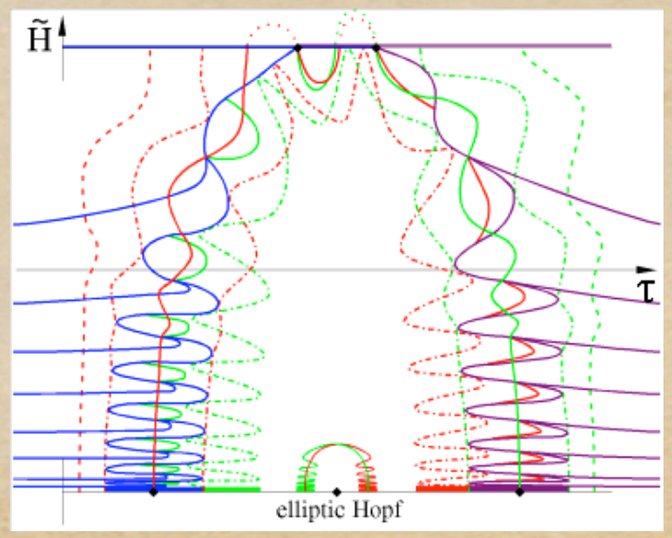
in Connectivity: Random Graphs



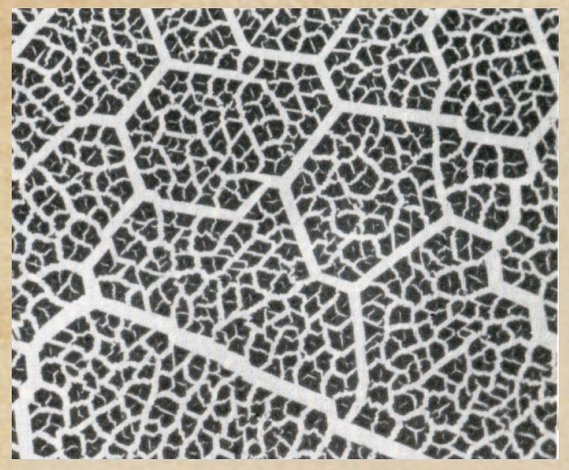
in Time: Intrinsic unpredictability (chaos)

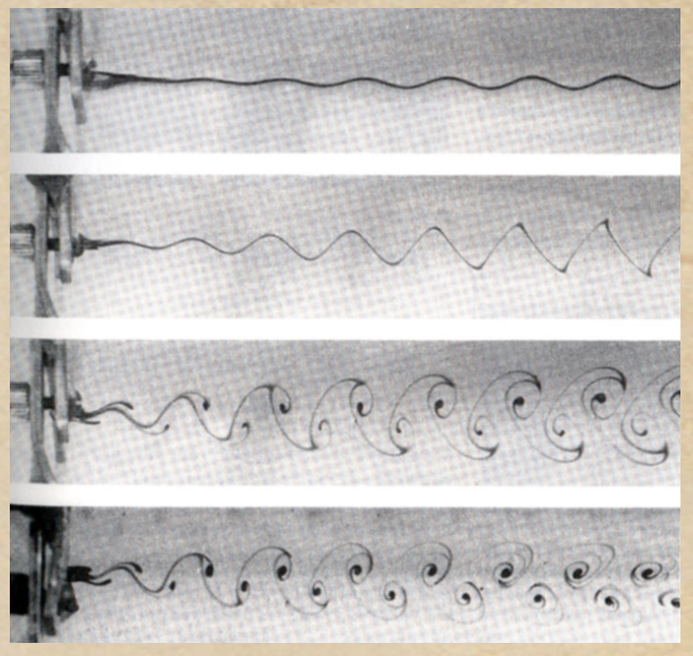


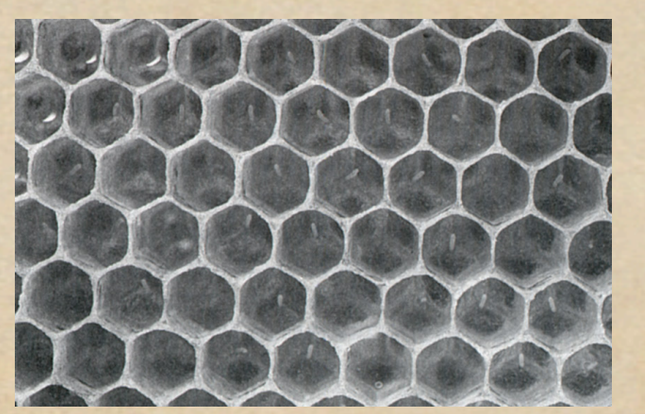




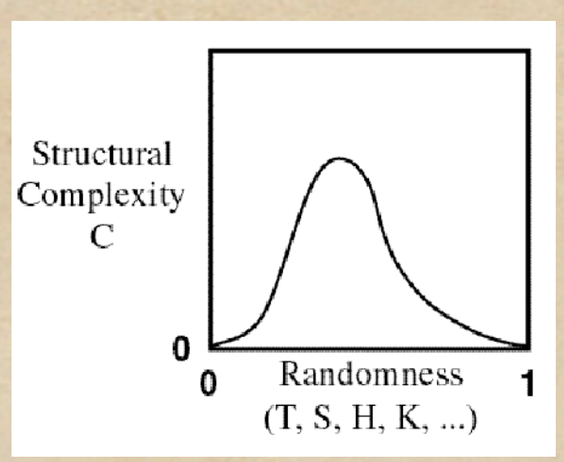
Structure





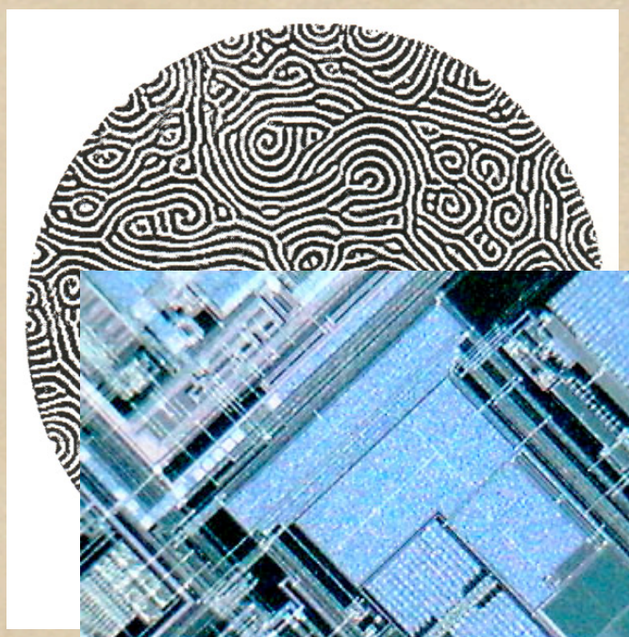


Complication versus Structure



Boredom

Delight



Confusion

Variatio Delectat

DARPA Agent-Based Computing (TASK)

- Dynamics of Learning
  - Online Causal Inference Algorithms
  - Tabula Rasa Learning
  - Pattern Discovery
- Emergence of Distributed Adaptation
  - Causal Synchrony
  - Measures of Coordination
  - Individual versus Collective Adaptation
  - Large-Scale MAS Dynamical Sysmtes

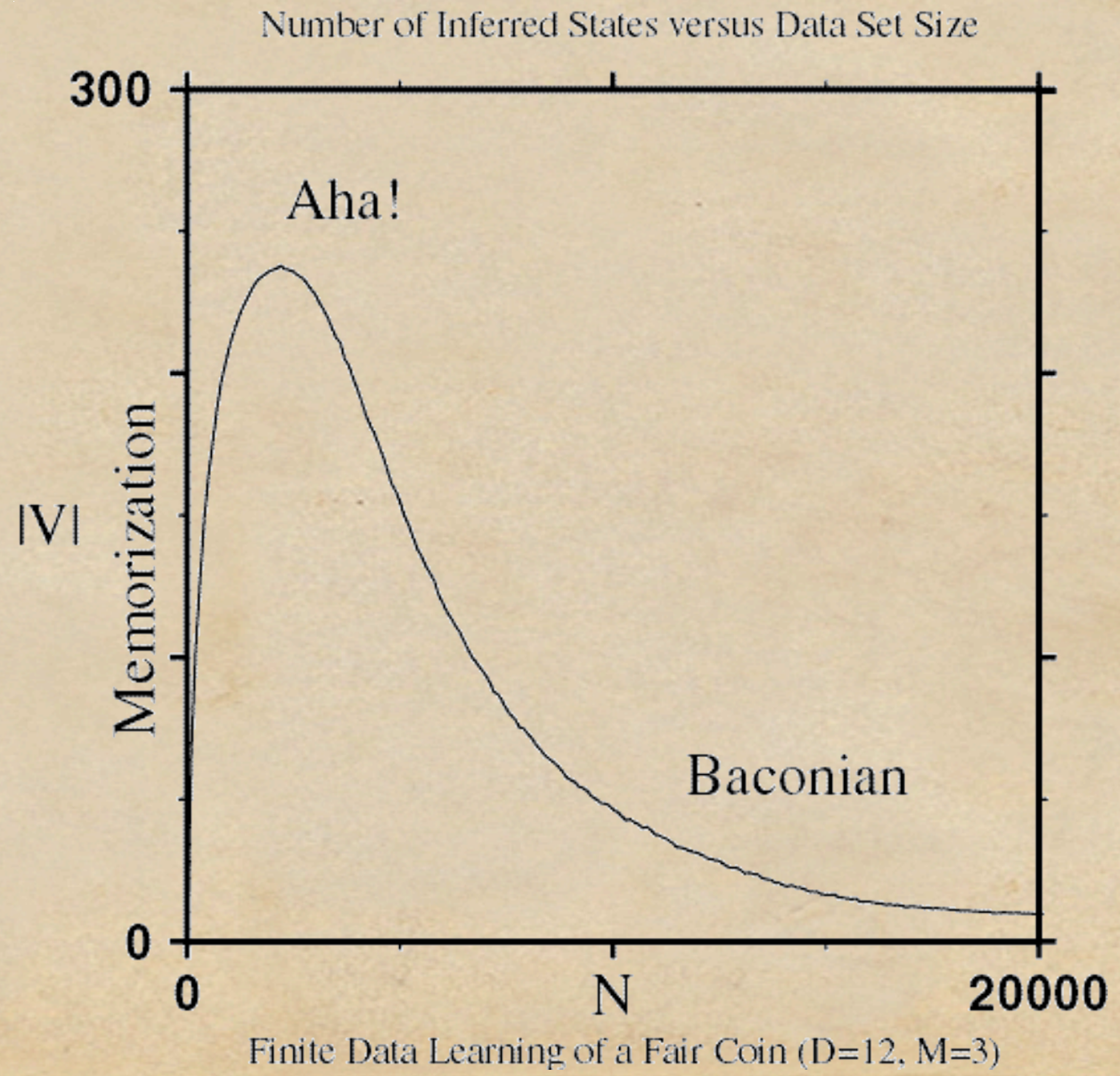
What is an Cognitive Agent?
Some Open Questions

Cognitive Information Processing

- Dynamical systems view of learning as a process whose behavior is predictive model building
- Define and measure agent "cognitive" abilities
- Development math'ly analyzable and simulatable models
- What state-space structures are responsible for cognition? E.g., Basins = robust memories; bifurcations = adaptation; models = attractor-basin portrait in subspace; …

Dynamics of Learning:
Learning Curves—The Aha! Effect

- Adapting to complex environments
- Learning paradigm
- Three phases
  - Rote memorization
  - Aha!
  - Refinement



What are Networks?

To say a system is a network calls attention to its architecture

Study of networks is a study of structure & organization

What's old:

Time-worn problem of "pattern"

What's new:

Mathematics: dynamics, complexity, ...

Tools: simulation, visualization, automated experiment

Openness to re-think current approaches

SFI Network Dynamics Program

(discuss.santafe.edu/dynamics)

Funded by Intel, an SFI Business Network Member

Theory Agenda:

- Network structure: mean path, clustering, degree distribution, betweenness
- Dynamics **on** networks: synchronization, emergence of patterns
- Dynamics **of** networks: perferential attachment, scale-free networks
- Self-adapting networks

Applications:

Ecology: food webs, allometric scaling

Internet and web: structure, dynamics, and growth

Social systems: scientific collaboration networks

Neural networks: intrinsic computation versus architecture

Epidemiology: spread of disease

...

Understandability of Large-Scale Cognitive Systems

- Stability & robustness
- Control
- Pattern discovery
- Right-sized?
- Right architected?
- Right dynamics?

What's needed?

- Modeling and Phenomenology
- Design Methods
- Failure Diagnosis (Robustness)
- Theory of Cognitive Information Processing --- Intrinsic Computation:
  - How much historical information is stored?
  - In which archicture is it stored?
  - How is it used to produce future behavior?

Action Item:

Workshops (e.g. JPCs at SFI)

- Evolutionary Dynamics (October 1998)
- Network Dynamics (August 2000)
- Collective Cognition (January 2002)
- TASK PI Meetings (4/2001, 10/2002)
- Pattern Discovery (2004)
- Dynamics of Learning (2004)
- ...

Action Items: Novel Cognition at SFI

- Dynamical Embodiments of Computation in Cognitive Processes (JPC proposal)
  - Collective Cognition
  - Theory Group in Learning
- Novel Computation (SFI group proposal)
  - Biological Computation
  - Quantum Computation
  - Network Computation