Computational modeling of complex systems

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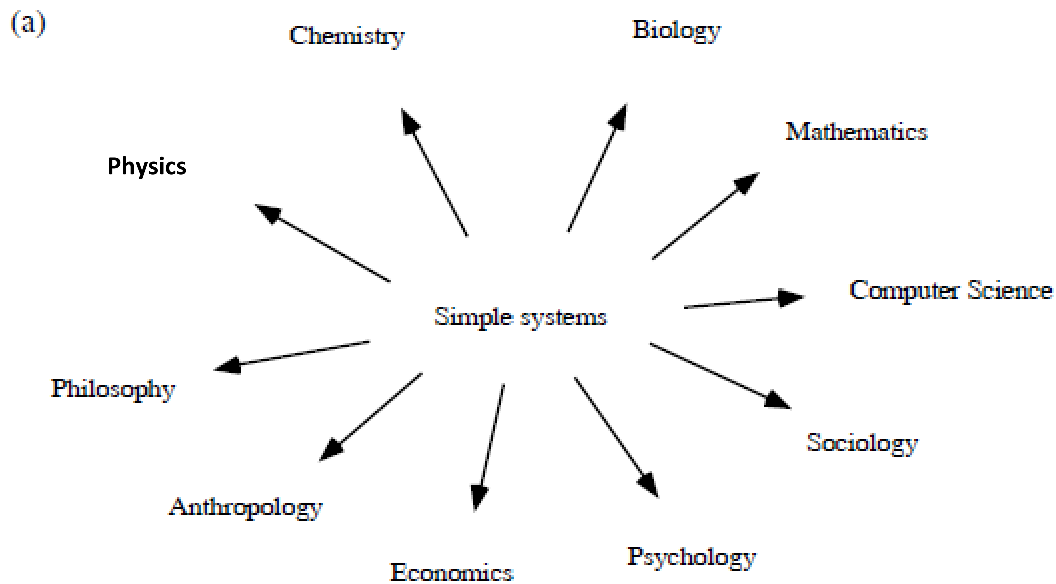
Content

- Introduction
- Nonlinear dynamics and chaotic systems, logistic equation
- Self-organized criticality: sandpiles, punctuated equilibrium and forest fires
- Population dynamics: prey-predator systems, Lotky-Volterra, cellular automata
- Social dilemma and game theory: prisoner’s dilemma
- Genetic algorithms, computational complexity
- Growth models, fractals, self-similarity
- Complex networks
- Econophysics and Sociophysics
- Modeling of language emergence and evolution: language games

Simple systems



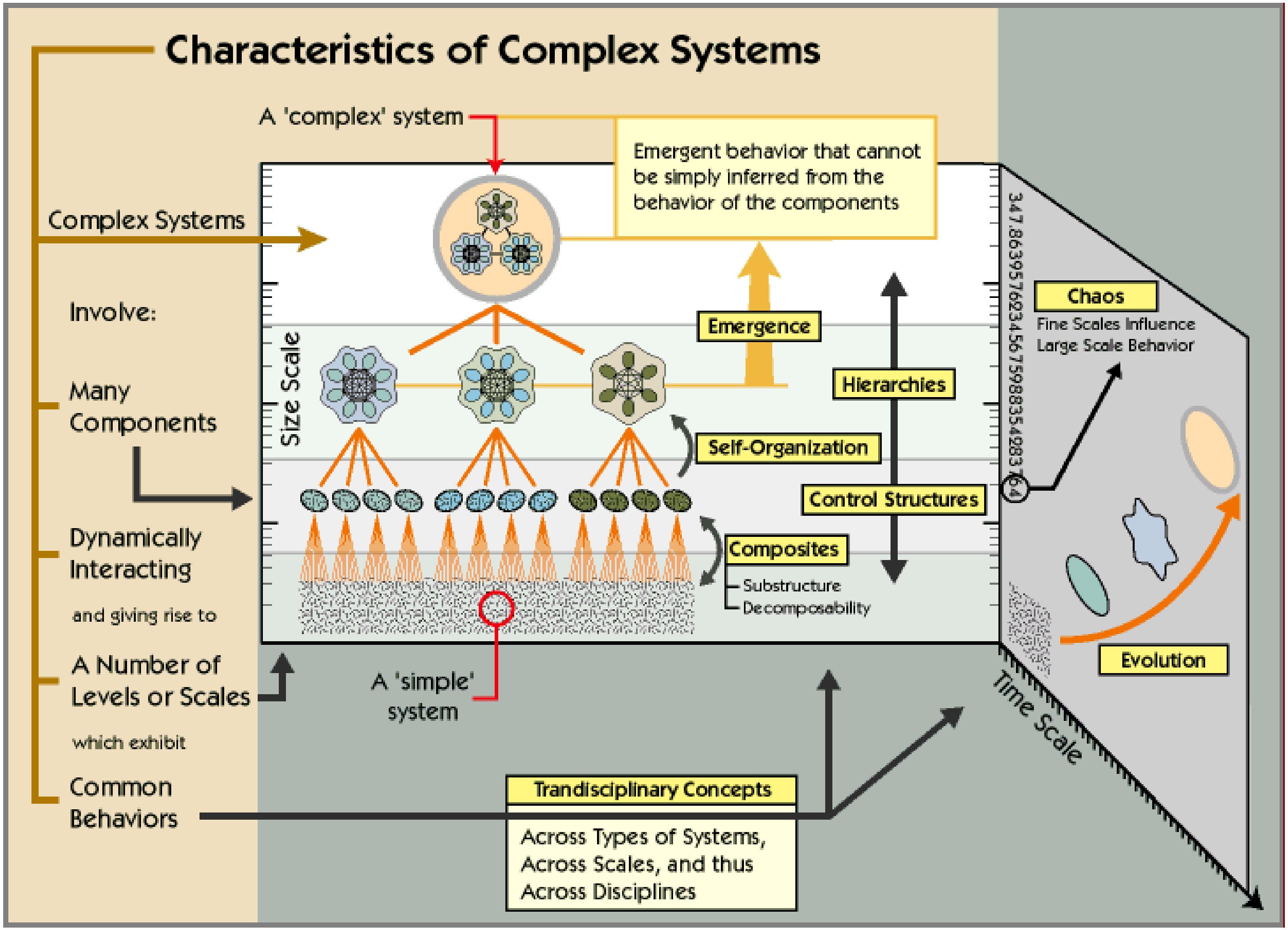
Examples of Simple Systems

An oscillator

A pendulum

A spinning wheel

An orbiting planet


Characteristics of Complex Systems
A 'complex' system
Emergent behavior that cannot be simply inferred from the behavior of the components
Complex Systems
Involve:
Many Components
Dynamically Interacting
and giving rise to
A Number of Levels or Scales
which exhibit
Common Behaviors
Size Scale
Emergence
Hierarchies
Self-Organization
Control Structures
Composites
Substructure
Decomposability
Chaos
Fine Scales Influence Large Scale Behavior
Evolution
Time Scale
A 'simple' system
Trandisciplinary Concepts
Across Types of Systems, Across Scales, and thus Across Disciplines

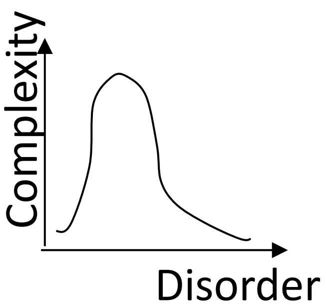
(Some) Ideas related to Complexity

- The Newtonian Paradigm is built on Cartesian Reductionism:
  - **Machine Metaphor** and Cartesian Dualism (Descartes): Body is a biological machine; mind as something apart from the body; Intuitive concept of machine: built up from distinct parts and can be reduced to those parts without losing its machine-like character: **Cartesian Reductionism**
  - The **Newtonian Paradigm** and the three laws of motion: General Laws of motion, used as the foundation of the modern scientific method. **Dynamics** is the center of the framework, which leads to trajectory

- Complexity results from failure of the Newtonian Paradigm to be generic:
  - Complex and simple systems are disjoint categories that **encompass all of nature**
  - But the real world is made up of complex things and the world of simple mechanisms is fictitious and created by science. Experiments involve **reducing the system to its parts** and then studying those parts in a context formulated according to dynamics

- Minimum Description Length: Kolmogorov Complexity is the minimum possible length of a description in some language (usually that of a Turing machine)

- (Dis)Order: Complexity is mid-point between order and disorder (edge of chaos)



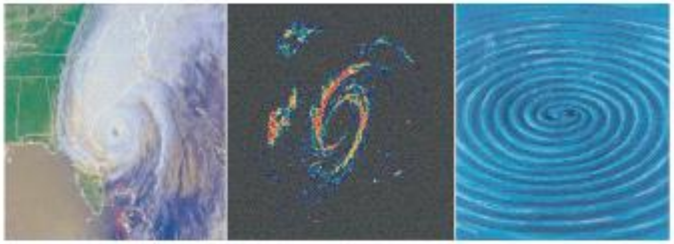
(Some more) Ideas related to Complexity

- Complex systems are often hierarchic (Pattee 1973, Allen and Star 1982).

- Simple laws or simple rules of behavior may generate complex behavior (Gleick 1987; Wolfram 1984a,b). Thus, a complex system does not necessarily require a complex, long description (it does not have to be ‘complex’ in the algorithmic sense). A complex pattern may be generated by simple mechanisms, hiding an order that can be expressed in a compressed form.

- In physics such phenomena are exemplified by phase-transitions, broken symmetries, dynamical instabilities and self-organization (Anderson 1972, 1991). Time-asymmetric self-organization -- from small and meso-scale phenomena to the cosmic scale, from the time of the big bang (with its simplicity and featurelessness) to the present -- is a real phenomenon of the physical universe.

- Complexity may need explanations of another type than simple reductionist ones; complex multi-level systems with biologic functions or with consciousness may need both effective, functional, form-like and intentional explanatory modes (Kant 1790; Rosen 1985; Popper 1982; Emmeche *et al*. 1997).



Examples of Complex Systems

Governments

Families

The human body—physiological perspective

A person—psychosocial perspective

The brain

The ecosystem of the world

Subworld ecosystems: desert, rain forest, ocean

Weather

A corporation

A computer

Family

- It is a set of individuals.
- Each individual has a relationship with the other individuals.
- There is an interplay between the relationship and the qualities of the individual.
- The family has to interact with the outside world.
- There are different kinds of families: nuclear family, extended family, etc.

General properties of complex systems

- Elements (and their number)
- Interactions (and their strength)
- Formation/Operation (and their time scales)
- Diversity/Variability
- Environment (and its demands)
- Activity(ies) (and its[their] objective[s])

System	Element	Interaction	Formation	Activity
Proteins	Amino Acids	Bonds	Protein folding	Enzymatic activity
Nervous system Neural networks	Neurons	Synapses	Learning	Behavior Thought
Physiology	Cells	Chemical messengers Physical support	Developmental biology	Movement Physiological functions
Life	Organisms	Reproduction Competition Predation Communication	Evolution	Survival Reproduction Consumption Excretion
Human economies and societies	Human Beings Technology	Communication Confrontation Cooperation	Social evolution	Same as Life? Exploration?

Emergence: From elements and parts to complex systems

e.g., local spin-spin interactions might induce long range magnetic ordering of the entire system

Why complex systems ?

The twenty-first century will be the "century of complexity”. We have already discovered the basic laws that govern matter and understand all the normal situations. We don’t know how the laws fit together, and what happens under extreme conditions

Steven Hawking

The whole is greater than the sum of its parts.

(Aristotle)

Why computer simulations ?

"Science is what we understand well enough to explain to the computer"

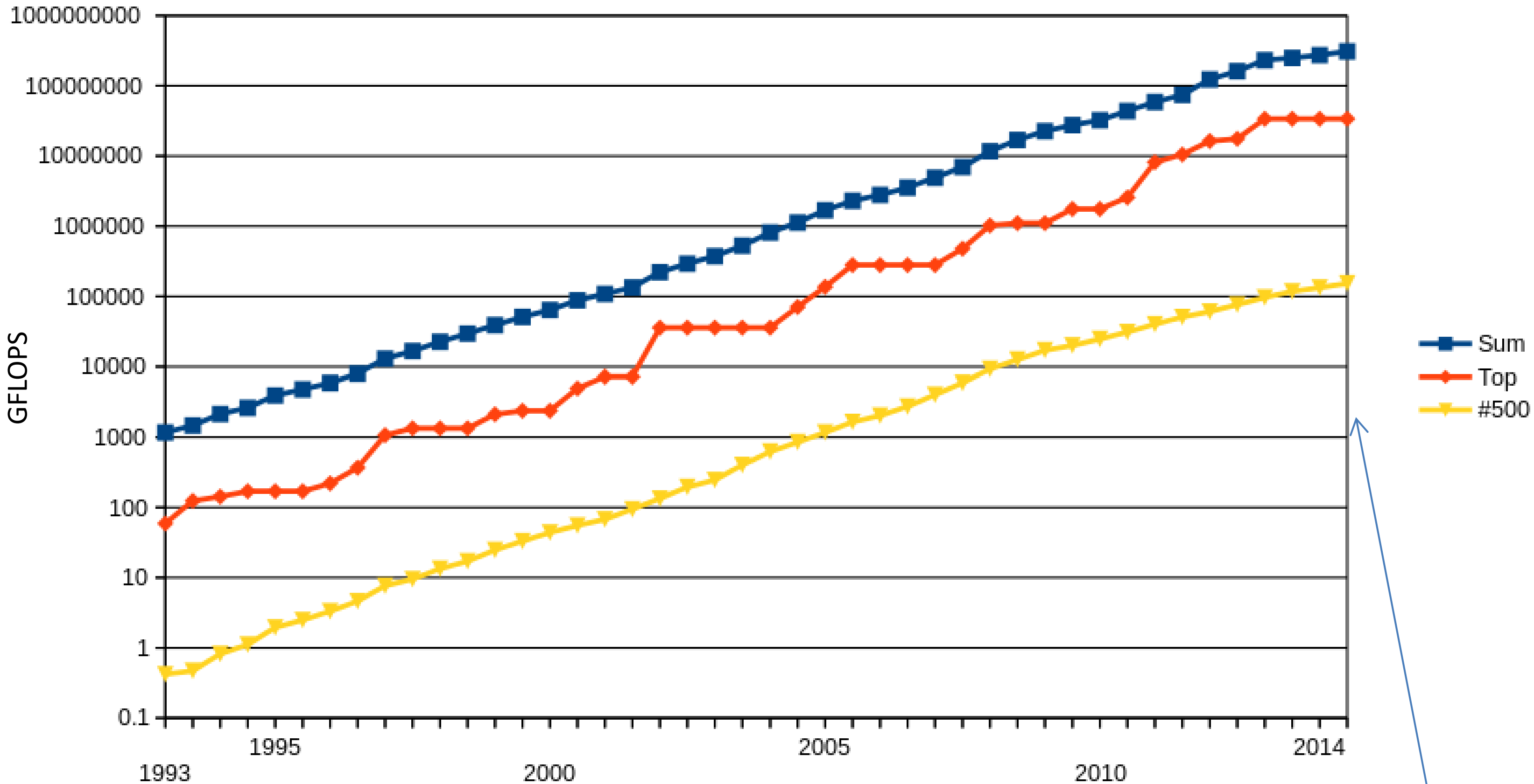
Donald Knuth

<u>THE ART OF WAR AND THE ART OF SCIENCE</u>

The best military historians in fact do recognize the difficulty in stating rules of generalship. They do not speak of a science of war, but rather of a pattern of military behavior that cannot be taught or stated precisely but that somehow or other sometimes helps in winning battles. This is called the art of war. In the same spirit I think that one should not hope for a science of science, the formulation of any definite rules about how scientists do or ought to behave, but only aim at a description of the sort of behavior that historically has led to scientific progress—an art of science.

Steven Weinberg, Dreams of a Final Theory ~Pantheon Books, New York, 1992!, p. 131.

Supercomputer on your desk



(1.8 Tflops (2016)

People

- People related to the field come from primarily from **mathematics, physics, computer science and biology**

- Among the most prominent people we find:

  – **Stuart Kauffman** - Pioneer in complexity theory; MD from University of California (1968), Professor in **Biophysics, Theoretical Biology and Biochemistry** (1969-1995), University of Chicago and University of Pennsylvania; Currently, consultant for Los Alamos National Laboratory and External Professor, **Santa Fe Institute**; Publication: “At Home In The Universe”, Oxford University Press, 1995

  – **Murray Gell-Mann** – Theoretical physicist; PhD (**Physics**) 01/51, MIT; Professor Emeritus of Theoretical Physics,California Institute of Technology; Professor and Co-Chairman of the Science Board of the **Santa Fe Institute**; Nobel Prize in 1969, work on the theory of elementary particles (co-discoverer of Quarks); Currently in the President's Committee of Advisors on Science and Technology; Author of the book: “The Quark and the Jaguar”, W. H. Freeman and Company, New York, 1994

People

- **Philip Anderson** – Condensed matter theorist; PhD Harvard (49); Professor of **Physics** at **Oxford University** and **Princeton University** (75-present); Nobel Prize in 1975 for investigations on the electronic structure of magnetic and disordered systems; Also at the **Bell Labs** (49-84) and **Santa Fe Institute** (70-present)

- **John Holland** – "first" PhD in **Computer Science** (University of Michigan); pioneer of evolutionary computation, particularly genetic algorithms; Professor of Cognition and Perception at the **University of Michigan** and **Santa Fe Institute**

- Others: Seth Llyod („Quantum Mechanic"), Joseph Sussman (Civil), Christopher Langton (Computer Science), Brian Arthur (economics), Jack Cowan (maths), Herbert Simon (economics), John Smith (biology), Per Bak (physics), K.Goedel, Kolgomorov, Wolfram (Mathematica), L.Barabasi (Complex Networks)

Institutions

- **Santa Fe Institute**
  - Private, non-profit, multidisciplinary research and education center, founded in 1984
  - Largely Supported by the NSF and MacArthur Foundation
  - Operates as a small visiting institution
  - Catalyzes new collaborative, multidisciplinary projects
  - Primarily devoted to Basic Research
  - Gathers about 100 members, 35 in residence at one time

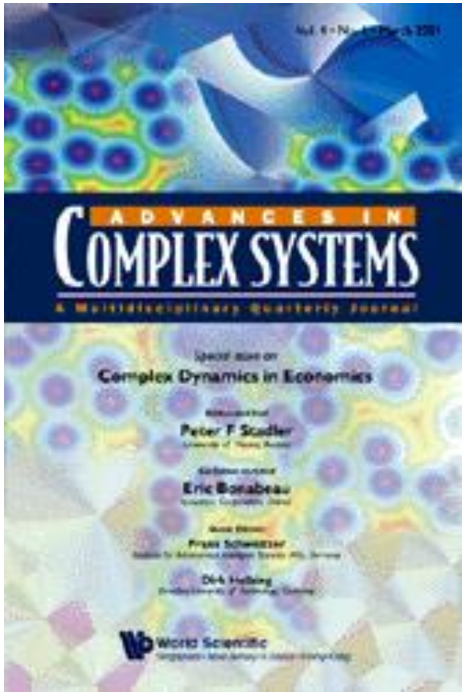
Research

- **Areas of research** (at SFI) include:
  - Computation in Physical and Biological Systems
  - Economic and Social Interactions
  - Evolutionary Dynamics
  - Network Dynamics;

- Can science achieve a **unified theory** of complex systems?
  - "**From Complexity to Perplexity**", by J. Horgan, Scientific American:
  - Some (at SFI) argue that it might be possible to have *"a new, unified way of thinking about nature, human social behavior, life and the universe itself"*
  - Some (also at SFI!) argue *"we don't even know what that means"*
  - Some researchers believe that one day computer power will be enough to predict, control and understand nature
  - R. Shepard (Stanford University): *"even if we can capture nature's intricacies on computers, those models might themselves be so intricate that they elude human understanding"*

Journals

- **Complex Systems**:
  - Founded by Stephen Wolfram in 1987
  - Contributors from academia, industry, government
  - General public in 40 countries around the world
  - Topics: mathematics, physics, computer science, biology



- **Advances in Complex Systems**:
  - Founded in 1998
  - Editor-in-Chief: Peter F. Stadler, Dept. of Theoretical Chemistry and Molecular Structural Biology, U. Vienna
  - Co-Editor-in-Chief: Eric Bonabeau, Santa Fe Institute
  - Fields: biology, physics, engineering, economics, cognitive science and social sciences