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: Wednesdays 11.00—13.00 (also by appointment)
- My home page: www.cs.unibo.it/babaoglu/
- Course home page: www.cs.unibo.it/babaoglu/courses/csns/
- Tutor: Francesco Alfieri (francesco.alfieri5@studio.unibo.it)

Course organization

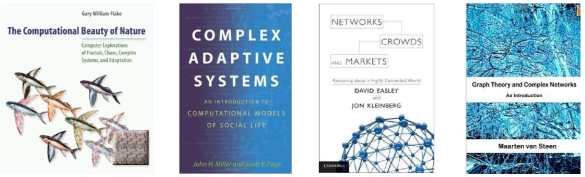
- Lecture schedule:
  - Monday 16.00—18.00 (Aula E1)
  - Wednesday 9.00—11.00 (Aula E3)
  - Thursday 13.00—15.00 (Aula E1)
- *Course evaluation* will be based on
  - Research paper presentation (40%)
  - Project written report (50%)
  - Project discussion (10%)

Course organization

- Research *paper presentation evaluation* will be based on
  - Relevance of the topic to the course,
  - Quality of the contents,
  - Quality of the delivery,
  - Quality of the slides,
  - Adherence to the time limit (30 minutes)

Textbooks

- *The Computational Beauty of Nature*, G. W. Flake
- *Complex Adaptive Systems: An Introduction to Computational Models of Social Life*, J. H. Miller, S. E. Page
- *Networks, Crowds, and Markets: Reasoning about a Highly Connected World*, D. Easley, J. Kleinberg
- *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/
- **Gephi**: interactive network *visualization* and *exploration* platform
  - https://gephi.github.io/
- **PeerSim**: simulation environment for P2P protocols and systems
  - http://peersim.sourceforge.net/

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 (among others)
  - Mathematics
  - Physics
  - Computer science
  - Biology
  - Sociology
- Tries to answer a set of questions about the way natural, artificial and technological systems work

Problems

- Warren Weaver, “Science and Complexity”, American Scientist, 36:536 (1948)
- 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, mass, acceleration (Newtonian mechanics: $F=ma$)
  - Pressure, volume, temperature (Gas Laws: $PV=nRT$)
  - Current, voltage, resistance (Ohm’s Law: $V=IR$)
  - 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 no longer 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 1,175 points on Monday 5 February 2018?
- How can one explain the behavior of organized groups of persons such as labor unions or 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?

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, require 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

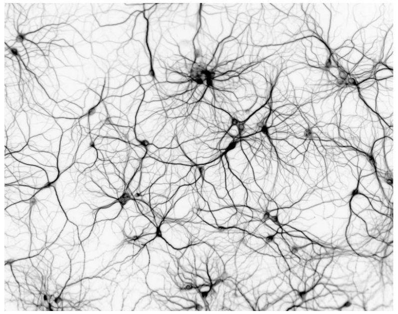
- Yet, considered in large numbers, they are capable of accomplishing complex tasks without any central control such as *foraging* looking for food

- Or building bridges

- And termite mounds

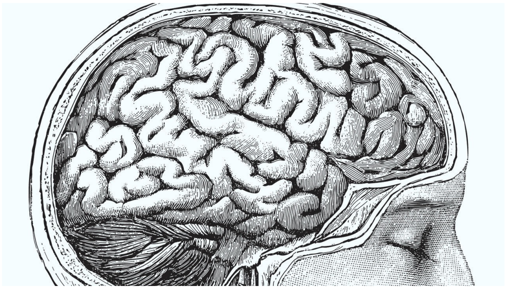
Human brain

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



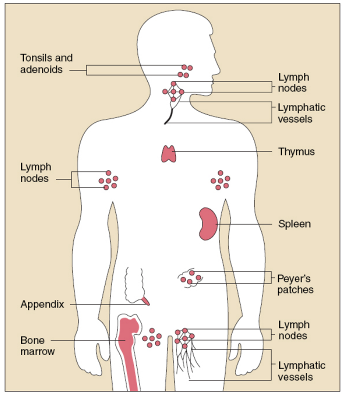
Human brain

- 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



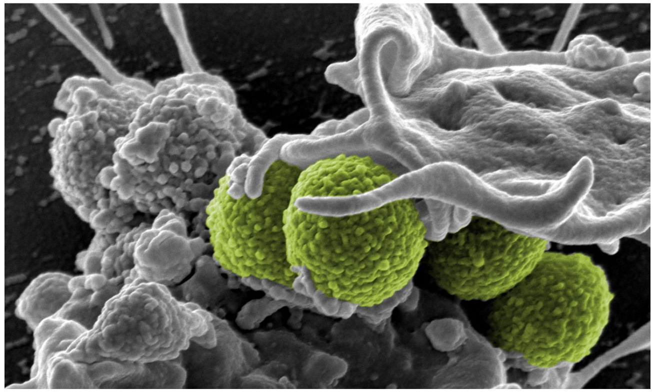
Immune system

- Involves many organs distributed over the body



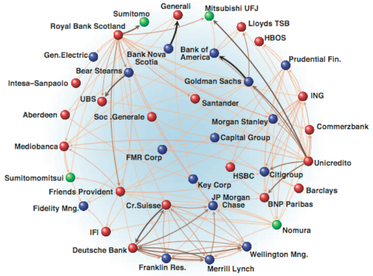
Immune system

- White blood cells attacking bacteria



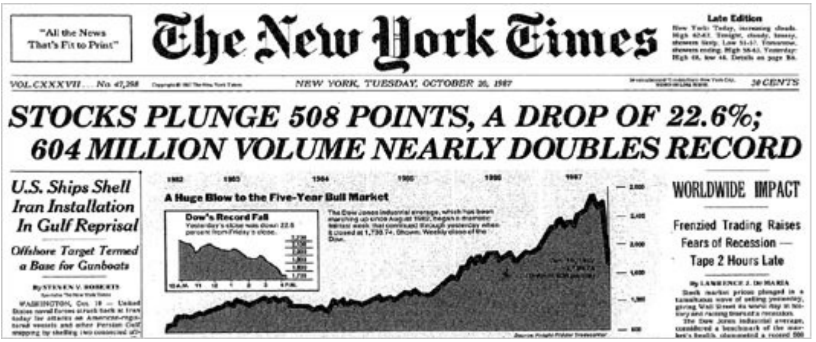
Economies and financial markets

- 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



Economies and financial markets

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



"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CXXXVII . . . No. 47,298

NEW YORK, TUESDAY, OCTOBER 20, 1987

30 CENTS

STOCKS PLUNGE 508 POINTS, A DROP OF 22.6%;
604 MILLION VOLUME NEARLY DOUBLES RECORD

U.S. Ships Shell Iran Installation In Gulf Reprisal

Offshore Target Termed a Base for Gunboats

A Huge Blow to the Five-Year Bull Market

Dow's Record Fall

WORLDWIDE IMPACT

Frenzied Trading Raises Fears of Recession — Tape 2 Hours Late

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 moderate numbers


Cities, traffic

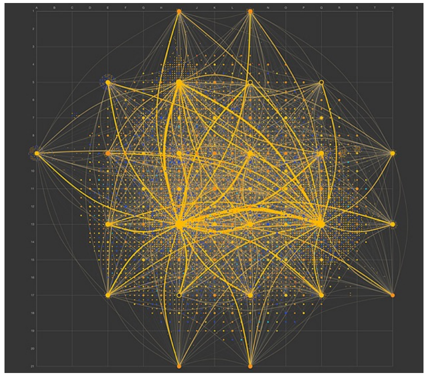
- Yet, large numbers or scarse resources, can lead to unexpected outcomes
  - Stampedes
  - Gridlock


Datacenters

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

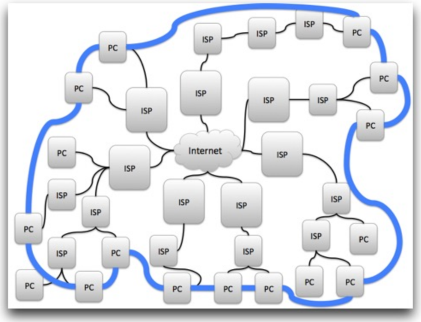
Internet (circa 2011)

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



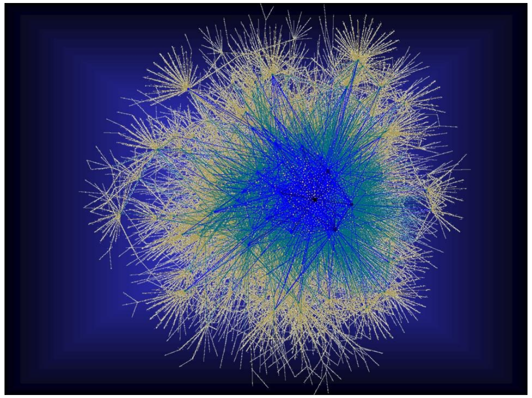
Peer-to-peer systems

- 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*, 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 eco systems
- *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"

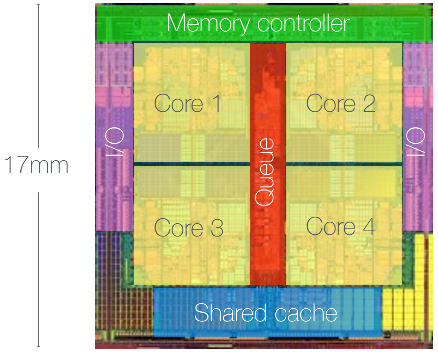
Complex versus complicated

- 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

---

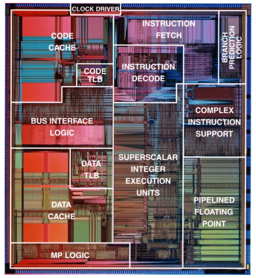
Reductionism applied to complicated systems

- AMD K10 "Opteron" quad-core processor chip
- 463,000,000 transistors, 283 mm², 65 nm technology



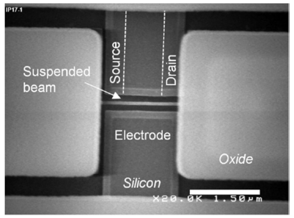
Reductionism applied to complicated systems

- 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