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, Kolmogorov, 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, ...
  - \( \square \)-Machine Reconstruction: Crutchfield, Young
  - Bottleneck Complexity: Bialek, Tishby, Neumenen

- **Nonconstructive complexities:**
  - Kolmogorov-Chaitin
  - Logical Depth
  - Sophistication
  - Thermodynamic Depth
Synopsis

Homework:
Complexity Measures---A bibliography

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, AlChemistry
- 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
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
- ...

Sofware Engineering Tools
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 (Existence: FP-5)

- Scaling in Social Networks
  - EU (Existence: FP-5)

- ...
Discussion please ...

This talk at

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