Structure and Dynamics of Complex Networks

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Instructor(s):

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Short Description of the Course:
Complex systems are composed of many interacting units and are characterized by nonlinearity, positive and negative feedback, and emergent collective behavior. Prominent examples include the brain, the cell, the internet, and economic or social systems. Recent advances in network science provide powerful conceptual and computational tools for analyzing such systems. The course introduces the fundamentals of complex network theory alongside applications drawn from information technology, economics, sociology, and biology, with both aspects developed in parallel throughout the course. Core topics include small-world and scale-free networks, key network measures, spreading and breakdown phenomena, and the analysis of weighted and directed graphs. A central component of the course is a project in which students acquire practical network-analysis skills through hands-on work. This includes Python-based network analysis as well as the use of graphical network analysis tools. Interested students may also choose to participate in network-related research projects.

Aim of the Course:

The aim of the course is to equip students with up-to-date knowledge of the fundamental principles of network topology and dynamics, as well as the analytical and visualization tools used in modern network science. Through a course project, students will gain practical experience in constructing networks from raw datasets, quantifying their structural properties (such as degree distributions, small-world characteristics, and clustering), and comparing empirical networks to appropriate random network models.

Students will also learn to use networks in dynamical simulations, including processes such as infection spreading and opinion dynamics. Practical work combines interactive tools with short Python scripts to run experiments and analyze data. By the end of the course, students will be able to apply their network-related skills to a broad range of real-world complex systems, including the Internet, social networks, economic networks, and biological systems.

Prerequisites:
Basic concepts of calculus and probability theory are required for this course.
Programming aptitude is required as the lab sessions involve writing python code, but knowledge of python is not, as all features that are used are covered during the labs.

Learning Objectives:

1. **Explain** the fundamental concepts of complex systems and network science, including nonlinearity, feedback, and emergent collective behavior.
2. **Describe and interpret** key structural properties of complex networks, such as small-world and scale-free characteristics, degree distributions, clustering, and path lengths.
3. **Apply** standard analytical measures to quantify network topology in weighted and directed networks.
4. **Construct** network representations from raw empirical datasets and **compare** real-world networks with appropriate random network models.
5. **Analyze and simulate** dynamical processes on networks, including spreading phenomena and opinion dynamics, and **interpret** the results of these simulations.

6. **Use** Python-based and interactive graphical tools to perform network analysis, visualization, and data-driven experiments.
7. **Transfer** network-science methods to the analysis of real-world complex systems from domains such as information technology, social and economic networks, and biological systems.

Detailed Program and Class Schedule:

Network Theory and Structure:

1. Introduction
    - Complex systems and complex networks
    - Examples from technology, society, and biology
2. Graph Representations and Network Types
    - Major graph types, representations
    - Bipartite networks
    - Adjacency matrices
3. Basic Network Measures
    - Node degree and degree distributions
    - Clustering coefficient
    - Distances, shortest paths and path-based measures
4. Small-Worls and Random Networks
    - The small word property
    - Classical random graph models
    - Scale-free networks and preferential attachment
5. Robustness and Percolation
    - Network robustness and resilience
    - Percolation theory
    - Robustness against random failures and targeted attacks
6. Community Structure
    - Concepts of communities in networks
    - Stochastic block models
    - Modularity and greedy modularity optimization
    - Community detection algorithms: Girvan-Newman and Infomap
7. Temporal networks
    - Temporal network representations and concepts
    - Deseasoning and temporal heterogeneity
    - Reachability and spreading in temporal networks
8. Motifs and Sampling
    - Network motifs and their interpretation
    - Sampling of networks based on measurement strategy
    - Sampling limitations due to data access
    - Sampling biases introduced by human behavior in online social networks
9. Advanced Topics (after the midterm)
    - Hierarchical networks: concepts, examples, measures
    - Core-periphery networks: concepts, examples, detection methods
    - Kumpula model of weighted network growth
    - Axelrod model of cultural dissemination
    - Schelling model of segregation and spatial dynamics

Network Dynamics and Biological Applications:

1. Agent-based modeling
    - Principles of agent-based modeling
    - Emergence of collective behavior from local interaction rules

2. Collective Motion and Flocking
    - Flocking models and self-organized motion
    - Adaptive communication networks among moving agents
    - Statistical measures characterizing collective states
3. State-Based and Stochastic Models
    - State machines and discrete-state dynamics
    - Disease spreading models (SIS, SIR-type frameworks)
    - Role of network structure in epidemic dynamics
4. Boolean and Discrete Network Models
    - Introduction to Boolean network dynamics
    - The Kauffman model of gene regulatory networks
    - Attractors, stability, and robustness in Boolean systems
5. Continuous Dynamical Models
    - Ordinary differential equation-based models
    - Coupled dynamical systems on networks
6. Biological Network Applications
    - Biology of transcription regulation
    - Network representations of gene regulatory systems
    - Circadian clocks as transcriptional oscillator networks
7. Regulatory Network Motifs
    - Functional network motifs in cellular regulation
    - Coherent and incoherent feed-forward loops
    - Dynamical roles of motifs in signal processing and control

Method of instruction:
Lectures, recitations, practical sessions, and project-based computer assignments

Homework:
Smaller homework assignments are given weekly on the practical sessions.

Tests:
A 90 minutes written test is taken at midterm, a mixture of test and programming.

Term projects:
After the midterm the students form small groups and pairs and complete a project of their choice related to the course. The projects are completed partially during the courses under the professors supervision and the main coding part home. There will be two presentations in the first one the students present their project idea with the proposed dataset and model, the second one it the final project presentation. The project makes up 40% of the final grade.

Optional Textbooks:

Albert-László Barabási: https://networksciencebook.com/

A. Barrat, M. Barthélemy, and A. Vespignani: *Dynamical Processes on Complex Networks*,(Cambridge UP, 2008)

Boccaletti, et al.: *Complex networks: structure and dynamics*, Phys. Rep. 424, 175-308;

M. E. J. Newman: *Networks: An Introduction* (Oxford UP, 2010)

Instructors' bio:

Andras Czirok (born 1973) is an associate professor of the Department of Biological Physics, Eötvös University. He obtained his Ph.D. in physics in 2000 at the same institution, where he studied biophysics and collective behaviour. He was a tenured associate professor of Cell Biology and Physiology at the University of Kansas Medical Center until his retirement in 2024. He published 100+ refereed journal articles. In 2022 Dr Czirok with his colleagues founded BioPhys-Concepts LLC, a startup commercializing various in vitro cell technologies.

János Török (born 1972) is an associate professor of the Department of Theoretical Physics, Budapest University of Technology and Economics. He received his Ph.D. in physics in 2000 jointly at the same institution and Université Paris-Sud. His major research topics are granular materials, rock fracture, opinion models, and social networks. He published more than 60 papers in refereed journals with an average of 30 citations per paper. He is a regular visitor of Aalto University, Finland and was twice awarded the Teaching Excellence prize.