Introduction to 'Complex systems' lectures

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Teaching related matters

- Lecture notes
- Supplementary material available at the course webpage

Complex systems science

- A new field of science studying how parts of a system give rise to the collective behaviours of the system, and how the system interacts with its environment.
- It focuses on certain questions about parts, wholes and relationships.

Complex systems

Examples of complex systems are:

- The brain
- The society
- The ecosystem
- The cell
- The ant colonies
- The stock market
- . . .

Complex systems science

CSS is interdisciplinary and it involves:

- Mathematics
- Physics
- Computer science
- Biology
- Economy
- Philosophy

...just to mention some.

Complex systems science

Three main interrelated approaches to the modern study of complex systems:

1. How interactions give rise to patterns of behaviour
2. Understanding the ways of describing complex systems
3. Understanding the process of formation of complex systems through pattern formation and evolution

Complex systems science

Three main objectives:

1. Understand
2. Make predictions
3. Control

Complex systems science

Some prominent research topics in CSS:

- Evolution & emergence
- Systems biology
- Information & computation
- Complex networks
- Physics of Complexity
- Innovation, sustainability and social systems

Reductionism vs. Holism

Reductionism: an approach to understanding the nature of complex things by reducing them to the description of their parts.

Holism: idea that the properties of a system cannot be determined or explained by its component parts alone, but they are rather explained in terms of the interactions among the parts. Summarised with the sentence “The whole is more than the sum of its parts”.

Complex vs. Complicated

Complex: from Latin (*cum + plexere*); it means “intertwined”.

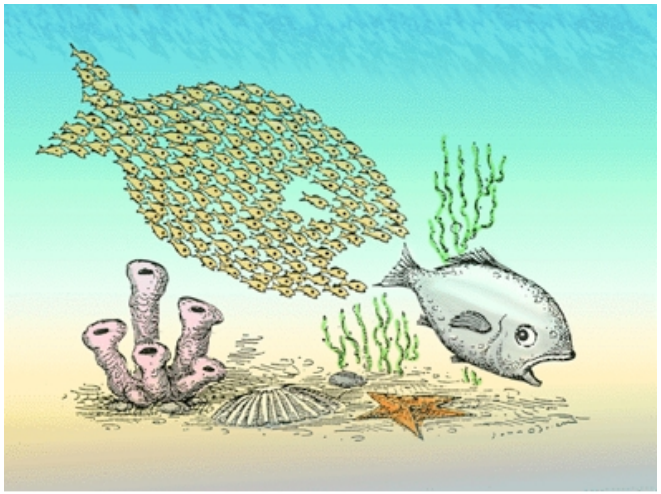
Complicated: from Latin (*cum + plicare*); it means “folded together”.

Properties of complex systems

Complex systems are characterised by (some of) these properties:

- Composed of many elements
- Nonlinear interactions
- Network topology
- Positive and negative feedbacks
- Adaptive and evolvable
- Robust
- Levels of organisation (tangled hierarchies)

Emergence



- One of the main concepts in CSS
- Controversial and elusive
- Highly dependent from the observer's point of view

Emergence (1)

"The term emergence describes the onset of novel properties that arise when a higher level of complexity is formed from components of lower complexity, where these properties are not present."

(from P.L. Luisi, "The emergence of life", Cambridge University Press, 2006)

Emergence (2)

"Emergence refers to the arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems. Emergent phenomena are conceptualized as occurring on the macro level, in contrast to the micro-level components and processes out of which they arise."

(from J. Goldstein, Emergence as a Construct,
Emergence 1(1):49–72)

Emergence (3)

"Emergence refers to all the properties that we assign to a system that are really properties of the relationship between a system and its environment."

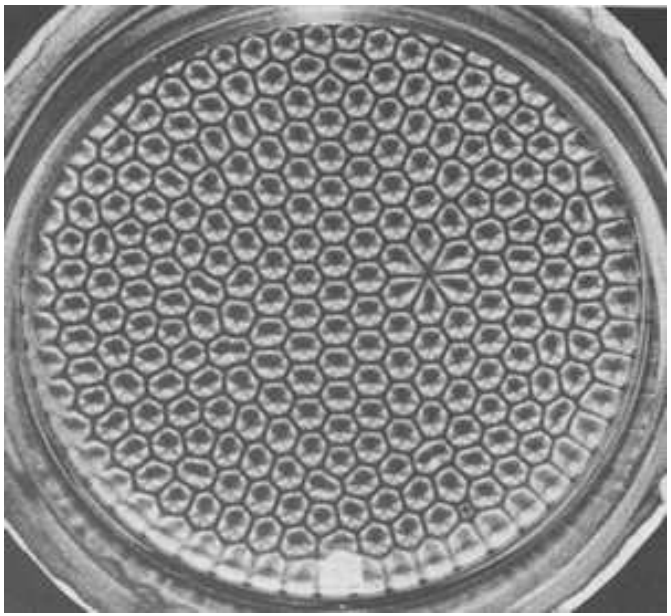
(from Y. Bar-Yam, Concepts in Complex Systems, 2000. http://necsi.edu/guide/concepts/emergence.html)

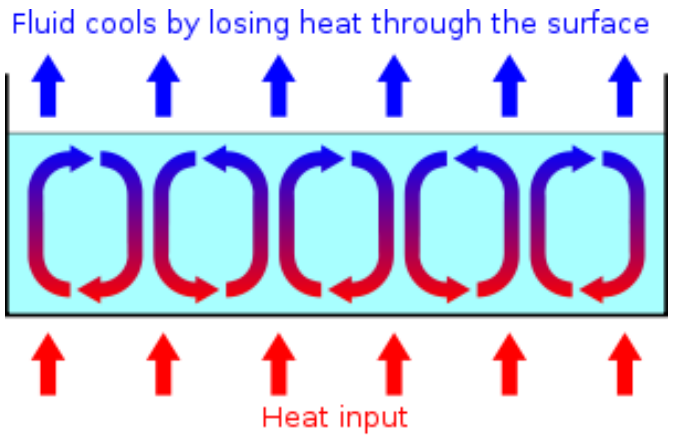
Self-organisation
A prominent case of emergence

Dynamical mechanisms whereby structures appear at the global level from interactions among lower-level components.

- Creation of spatio-temporal structures
- Possible coexistence of several stable states (multistability)
- Existence of bifurcations when some parameters are varied

Example: Bénard cells





Further examples of emergence

- Synchronisation in fireflies
- Foraging and nest building in insects
- Flocking
- Organs and tissues in multicellular organisms*
- Clouds*
- Factions in political parties*

(*) examples of *sandwiched emergence*

Universality

- CSS tries to identify principles that can be **universally** applied to some system classes
- In spite of specific differences, many systems exhibit the same properties
- Prominent example: phase transitions

Example: Cellular automata