Complex Systems and Network Science: Introduction

Ozalp Babaoglu
Dipartimento di Informatica — Scienza e Ingegneria
Università di Bologna
www.cs.unibo.it/babaoglu/

Administrative information

- Office: Mura Anteo Zamboni 7, Room 104
- Office hours: Tuesdays 13.30—15.30
- My home page: www.cs.unibo.it/babaoglu/
- Course home page: www.cs.unibo.it/babaoglu/courses/csns/
- Tutor: dott. Angelo Trotta

Course organization

- Lecture schedule:
  - Tuesday, Wednesday, Thursday 11.00—13.00 (Aula Ercolani E3)
- Evaluation will be based on
  - Class presence and participation (20%)
  - Oral presentation (30%)
  - Programming project (50%)

Textbooks

- The Computational Beauty of Nature, G. W. Flake
- Networks, Crowds, and Markets: Reasoning about a Highly Connected World, D. Easley, J. Kleinberg
- Complex Adaptive Systems: An Introduction to Computational Models of Social Life, J. H. Miller, S. E. Page
- Graph Theory and Complex Networks: An Introduction, M. van Steen
Software tools and systems

- **NetLogo**: programmable multi-agent environment for modeling network dynamics
  - [https://ccl.northwestern.edu/netlogo/](https://ccl.northwestern.edu/netlogo/)
- **Gephi**: interactive visualization and exploration platform for networks
  - [https://gephi.github.io/](https://gephi.github.io/)
- **PeerSim**: simulation environment for P2P protocols and systems

What is this course about?

- Different possible titles
  - Complexity
  - Complexity science
  - Complex systems
  - Complex networks
  - Complex systems and network science
- "Complex" and "complexity" are loaded terms that have common colloquial usage — give a more technical definition
- Survey the mathematical foundations, goals and methodologies of complexity science as a discipline
- "Modeling" as a core methodology

What is complexity science?

- Interdisciplinary study whose core disciplines include
  - Mathematics
  - Physics
  - Computer science
  - Biology
  - Sociology
- Tries to answer a set of questions about the way natural, artificial and technological systems work

Questions

- Weaver identifies three classes of problems:
  - Problems of *simplicity*
  - Problems of *disorganized* complexity
  - Problems of *organized* complexity
Problems of simplicity

- Pre 1900 physical sciences — few variables with well-known relations between them
- Examples:
  - Force, acceleration (Newtonian mechanics)
  - Pressure, temperature (Gas Laws, Boyle, Charles, Avogadro)
  - Current, voltage, resistance (Ohm's Law)
  - Population, time (Lotka-Volterra model)

Problems of disorganized complexity

- Huge number (billions, trillions) of variables
- “Disorganized” in the sense of “random” and almost independent variables with little interaction among them
- Allows statistical methods for describing the behavior of large aggregates through averages
- Related to “linear systems” where the “whole is the sum of its parts"
- Example:
  - Temperature and pressure of gases resulting from the motion of trillions of air molecules

Problems of organized complexity

- Middle ground between few and many variables
- Moderate number of variables but with strong, nonlinear interactions among them
- Statistical methods for describing average behavior are not applicable
- “The whole is more than the sum of its parts”
- “Problems which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole”

Questions of organized complexity

- On what does the price of wheat depend?
- How can currencies be effectively stabilized?
- To what extent must systems of economic control be employed to prevent the wide swings from prosperity to depression?
- Why did the Dow Jones stock index drop more than 1,100 points on Monday 5 February 2018?
- How can one explain the behavior of organized groups of persons such as labor unions or a racial minorities?
- Why do rural families in countries such as Bangladesh still produce an average of 7 children a piece even when birth control is freely available?
More questions

- Why did the forty-year hegemony of the Soviet Union over Eastern Europe collapse within a few months in 1989?
- How did the first living cell emerge from a primordial soup of amino acids and other simple molecules four billion years ago?
- How can a 1kg lump of gray matter give rise to qualities such as feeling, awareness, thought and creativity?
- What makes an evening primrose open when it does?

Challenges of complexity science

- “These problems … are just too complicated to yield to the old nineteenth-century techniques which were so dramatically successful on two-, three-, or four-variable problems of simplicity. These new problems, moreover, cannot be handled with the statistical techniques so effective in describing average behavior in problems of disorganized complexity.”
- “These new problems, and the future of the world depends on many of them, requires science to make a third great advance, an advance that must be even greater than the nineteenth-century conquest of problems of simplicity or the twentieth-century victory over problems of disorganized complexity. Science must, over the next 50 years, learn to deal with these problems of organized complexity.”

Examples of complex systems

- Social insects
- The human brain
- The mammalian immune system
- Economies, financial markets
- Cities, traffic
- Data centers
- The Internet
- Peer-to-peer systems
- The World Wide Web

Social insects

- Ants
- Termites

When considered in isolation, these insects exhibit extremely primitive behavior lacking any hint of intelligence or purpose.
Social insects

- Yet, considered in large numbers, they are capable of accomplishing complex tasks without any central control such as *foraging* looking for food.
- Or building bridges.
- Or termite mounds.

Human brain

- The human brain consists of about 100 billion neurons and 100 trillion connections (synapses) between them.

Human brain

- Each neuron alone is rather simple with limited functionality.
- Yet, taken as a whole forming the human brain, they enact sophisticated control over bodily functions and give rise to complex functions including awareness, thought and creativity.

Immune system

- Involves many organs distributed over the body.
Immune system

- White blood cells attacking bacteria

Economies and financial markets

- Agents are people, banks, financial institutions, governments
- In capitalist economies, there is very little central control and, for the most part, the agents act on their own
- In a global economy, agents may be intimately interrelated

Strong, nonlinear interactions among the agents can lead to highly unpredictable (and undesirable) global outcomes

Cities, traffic

- Cities consist of (among others) people and vehicles as agents
- In many ways, cities are like living organisms — they grow, scale, adapt and function similar to multi-cell organisms
- Cities usually have sufficient resources (space, roads, housing, markets, etc.) such that no surprises arise for small numbers
Cities, traffic

- Yet, large numbers or scarce resources, can lead to unexpected outcomes
  - Stampedes
  - Gridlock

Datacenters

- Tens of thousands of multi-core servers, software, networking devices, storage devices, power infrastructure, cooling plant

Internet (circa 2011)

- More than 800M hosts organized as 19,869 autonomous systems, joined by 44,344 connections

Peer-to-peer systems

- P2P is a disruptive technology that allows (millions of) end users to develop and deploy Internet applications without requiring any centralized resources or authorization
- Particularly popular for sharing applications
- Built on self-organizing “overlay networks”
World Wide Web

- 30 billion pages, 160 billion hyperlinks

Networks and network science

- Interactions among agents is central to complex systems
- Networks allow us to model these interactions
- Networks play a fundamental role in the transmission of information, transportation of goods, spread of diseases, diffusion of innovation, formation of opinions and adoption of new technologies
- Understanding the structure and dynamics of these networks is essential for understanding the behavior of the underlying complex system
- The decentralized manner in which these networks self organize itself constitutes a "complex system"
- We will study networks in detail in the second half of the course

Common properties

- Despite the great variability in scale, context and function of these examples, they all possess certain common properties:
  - Simple components — agents, actors
  - Decentralized control — no distinguished “master”
  - Nonlinear interactions — components act autonomously but interact with other components directly or indirectly
  - Emergent behavior — the global system exhibits properties that cannot be derived or predicted from understanding behaviors of individual components

Emergent behavior

- Hierarchical structure — proteins to nucleic acids to cells to tissues to organs to organisms to colonies to ecosystems
- Self organization — people into economies, birds into flocks, ants into bridges, social networks into communities
- Adaptation — agents react to changes in their environment in an effort to maintain favorable outcomes, resulting in learning and evolution
- Information processing — while individual agents remain ignorant, the system as a whole is able to process information and even compute
Starling murmurations

Linear and nonlinear systems

- In general, linear systems obey the superposition principle:

  \[ F(a_1x_1 + a_2x_2 + \cdots) = a_1F(x_1) + a_2F(x_2) + \cdots \]

- “The whole is the sum of its parts”
- Superposition principle is the basis for reductionism — a system can be understood by studying its individual parts

Reductionism

- Reductionism guided much of the progress in pre 1900 physical sciences — biology, anatomy, astronomy, physics, chemistry
- To understand a certain process or object, reduce it down to its constituent parts and study them individually
- If the parts are truly independent, understanding the constituent parts fully is sufficient for understanding their composition
- Reductionist hypothesis taken to its logical conclusion would mean that particle physics is the key to understanding the entire universe
- Economics ➝ Sociology ➝ Psychology ➝ Biology ➝ Chemistry ➝ Physics

Reductionism versus constructionism

- Components of complex systems are not independent but interact with each other in nonlinear ways
- Even if we could understand perfectly each component, we would be far from understanding their composite behavior — constructionism (reductionism in reverse) does not work for complex systems
- “The whole is not only more than but also very different from the sum of its parts”
Complex versus complicated

- In colloquial language, we often use “complex” as a synonym for “complicated” — many components, many connections but the interactions are weak and linear
- Reductionism effective for understanding complicated systems but not effective for understanding complex systems

Reductionism applied to complicated systems

- We can understand the behavior of the entire chip by understanding its constituent parts: cores, cache, queue, etc.
- Each one of the cores can be further reduced to simpler functional units

Reductionism applied to complicated systems

- Reduction continues until we reach single-transistor “gates”

- More importantly, we can apply constructionism to understand how an AMD Opteron processor works
- Starting with single-transistor gates, we can build gates that perform other logical functions, and from such gates build registers, ALU, memory, etc.
Key concepts in complex systems

- **Dynamics** — how behaviors and structures change over time
- **Information** — how data is represented and communicated
- **Computation** — how information is processed
- **Evolution** — how systems adapt to changes in the environment

Methodologies of complex systems

- The usual scientific method — Theory, Experimentation
- “Computation” (or “simulation”) is increasingly becoming the third pillar of the scientific method