Complex Systems Theory?

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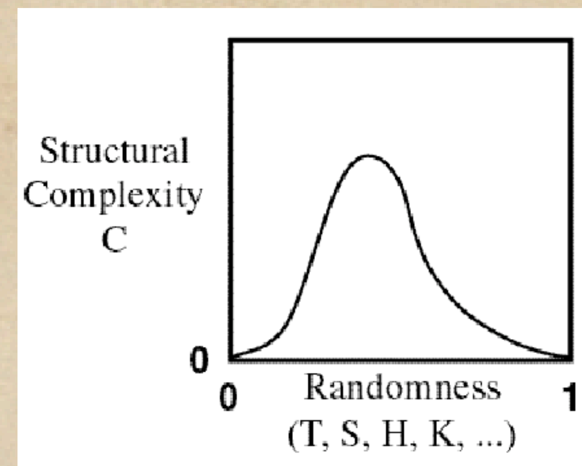
Agenda

- History
- Complex Systems?
- Theory?
- Frontiers

Some History, but not too much

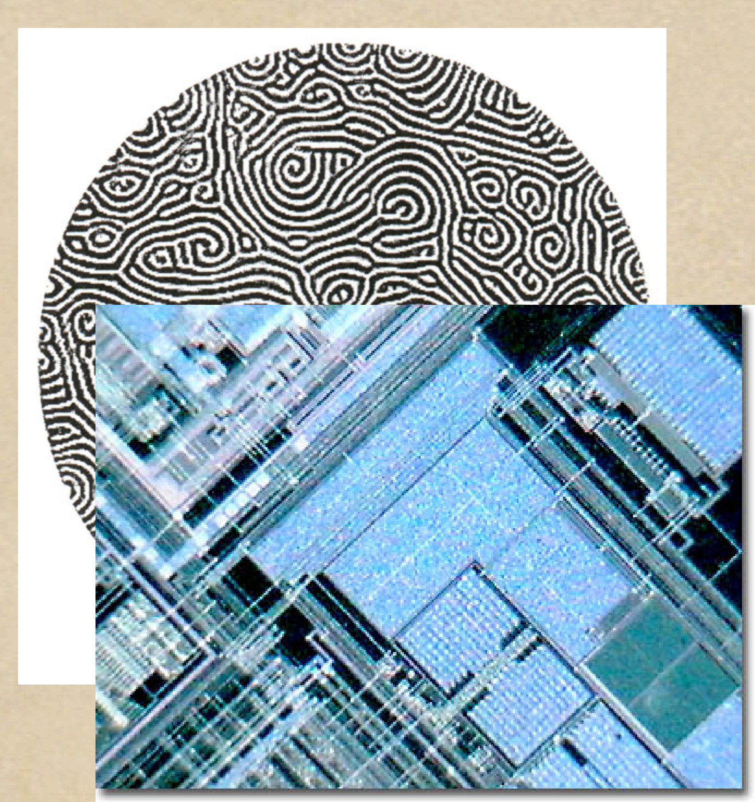
- Humpology
- Complexity Measures
- Synopsis

Humpology: Complication versus Structure



Boredom

Delight



Confusion

Variatio Delectat

Complexity Measures

- Deterministic Complexities:
  - Algorithmic Complexity: Kolmogorov, Chaitin, Solomonoff, Martin-Lof, Levin, ...
  - Computational Complexity: Blum, Cook, Hartmanis, Karp, Cook, ...
  - Measures of Randomness: Thermodynamic entropy density, source entropy rate, metric entropy: Boltzmann, Shannon, Kolmorogov, Sinai, ...
  - Thermodynamic depth: Pagels, Lloyd
- Statistical Complexities:
  - Randomized (Computational) Complexity: Cook, Karp, ...
  - Information-Theoretic: Entropy convergence & mutual information
    - Excess Entropy: del Junco, Rahe, Crutchfield, Packard, Feldman, Debowski
    - Stored Information: Rothstein, Shaw
    - Effective Measure Complexity: Grassberger, Lindgren, Nordahl
    - Reduced Renyi Information: Szepfalusy, Gyorgyi, Csordas
    - Complexity: Bennett, Li, Arnold, ...
  - Regular-Language Complexity: Wolfram
  - Structural Complexity: Crutchfield, Feldman, Shalizi, Young, Upper
  - Logical Depth: Bennett
  - Sophistication: Atlan, Koppel, ...
  - Effective Complexity: Gell-mann, Lloyd, ...
  - Grammatical Complexity: Auerback, Procaccia, ...
  - Coarse-Grained Complexity: Zhang

Complexity Measures ...

- Inference Complexities:
    - Minimum Message Length: Boulton, Wallace, ...
    - Stochastic/Predictive Complexity, Minimum Description Length: Rissanen, Dawid
    - Akaike/Boltzmann Information Criterion: Akaike, ...
    - □-Machine Reconstruction: Crutchfield, Young
    - Bottleneck Complexity: Bialek, Tishby, Neumenen
- Nonconstructive complexities:
    - Kolmogorov-Chaitin
    - Logical Depth
    - Sophistication
    - Thermodynamic Depth
    -

Synopsis

- Homework:

  Complexity Measures---A bibliography

  www.santafe.edu/projects/CompMech/tutorials/ComplexityMeasures.pdf

Complex Systems ≈ Non*

- Nonlinear
- Nonstationary
- Nonreductionist
- Nonequilibrium
- Nonperturbative
- ...

What is interesting, motivating, unique, difficult about complex systems?

- For a very broad class, one cannot develop predictive theories: $h_\mu > 0$
- Over time the systems generate patterns than are not specified in the equations of motion
- Must infer from the system itself how it should be described & represented
- Discipline-conventional representations often lead to systems appearing more random and more structurally complex than they are
- ...

What is Complex Systems Theory?

Borrows heavily from

- Statistical Physics
- Dynamical Systems Theory
- Theory of Computation
- Machine Learning
- Modern Statistics (MaxEnt, Bayes, MDL, Graphical Models, ...)

Does a Theory of Complex Systems Exist?

Is Theory Even Important?

Ascientific Views

- Wolfram: No, it's all a special case that needs subjectivity at every stage
- Gould historicism: No, it's largely frozen accidents
- Deconstructionists

Avoidances

- Already have what we need, we simply need to apply it!
- Math anxiety
- Butterfly collecting
- What has theory done for me lately? Nothing! ... bias toward experiment

What Kind of Theory for Complex Systems?

- Complex Systems (truly novel) require new scientific methodologies
- Experimental epistemology
- Task philosophy to help (can philosophers?)

Kinds of Theory

- Phenomenological Theory
  - Descriptive: power laws, scaling laws, ...
  - Impose observables: modifier genes, morphogenetic fields, ...
  - Power laws,
- Predictive Theory
  - First principles
  - Provide counterfactuals
- Qualitative Theory: symmetries, algebraic & number-theoretic properties, ...
- Formal Theory
  - Conceptual hygiene
  - Check logical consistency
  - Identify tractable problems
- Exploratory Theory
  - Inventive: Self-Organized Criticality, AlChemy
- Narrative Theory
  - Just-So Story
  - It could happen this way (though it needn't)
- Metaphorical Theory: X is Y
  - X = culture & Y = biological evolution
  - X = economy & Y = ecology
- Simulation?
  - Is simulation theory? No, methodologically & practically akin to experiment.

What Kinds of Experiment for Complex Systems?

- Contrast with conventional:
    - Huge amounts of data to do qualitative work
- Examples:
    - Brain Imaging (e.g. MEG)
    - "System"-level Neurophysiology
    - In vivo Evolutionary Population Dynamics
- Gray area between:
    - Simulation and exploratory theory building

Theory's Role at SFI

- What kind of theory is SFI engaged in and should SFI do theory at all?
-
- Focus on mathematical foundations and new theoretical frameworks
- Mathematical invention must be a primary activity
- Aid in articulating mathematical work and problems that need attention by the larger nonSFI mathematical community
- Must engage the mathematical community more actively
- Provide results that the applied disciplines use and that are adapted to their particular (complicated) systems.
- Goal: Making the world safe for theory

Theoretical Frontiers

- What is information? ... in good shape.
- What is structure? ... in okay shape.
- What is meaning?
- What is function?
- What is adaptation?
- What is coordination?
- What are trust and reputation?
- And how do these arise when they are not originally present?

Topical Areas

- Dynamics
- Networks
- Statistical Inference
- Theoretical Tools
- Software Engineering Tools

Dynamics

Dynamical systems & statistical mechanics analyses of:

- Learning
- Adaptation
- Evolution
- Collectives: Multiagent systems, ...
- Coordination & Cooperation
- ... your favorite here ...

Networks

- Structure: Architecture, in good shape
- Dynamics: Architecture's interaction with behavior, the frontier

See Complexity Magazine Special Issue on Networks

Fall 2002

Statistical Inference

How to connect complex systems theory to experiment?

- Measurement Theory
- Nonlinear Modeling
- Quantifying complexity (estimation of measures)
- Randomness versus structure; stochasticity versus causality
- Information processing and computation
- ...

Theoretical Tools

Well established, but required for work in complex systems theory

- Statistical mechanics
  - Phase transitions and critical phenomena, Ergodic theory, Canonical models & phenomena, ...
- Nonlinear dynamics
  - Deterministic chaos, Bifurcation/singularity theory, Stability/instability measures, Symbolic dynamics, ...
  - Pattern formation theory (center manifold theory)
- Stochastic processes
- Information and coding theories
- Computation theory
- ...

Software Engineering Tools

- Simulation platforms
  - SWARM
  - Tierra
- Analysis tools
- Visualization
- Database
- Language development
- ...

Recent nonUS Complex Systems Initiatives

- Novel Computation:
  - EPSRC: www.epsrc.ac.uk/website/gow/ViewPanel.aspx?PAnelID=3790&bannerlink%5C=Panel%20Details
- Complex Networks:
  - EPSRC: www.comp.leeds.ac.uk/seth/cluster/
- Biologically Inspired Self-Organization in Dynamical Networks (BISON)
  - EU (Exystence: FP-5)
- Scaling in Social Networks
  - EU (Exystence: FP-5)
- ...

Discussion please ...

This talk at

www.santafe.edu/~chaos/Talks/CSTheoryRetreat.pdf