COMPLEX ADAPTIVE SYSTEMS:

Overview

- intro 1-

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Causation, Science and Common sense

We have a somewhat problem free handle on talk about
causes (c), effects (e) and causal explanations.

Example:
The beer got me so drunk that I fell down the stairs causing a fracture in my leg.
That explains why I am moving around using these crutches.

In main stream science, acknowledging causes and effects is central!

The regularity view of causation

c causes *e* iff

(I) *c* is spatiotemporally contiguous to *e*

(II) *e* succeeds *c* in time, and

(III) all events of type *C* (i.e., events that are like *c*) are regularly followed by or constantly conjoined with events of type *E* (i.e. events like *e*)
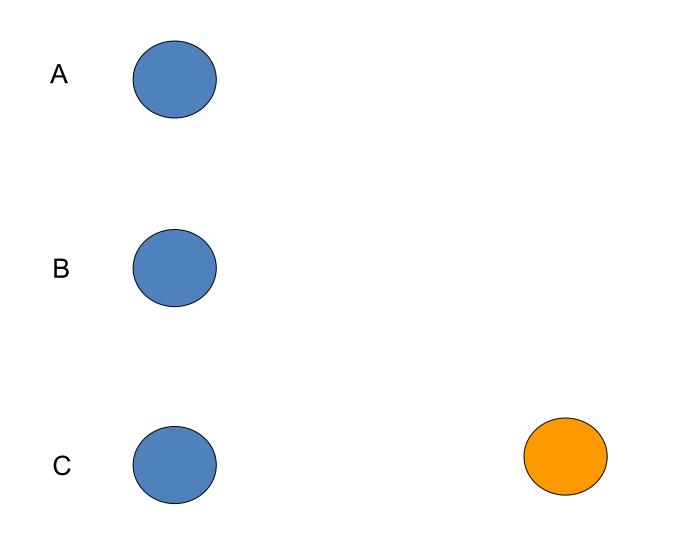
(this formulation can be found in Psillos, 2002, p.19)

Our 'received view' of causation tells us that causation happens in virtue of 'something else'.

If *c* causes *e*, it is because there is some real connection between *c* and *e* (that necessitates *e* happening when *c* happens).

REF: Psillos, S. (2002). *Causation and explanation* (Vol. 8). McGill-Queen's Press.
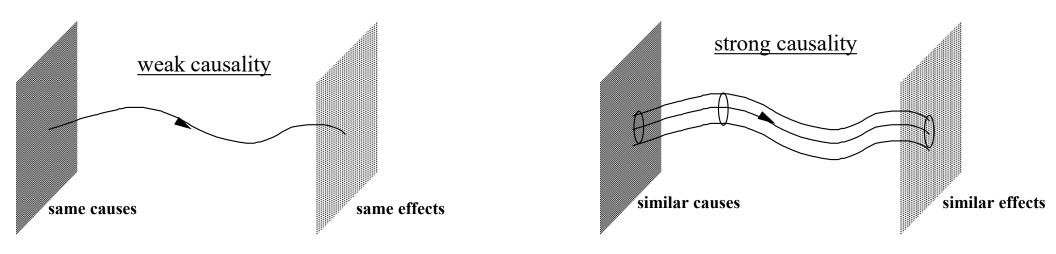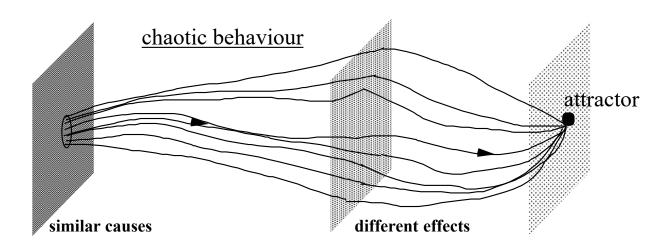
What are causes and effects?

A

B

C

To explain the world, we need to know…

- The cause -- effect relationships

- Factors altering functional relationships

- Systematic context for that information
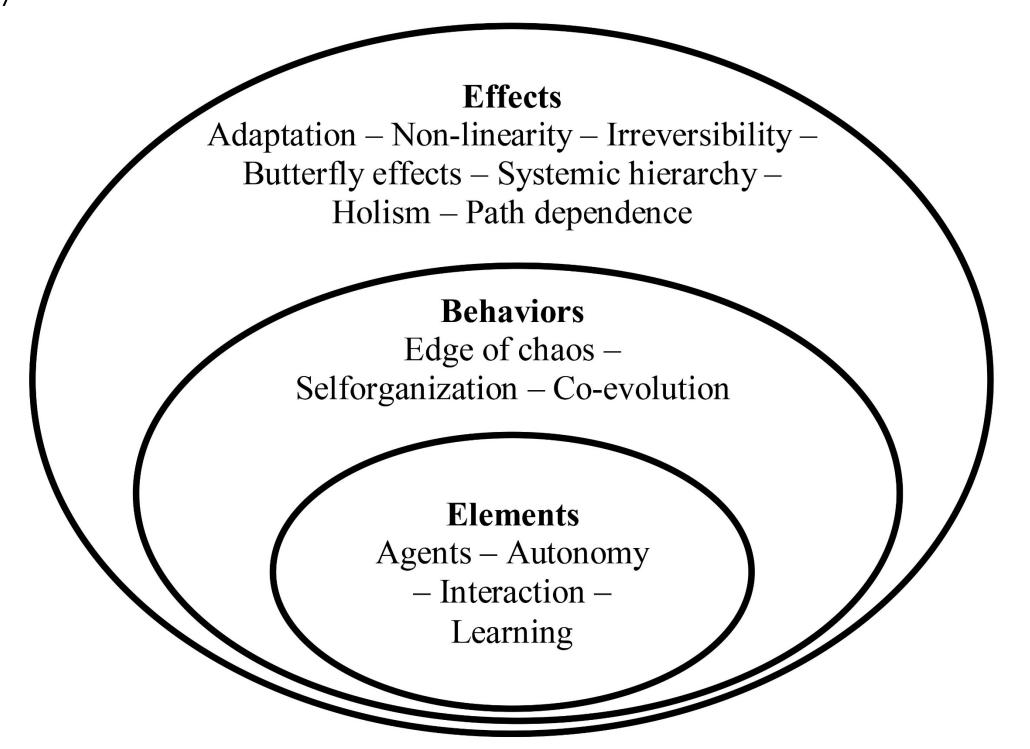
Big Question: Is this enough?

Three Kinds of Causality

weak causality

same causes

same effects

strong causality

similar causes

similar effects

chaotic behaviour

similar causes

different effects

attractor
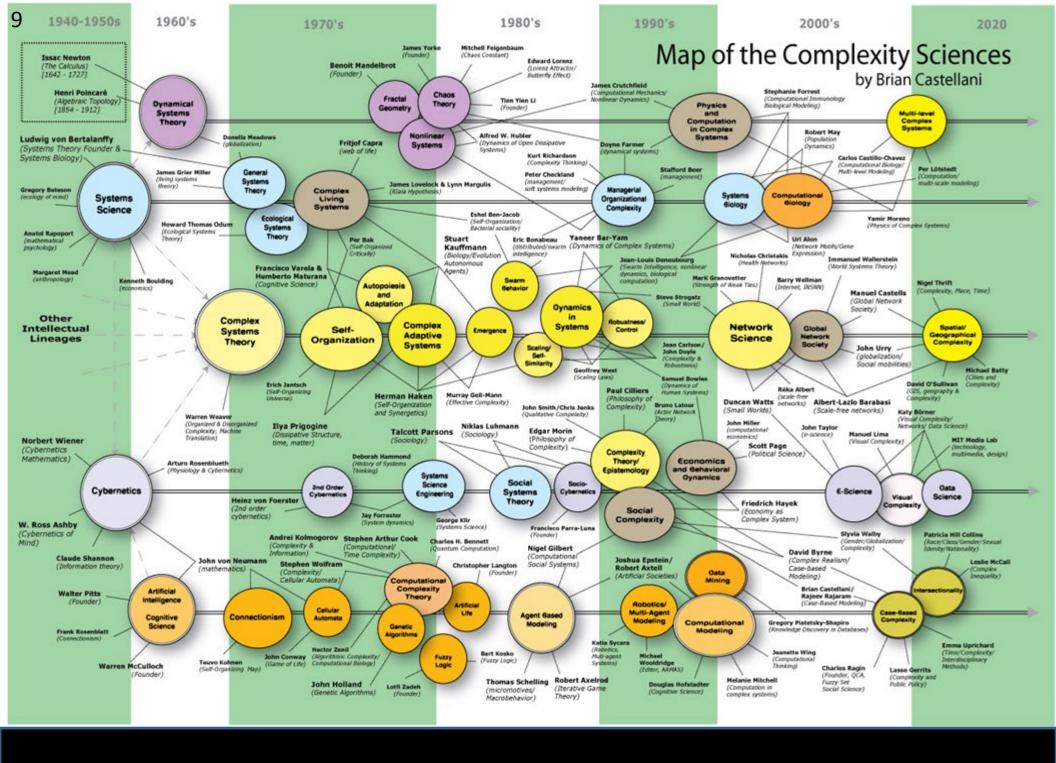
REF: Seifritz, W. (1987). Wachstum, Rückkopplung und Chaos (München: Carl Hanser)

Effects
Adaptation – Non-linearity – Irreversibility –
Butterfly effects – Systemic hierarchy –
Holism – Path dependence

Behaviors
Edge of chaos –
Selforganization – Co-evolution
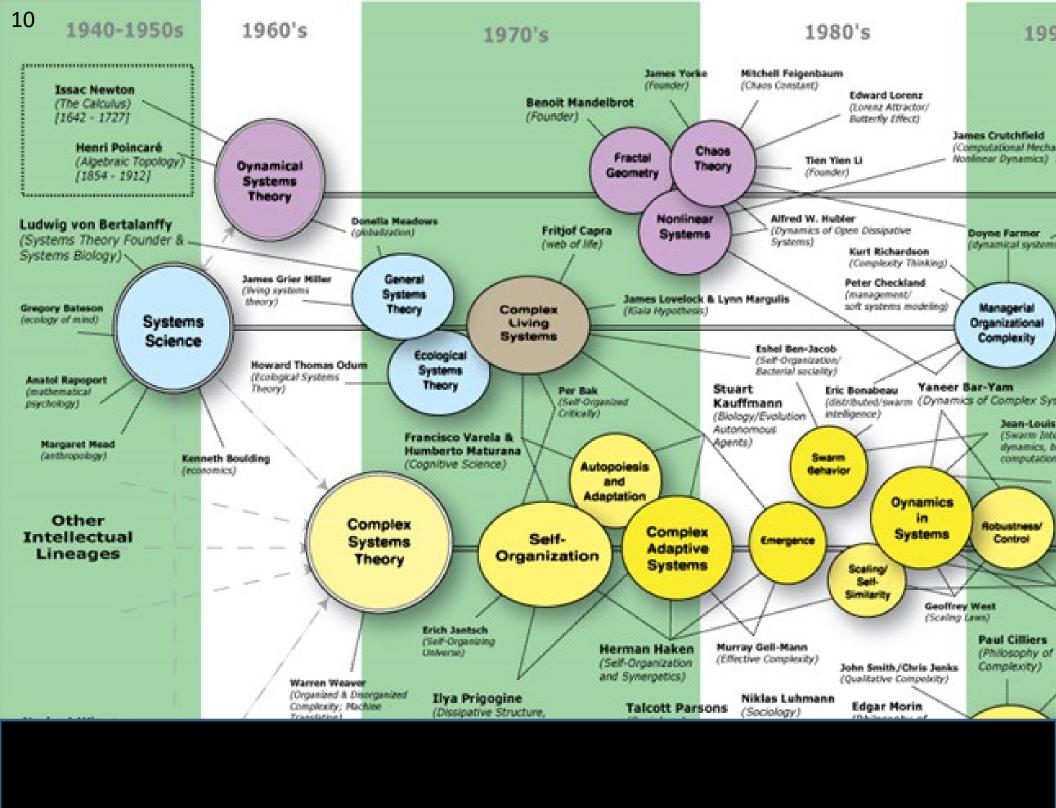
Elements
Agents – Autonomy
– Interaction –
Learning
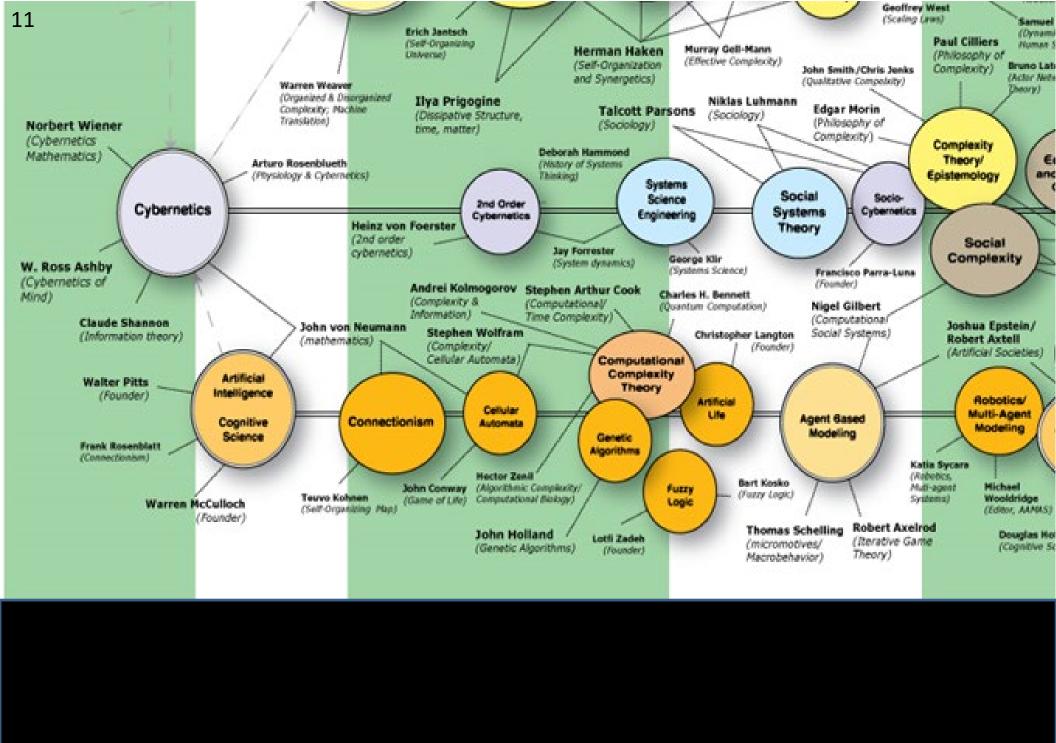
The Main Challenge for Designers…

Characteristics of a "Wicked Problem"
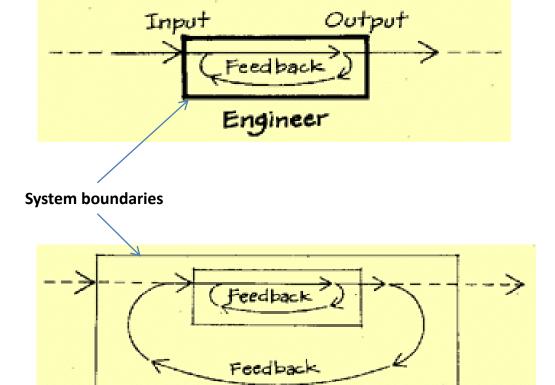
- Difficult to clearly define
- Many interdependencies and often multicausal
- Attempts to address the problem often lead to unforeseen consequences
- Frequently not stable
- Usually no clear solution
- Socially complex
- Rarely is the responsibility of only one stakeholder
- Solutions involve changing behaviors
- Can be characterized by chronic policy failure

REF: Buchanan, R. (1992). Wicked problems in design thinking. *Design Issues*, *8*(2), 5-21.

Map of the Complexity Sciences
by Brian Castellani

Erich Jantsch
(Self-Organizing Universe)

Herman Haken
(Self-Organization and Synergetics)

Murray Gell-Mann
(Effective Complexity)

Geoffrey West
(Scaling Laws)

Samuel
(Dynamic Human Systems)

Paul Cilliers
(Philosophy of Complexity)

John Smith/Chris Jenks
(Qualitative Complexity)

Bruno Latour
(Actor Network Theory)

Warren Weaver
(Organized & Disorganized Complexity; Machine Translation)
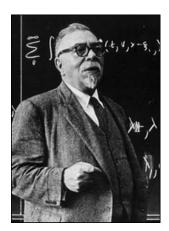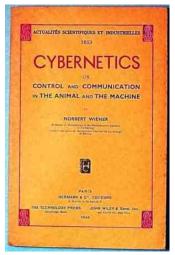
Ilya Prigogine
(Dissipative Structure, time, matter)

Talcott Parsons
(Sociology)

Niklas Luhmann
(Sociology)

Edgar Morin
(Philosophy of Complexity)

Norbert Wiener
(Cybernetics Mathematics)

Arturo Rosenblueth
(Physiology & Cybernetics)

Deborah Hammond
(History of Systems Thinking)

Complexity Theory/ Epistemology

Cybernetics

2nd Order Cybernetics

Systems Science Engineering

Social Systems Theory

Socio-Cybernetics

Heinz von Foerster
(2nd order cybernetics)

Jay Forrester
(System dynamics)

George Klir
(Systems Science)

Francisco Parra-Luna
(Founder)

Social Complexity

W. Ross Ashby
(Cybernetics of Mind)

Andrei Kolmogorov
(Complexity & Information)

Stephen Arthur Cook
(Computational/ Time Complexity)

Charles H. Bennett
(Quantum Computation)

Nigel Gilbert
(Computational Social Systems)

Claude Shannon
(Information theory)

John von Neumann
(mathematics)

Stephen Wolfram
(Complexity/ Cellular Automata)

Computational Complexity Theory

Christopher Langton
(Founder)

Joshua Epstein/ Robert Axtell
(Artificial Societies)

Walter Pitts
(Founder)

Artificial Intelligence

Cognitive Science

Connectionism

Cellular Automata

Artificial Life

Agent Based Modeling

Robotics/ Multi-Agent Modeling

Frank Rosenblatt
(Connectionism)

Genetic Algorithms

Fuzzy Logic

Katia Sycara
(Robotics, Multi-agent Systems)

Michael Wooldridge
(Editor, AAMAS)

Warren McCulloch
(Founder)

Teuvo Kohonen
(Self-Organizing Map)

John Conway
(Game of Life)

Hector Zenil
(Algorithmic Complexity/ Computational Biology)

Bart Kosko
(Fuzzy Logic)

Douglas Ho
(Cognitive So

John Holland
(Genetic Algorithms)

Lotfi Zadeh
(Founder)

Thomas Schelling
(micromotives/ Macrobehavior)

Robert Axelrod
(Iterative Game Theory)

Designing Systems from Inside Out!

Norbert Wiener
1894 - 1964

Gregory Bateson
1904-1980

Margaret Mead
1901-1978

System boundaries

Input   Output

Feedback

Engineer

Feedback

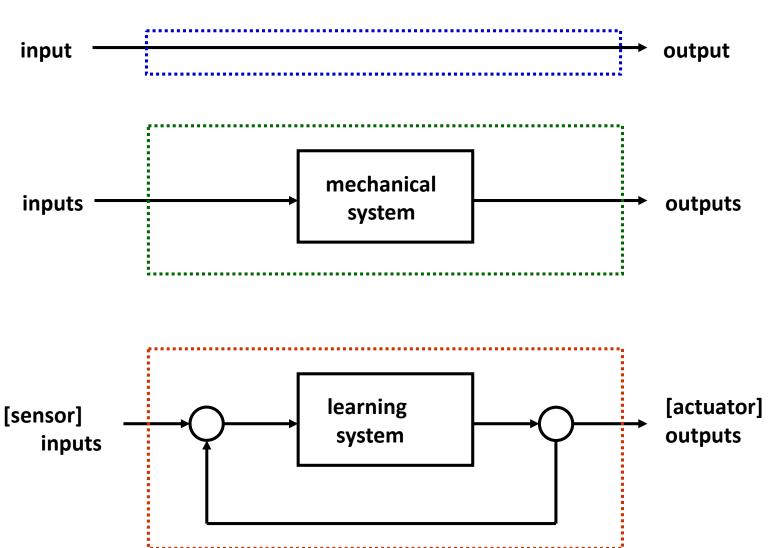Feedback

Engineer

REF: CoEvolutionary Quarterly, June 1976, Issue no. 10, pp. 32-44.

Input – Output relations

Norbert Wiener

input ――――――――――――――――→ output

inputs ――――→ | **mechanical system** | ――――→ outputs

[sensor] inputs ――→ ◯ ――→ | **learning system** | ――→ ◯ ――→ [actuator] outputs

Putting the User into the Loop

The Real Design Challenge is…

Sensor input → Intelligent System → Actuator output → Feedback

Actuator output ← Intelligent System ← Sensor input ← Feedback

Five Adaptation Levels…

Emile AARTS

Personalisation	Adaptation Levels	Services delivery dependent on
Model	Proactive	History and predictions as well as user explicit and implicit inputs and context *e.g. recommender system*
Profile	Responsive	User explicit and implicit inputs as well as context *e.g. smart home*
Preferences	Perceptive	User explicit and implicit inputs *e.g. brain-computer interaction*
Identity	Interactive	User actions and reactions *e.g. personal computer*
Anonymous	Reactive	User actions *e.g. thermostat*

REF: Aarts, E. & de Ruyter, B. (2009). New research perspectives on Ambient Intelligence. *Journal of Ambient Intelligence and Smart Environments* **1, 5–14**

Complex, Adaptive Systems:

Exhibit behaviors arising from non-linear spatio-temporal interactions among a large number of components and subsystems.

Proposition:
CAS studies *indirect effects*. Problems that are difficult to solve are often hard to understand because the causes and effects are not obviously related. Pushing on a complex system "here" often has effects "over there" because the parts are interdependent.

Takeaway:
CAS is a viable method for modeling complex physical and social systems to understand their behavior based on observed data.

[**REF**: adapted from presentation of Stephen H. KAISLER, D.Sc. And Gregory MADEY, Ph.D.]

What is Complexity?

- **Complex**: consisting of interconnected or interdependent parts
  - Not easy to understand or analyze
- **Simple systems**: e.g., an oscillator, a pendulum, a spinning wheel, an orbiting planet
- **Complex Systems**: e.g., government, an economy, families, the human body— physiological perspective, a person—psychosocial perspective, the brain, the ecosystem of the world

  - Not Shannon, Turing, or …

horizontal complexity

vertical complexity

$1 + 1 = 2$ $e = m\ c^2$

REF: Rauterberg M., Schluep S., Fjeld M.(1998). Modelling of cognitive complexity with Petri nets: an action theoretical approach. In: R. Trappl (ed.) Proceedings of Cybernetics and Systems EMCSR'98 (Vol. 2, pp. 842-847), Vienna: Austrian Society for Cybernetic Studies.
REF: Flückiger M. (1995). Komplexität und Messung von Komplexität. *Technical Report* IfAP/ETH/CC-01-95, ETH Zurich.

Why Define Complexity?

- To estimate how long a particular system will take to solve a problem.

- To estimate difficulty in engineering complex systems.

- To understand the limits of prediction, approximation, and simulation.

- To answer fundamental scientific questions.

- Does complexity increase through evolution – biological or otherwise?

> *"As evolution proceeded on the surface of the earth, there has been a progressive increase in size and complexity"*
>
> - J. T. Bonner Evolution of Complexity.

> *"Evolution tends to push systems towards the edge of chaos, where complex, interesting behaviors such as life can occur? "*
>
> - Chris Langton

> *"The universe, the biosphere, the econosphere have all become more complex"*
>
> - Stuart Kauffmann

Big question: Can we quantify the increase in complexity over time?

REF: Rauterberg M. (2010). From genes to memes: Culture as an evolutionary arena. *Bussei Kenkyu*, vol. 94, no. 1, pp. 130-131

Complexity vs. Complicated

- Complexity is difficult to describe

- If we say something is <u>complex</u> in 'everyday' language we mean something that is difficult or impossible to understand with simple logic (i.e., long term weather patterns)

- A car is not complex, just *complicated*.
  - Cars do exhibit "unwanted functionality"

- *Complicated Systems*: Often difficult to describe, but succumb to divide-and-conquer approaches.

- Complicated is easier to cope with than complex – Seth Bullock
  - Numerous techniques to resolve complicated systems
  - As a last resort, use brute force/trial and error

- But, complicated systems are often complex:
  - Software does suffer from "emergent" bugs!!

Explanation vs Prediction

- Low-level behavior is unpredictable (gas molecules bouncing around, pigs pigging about)

- We can explain how more gas increases temperature (ideal gas law) but not easy to explain how more pigs brings about an abrupt phase transition in pig violence

- For simple (linear) systems:
    - a small change to a system's components $\rightarrow$ a small change at the system level

- For complex (non-linear) systems:
    - a small change to a system's components $\rightarrow$ large/small/no change at the system level
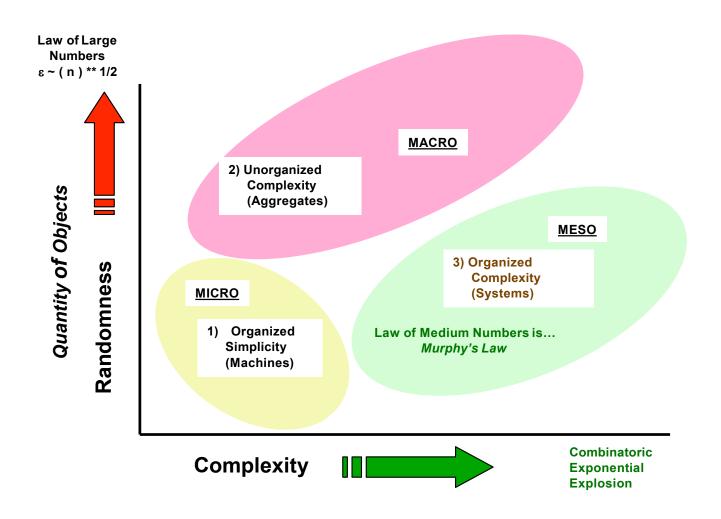
REF: Seth Bullock, Introduction to Complexity Science, 2006

Complexity Issues

- Complex behavior originates from the operation of simple underlying rules (Simon's conjecture).

- But, sometimes, deducing behavior from rules is not possible.

- There is no practical way to study the network of causality in detail.

- Therefore, we need ways to synthesize understanding from large state spaces and multidimensional meshes.

- However, the spectre of computational intractability haunts the space between rules and consequences.

REF: G.M. Weinberg, An Introduction to General Systems Thinking, John Wiley & Sons, New York, 1975, p 18.

Complexity Issues

Law of Large Numbers
$\varepsilon \sim (n)^{**1/2}$

Quantity of Objects

Randomness

MACRO

2) Unorganized Complexity (Aggregates)

MESO

3) Organized Complexity (Systems)

MICRO

1) Organized Simplicity (Machines)

Law of Medium Numbers is…
Murphy's Law

Complexity

Combinatoric Exponential Explosion

REF: G.M. Weinberg, An Introduction to General Systems Thinking, John Wiley & Sons, New York, 1975, p 18.

Systems Theory Definition

Systems are elements in interaction
Systems thinking vs. traditional thinking

Characteristic	Traditional thinking	Systems thinking
Overall view	Reductionistic, focus is on the parts	Holistic, focus is on the whole
Key processes	Analysis	Synthesis
Type of analysis	Deduction	Induction
Focus of investigation	Attributes of objects	Interdependence of objects
State during investigation	Static	Dynamic
Basic assumption	Cause and effect	Multiple, probabilistic causality
Problem resolution	A static solution	An adaptive system or modeling
Operation of parts	Optimal	Suboptimal
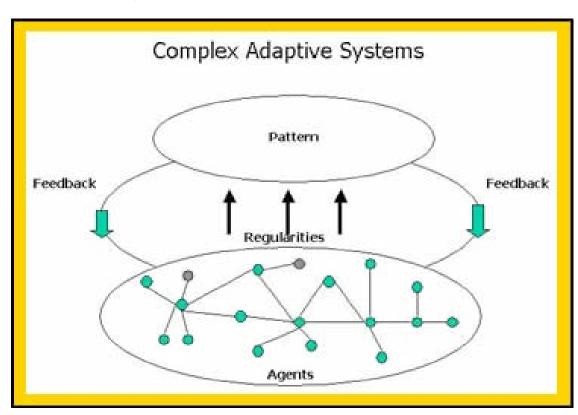
What is a System?

- A *system* is a purposeful collection of interrelated components that work together to achieve some objectives.

- Many types of systems: physical, political, biological, social, …

- We are primarily interested in socio-technical systems:

  - technical system + knowledge of goals to achieve
    (operational processes + people involved)

- Complex systems exhibit four characteristics:

  - Self-organization

  - Non-linearity

  - Order/Chaos Dynamic

  - Emergence

- Further complexity ensues by allowing a system to *adapt* to its environment.

Complex Systems

π **A *complex system* is any system:**

– That involves a (**large**) number of elements, arranged in structure(s) which can exist on many scales.

– These elements interact locally: every element is connected to every element in the system, even indirectly.

– Structures go through a process of change not describable by a single rule or reducible to a single level of explanation.
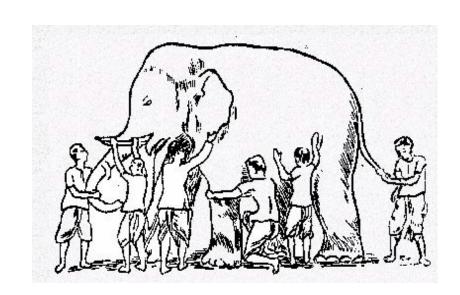
– Features emerge that cannot be predicted from the current description of the structure(s).

What are Complex Systems?

- **At their lowest level, they are comprised of a set of individual *agents (a general term!)***
  - Agents are *heterogeneous*, differing in important characteristics.
  - Agents are *indivisible.*
  - Agents are/may be *organized* into some sort of group or hierarchy, which is/may be structured. These organizational structures in turn influence system dynamics.
- **The system is *dynamic* – it changes over time:**
  - The agents interact, adapt and undergo natural selection in response to their own environment. The system dynamics are *non-linear*.
  - Agent change often occurs in response to *feedback* from their actions.
- **Complex systems may possess the characteristic of *emergence*.**
  - The macro- or system-level behavior that emerges from the activities and behaviors of the component parts of the system, but which cannot be explained at the agent level alone.
  - It's usually the system-level behavior that intrigues us.

Complex Systems Theory

- *Complex Systems Theory* is a scientific framework that explains how rules govern emergence and the constraints mediating self-organization and system dynamics.

- The science of complexity, is <u>not </u>a single body of theory, but rather is comprised of a collection of fields, including:

  - *Artificial Intelligence* (AI)
  - *Artificial Life*
  - *Cognitive science*
  - *Computer science*
  - *Ecology*
  - *Economics*
  - *Evolution*
  - *Game theory*
  - *Immunology*
  - *Linguistics*
  - *Philosophy*
  - *Social science*

Some Measures of Complexity

- Computational complexity:
  - How long a program runs (or how much memory it uses).
  - Asymptotic.

- Language complexity (Formal Language Theory):
  - Classes of languages that can be computed (recognized) by different kinds of abstract machines (e.g., Turing machine).
  - Decidability, computability.

- Information-theoretic approaches (after Shannon and Brillouin):
  - Algorithmic Complexity (Solomonoff, Komogorov, and Chaitin):
    - Length of the shortest program that can produce the phenomenon.
  - Mutual information (many authors; e.g. Rauterberg)

- Logical depth (Bennett).

- Thermodynamic depth (Lloyd and Pagels)

Adaptive Systems

- An *adaptive system* is a system that <u>changes </u>in the face of perturbations so as to <u>maintain </u>some kind of <u>invariant state </u>by altering its properties or modifying its environment:

  - Perturbations = changes in environment

  - Invariant = such as 'survival'

  - Property = such as behavior or structure

- The *ability* to adapt depends on the observer who chooses the <u>scale and granularity of description.</u>

- An adaptive system is necessarily complex, but the obverse is not necessarily true.

- Evolution is a result of an adaptive system.

REF: Ahn R., Barakova E., Feijs L., Funk M., Hu J., Rauterberg M. (2014). Interfacing with adaptive systems. *Automation, Control and Intelligent Systems*, vol. 2, no. 4, pp. 53-61.

Kinds of Adaptation

- <u>Task-based</u>: changes that allow the completion of a goal when this is challenged.
  - Artificial systems

- <u>Sub-organismic</u>: a system/mechanism within the organism that maintains some internal property
  - Ex. homeostasis in individual cells, etc.
  - Can give rise to organismic level phenomena such as habituation (which may be non-adaptive at this higher level)

- <u>Organismic</u>: changes that maintain essential properties of the organism
  - those that guarantee survival, identity, autonomy

- <u>Ecological</u>: changes that maintain certain patterns of behaviour of one or many organisms.
  - Recovery of sensorimotor invariants and habitual behaviour (group, social norms)
  - Radical adaptation to body reconfiguration.

- <u>Evolutionary</u>: changes in distribution of phenotypes due to differential rates of survival and reproduction. Resulting phenotypic properties can be said to be adapted. Occurs at population level.

- End of part 1 -