COMPLEX SYSTEMS:
CONCEPTUAL
INTRODUCTION
THE CENTURY OF COMPLEXITY?

I think the next century will be the century of complexity."
Stephen Hawking (Complexity Digest 2001.10 March-05-2001)

The differences between 20th century sciences and Complexity are significant. The former, including biology, was dominated by mechanistic reductionism. In that view, the universe and all of its contents, including life forms, were viewed as machines ("mechanisms"), and thus, understanding any system required study of the whole system by reduction to its parts. Knowledge of the parts was thought to yield full understanding of the whole.
In contrast, Complexity acknowledges that in addition to reductionism, a more complete understanding of complex dynamical (always-changing) systems requires holism, a (w)holistic approach that focuses on the properties and behavior of *intact* systems.

Holistic studies yield unique insights into systems that are not available via reductionism. This is because, as explained by a fundamental principle of Complexity, a system’s properties emerge from the interaction of its parts. Thus, knowledge of the independent parts does not yield an understanding of the whole, because the whole is GREATER than the sum of its parts.
The architecture of complexity

Herbert Simon
(1916-2001)

Nobel prize in Economics 1978
bounded rationality
artificial intelligence: "complex information processing"
Models of My Life [Autobiography]
Decision Making and Problem Solving
Hierarchical Organization

Two watchmakers in Herbert Simon’s classic essay "The Architecture of Complexity"

"Suppose each watch consists of 1000 pieces. The first watchmaker constructs the watch as one operation assembling a thousand parts in a thousand steps. The second watchmaker builds intermediate parts, first 100 modules of 10 parts each, then 10 subassemblies of 10 modules each, then a finished watch out of the subassemblies, a somewhat longer process, 110 steps longer.

It would seem that constructing a watch in a single sequential process would progress faster and produce more watches. Alas, life being what it is, we can expect some interruptions. Stopping to deal with some environmental disturbance, like a customer, the
watchmaker puts down the pieces of an un-finished assembly.

Each time the first watchmaker puts down the single assembly of 1000, it falls apart and must be started anew, losing up to 999 steps. Interrupting the second watchmaker working on a module of 10 using hierarchical (in the first sense) construction means a loss of at most 9 steps."

For organizing complexity, the moral is this: taking a few extra steps in the short run, saves many steps in the long run.

In anything less than an environment of no change, the second watchmaker will be much more successful in finishing the complex whole. Using an elegant mathematical demonstration, Simon shows how dramatically more successful the modular-levels principle is in producing stable and flexible complexity. Nature, he says, must use this principle. And,
indeed, systems scientists have extensively documented this level pattern of organization, whether physical (such as particle, atom, and molecule), biological (like the example of cell, organ, and body), social (for example, local, regional, and national government), or technological (one example is phones, local exchanges, and long-distance networks"

Complexity takes the form of hierarchy and that hierarchical systems evolve faster than nonhierarchical ones. Very generally, a hierarchy is a recursive partition of a system into subsystems. Examples of hierarchies are common in social, biological, physical and symbolic (e.g. books) systems. In biological systems, it is argued that hierarchical systems evolve faster because the many subsystems form as many intermediate stable stages in the process. Similarly in the problem solving activity, mainly a selective trial-and-error process, intermediate results constitute stable subassemblies that indicate progress.
Characteristics of simple and complex systems

+ System and its environment

A system is a delineated part of the universe which is distinguished from the rest by an imaginary boundary.
One of the basic concepts in the systems approach is that all systems interact with their environment. How can we then identify what a system is? Aren’t we always making an artificial boundary? In order to perceive or know anything, one must make a distinction. The key idea of "SYSTEM" is that once a system is identified (the boundary described) then one describes:

- the properties of the system, (how to characterize the state of the system);
- the properties of the universe excluding the system which affect the system, and
- the interactions / relationships between them.

Thus, it is not necessary to assume that a system is isolated from or independent of the environment, it is simply a task of the describer to identify the way in which the system is interdependent with the environment.
+ Simple systems

cause $\rightarrow$ effect
(linear relationship)
predictability

DYNAMICS !!

Kepler and Newton:

from **INTEGRAL LAWS** to
**DIFFERENTIAL LAWS**

integral laws: global description of the whole motion
differential laws: local mechanism of the motion
Kepler’s laws

http://www.cvc.org/science/kepler.htm

LAW 1: The orbit of a planet/comet about the Sun is an ellipse with the Sun’s center of mass at one focus.

Law 1

LAW 2: A line joining a planet/comet and the Sun sweeps out equal areas in equal intervals of time.

Law 2
The third law creates a relationship between two arbitrary orbits:

LAW 3: The squares of the periods of the planets are proportional to the cubes of their semimajor axes:

\[ \frac{T_a^2}{T_b^2} = \frac{R_a^3}{R_b^3} \]
Newton's laws

1) A body will continue in a uniform motion in a straight line or remain at rest unless acted upon by an external force.

2) When an external force acts on a body of constant mass then the acceleration produced is directly proportional to the force: \( F = ma \)

3) Every action has an equal and opposite reaction.

Repetition from high school:
http://www.glenbrook.k12.il.us/gbsscience/phys/Class/newtlaws/newtltoc.html
+ Complex systems

* circural causality

Circular causality in essence is a sequence of cause and effect whereby the explanation for a pattern leads back to the first cause and either confirms or changes that first cause; Example: A causes B causes C that causes or modifies A.

* logical paradox

A person from the island of Crete asserts, "All Cretans are liars." We can conclude that if he is telling the truth, then he is lying. But if he is lying, then he is telling the truth.
* emergence of complexity

Emergence is: 1. What parts of a system do together that they would not do by themselves: collective behavior.

HOW collective properties arise from the properties of parts. More generally, it refers to how behavior at a larger scale of the system arises from the detailed structure, behavior and relationships on a finer scale. In the extreme, it is about how macroscopic behavior arises from microscopic behavior.

2) What a system does by virtue of its relationship to its environment that it would not do by itself: e.g. its function.

* Complex Dynamic Behaviour: CHAOS and related area
Chemical systems: temporal, spatial and spatiotemporal pattern formation

The Belousov-Zhabotinsky (BZ) reaction is named after B. P. Belousov who discovered the reaction and A. M. Zhabotinsky who continued Belousov’s early work. The mechanism of this oscillating reaction was published in 1972 by R. J. Field, Endre Körös, and R. M. Noyes. The work by Field, Körös and Noyes opened an entire new research area:

Nonlinear Chemical Dynamics

Oscillatory Chemical Reaction
Chemical Chaos

Chemical Wave Propagation

Turing structures
Biological complexity: from cellular to ecological levels

Biochemical complexity

Slime mold amoebae of the species Dictyostelium discoideum aggregate as the result of chemotaxis. In these circumstances we observe propagating target and spiral patterns as the amoebae, aggregating into slugs, signal to each other using waves of cyclic AMP that propagate by a diffusion-autocatalysis process analogous to that found in the BZ-waves, and with the same dynamical properties. The slugs are able to exploit the chemical dynamics for aggregation and differentiation, leading to dispersal, and subsequent replication. BZ-type dynamics are an integral part of their survival strategy.
Pattern formation in Dictyostelium discoideum

Pigmentation Patterns in Seashells
BIOLOGICAL NETWORKS

A network can be viewed as a set of largely identical subunits that interact, i.e. communicate, with each other. Once the collection of these sub-units has been identified, three important properties that govern the behaviour of a network can be distinguished:

(a) the connectivity of the network that determines which subunits interact with which other subunits

(b) the strength and nature of these interactions

(c) the total size of the network.

Conceptual basis that enables us to discover and examine common rules governing different biological networks.
Metabolic network

A chemical reaction system that generates essential components such as amino acids, sugars and lipids, and the energy required to synthesize them and to use them in creating proteins and cellular structures is a metabolic network.

Valine, leucine and isoleucine biosynthesis
Neural Networks
cells and synapses

Ecological networks
foodweb
Social Networks and Complexity

- **Acquaintanceship Networks**


The experiment was designed to see if randomly selected starter-people from all walks of life would be able to find a target-person using only a network of friends. Two separate studies were done, in both cases the target-people were in Cambridge, MA. The starting cities were Omaha, NB. and Wichita, KA.

About 150 people were selected from each of the cities and given a document folder that contained the following:

1. The name and address and some personal data on the target-person.

2. A set of rules. The most important of which was: "if you do not know the target-person on a firstname basis, then pass the document folder on to one friend that you feel is most likely to know the target. That friend must be someone you know on a first-basis."

3. A roster. Each person who got the folder had to put their name on the list. This served to show who it came from and also kept the folder from making any loops.
4. Tracer cards. Each person who transmitted the folder had to fill out and mail the tracer card.

The results: It took a median of 5 intermediate friends to go from the starter to the target person. The range was from 2 to 10.

What is the probability that any two people, selected arbitrarily from a large population, will know each other?
What is the length of the shortest chain of acquaintances between two people chosen at random?

- **Hollywood Universe**

Find the shortest path from any actor to Kevin Bacon, using the association rule

Unlike society in general, film actor associations are well documented

- **Collaborative graphs**

Paul Erdős

(1913-1996)
Graphs

<nodes or vertices, edges>
Euler and the bridges
Königsberg (Kaliningerad)

STATISTICAL analysis of large graphs
Brian HAYES: Graph Theory in Practice I,II
American Scientist 88(1), 88(2), 2000
REGULAR, RANDOM and REAL WORLD GRAPHS

lattice-like (several neighbors)
regular + random effects
random
Economics and Complexity

Why a New Approach is Needed?

- *Neoclassical economics*
  * Behavioral model for people:
    : Fully-informed
    : Rational
  * People interact only indirectly with one another (through markets)
  * Focus on equilibrium outcomes

- *Complexity approach*
  * People are adaptive
  * They interact directly with one another
  * Focus on dynamics
  * Methodology: equation vs. agent-based modeling?

W. Brian Arthur
http://www.santafe.edu/ wba/Papers/Papers.html
Econophysics

Econophysics tries to apply physics methods to theoretical economics
http://www.unifr.ch/econophysics/

Minority game
A minority game (MG) is a repeated game where N (odd) players have to choose one out of two alternatives (say A and B) at each time step. Those who happen to be in the minority win. Although being rather simple at first glance this game is subtle in the sense that if all players analyze the situation in the same way, they all will choose the same alternative and will lose. Therefore, players have to be heterogeneous. Moreover, there is a frustration since not all the players can win at the same time: this is an essential mechanism for modelling competition.

MG is an abstraction of the famous El-Farol's bar problem (Brian W. Arthur, Am. Econ. Assoc. Papers and Proc 84, 406, (1994)):
100 people would like to go to a bar (El Farol) which is too crowded if there are more than 60 people.
MEASURES of COMPLEXITY

"COMPUTATIONAL COMPLEXITY"

ALGORITHMIC INFORMATION COMPLEXITY

The Algorithmic Information Complexity of a string of symbols is the length of the shortest program to produce it as an output. Solomonoff, Kolmogorov, Chaitin

1. The more ordered the string, the shorter the program, and hence less complex.
2. Incompressible strings (those whose programs are not shorter than themselves) are indistinguishable from random strings.
ARITHMETIC COMPLEXITY

The minimum number of arithmetic operations needed to complete a task.

TIME and SPACE COMPUTATIONAL COMPLEXITY

Computational complexity is now a much studied area with many formal results. It is usually cast as the order of the rate of growth of the resources needed to compute something compared to the size of its input. They are fairly rough measure because they only give the degree of increase to within a constant factor, e.g. the order of the polynomial with which they increase.
"STRUCTURAL COMPLEXITY"

CONNECTIVITY

The greater the extent of inter-connections between components of a system, the more difficult it is to decompose the system without changing its behaviour. Thus the connectance of a system (especially when analysed as a graph) becomes a good indication of the potential for complex behaviour. ——> cyclomatic number.

CYCLOMATIC NUMBER Complexity – Software Metrics

Cyclomatic number \( (CN) = E - N + p \)
where \( E \) = the number of edges of the graph

\( N \) = the number of nodes of the graph

\( p \) = the number of connected components

new edge \( \rightarrow \) \( CN \) \( \rightarrow \) \( CN+1 \)

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examples
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**TREE GRAPHS:** diversity of subtrees
Huberman,BA; Hogg,T; 1986, Complexity and Adaption, Physica D, 22, 376-384
"ORGANIZATIONAL COMPLEXITY"

ENTROPY

In physics, entropy measures the level of disorder in a thermodynamic system. Entropy-based measures are essentially probabilistic.

information and coding theory,
dynamical systems,
logic and the theory of algorithms,
dynamical systems,
statistical inference and prediction,
the physical sciences,
economics,
biology,
the humanities and social sciences.

**INFORMATION**

Information can be measured deterministically using algorithmic information complexity or probabilistically using entropy.

The Shannon measure of information is a statistical measure based on the probability of receiving a message. If $p(m_1), p(m_2),...$ are the probabilities of receiving the messages $m_1,m_2,...$ then the information carried by the message $n_1,n_2,...$ is defined as $-\sum \log(p(n_i))$.

The more improbable the message, the more information it gives the recipient.

**MUTUAL INFORMATION**

The amount of shared information as a measure of complexity $MI(X,Y) = H(Y) - H(Y|X) = H(X) + H(Y) - H(X,Y)$

$H(X,Y)$: joint entropy;

$H(Y|X)$: conditional entropy
"DYNAMICAL and FUNCTIONAL COMPLEXITY"

DIMENSION of ATTRACTOR

It is possible to estimate the processes’ attractor in state space; this is often fractal with chaotic processes. The dimension of the attractor is a measure of how complex the process is.

COGNITIVE COMPLEXITY

in a narrow sense related to personality theory:


It has been used as a basis for discussion on the complexity of personal constructions of
the real world (and particularly of other people) in psychology.

It asks the subjects to rate a number of people known to them on a number of attributes. The dimension of the inferred mental model of these people is then estimated as their cognitive complexity.

So, for example, people who assign to all their friends positive attributes and to their enemies negative attributes would have a one-dimensional mental model of their acquaintances, as everybody is aligned along this good/friend - bad/enemy scale. Such people are said to be cognitively simple. A person who indicated that some of both their friends and enemies were good and bad would have at least a two-dimensional model with people placed across a good-bad, friend-enemy pair of axes. This person would have a higher score and would be called more cognitively complex.