Structure and Dynamics of Complex Networks

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Instructor(s):

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Short Description of the Course:
Complex systems consist of many interacting units and are characterized by nonlinearity, positive and negative feedback, and emergent cooperative phenomena. Examples are the brain, the cell, the internet, the economy etc. Recent developments in network science provide efficient tools to handle such systems. In the first part of the course we will present the basics of complex network theory, including small world and scale-free properties, important measures, spreading and breakdown phenomena, and weighted and directed graphs. In the second part examples will be analyzed from information technology, economy, sociology and biology. The course also contains a laboratory part, where network analytical skills can be acquired during hands-on interactive classes focusing on python scripting but also covering graphical network analysis tools. We also offer optional participation in network-related research projects.

Aim of the Course:
The aim of the course is to enable the enrolling students to acquire up-to-date knowledge of the basic principles, analytical and visualization tools of network topology and dynamics. The practical (laboratory) part of the course will enable students to construct networks from raw data-sets, to determine their properties (degree distribution, small worldness, clustering, etc.) and compare real networks to random network models, as well as utilize networks in simulations, like infection spreading and opinion dynamics. Both interactive tools and short python scripts are used to run experiments and investigate data during the lab sessions. The course will also enable students to apply their acquired network-related skills to a variety of real-world complex networks such as the Internet, social networks, networks of the economy 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.

Detailed Program and Class Schedule:

1. Introduction
    - Complex systems and complex networks
    - Major graph types, bipartite networks
    - Adjacency matrix, sparse and dense networks
2. Basic network characteristics
    - Node degree, clustering coefficient, distance and paths
    - The small word property
    - Centralities, components
3. Advanced network characteristics
    - Degree distribution
    - Scale-free networks and classical random graphs
    - Scale-free degree distribution and divergence
4.

Degree correlations
  - Assortative and disassortative networks
  - Full statistical description of degree correlations, Average Nearest Neighbors Degree, Pearson-correlation
5. Network models I.
   - The Erd?s-Rényi model
   - The Watts Strogatz small world network model
   - The Barabási-Albert model
6. Network models II.
   - Variations of the Barabási-Albert model: Holme-Kim model, fitness models
   - The configuration model
   - Network randomization
7. Robustness and spreading
   - Percolation transition in networks
   - Resilience of networks against random break down and intentional attack
   - Epidemic spreading on networks, SIS and SIR models, epidemic threshold
8. Motifs and communities
   - Network motifs, Feed Forward Loop, motif significance profile and z-score
   - Communities, hierarchical clustering, the Girvan-Newman algorithm
   - Modularity, modularity optimization, resolution limit
   - Overlapping communities, the Clique Percolation Method
9. Biological aspects of network analysis
   - Network hubs and modules in cellular changes, network cores, skeletons, backbones
   - Differences between changes in evolution and engineering
10. Dynamics of biological networks
    - Signal and noise in biological networks; topological phase transitions of biological and other networks
    - Changes of modular and core/periphery network topologies in stress and in environmental changes
    - Rigid and flexible network topologies and their transitions
11. Cellular networks
    - Protein structures: hot-spots, dynamics and evolution
    - Protein-protein interaction networks: hub and module dynamics in cellular changes
    - Signaling and gene regulatory networks
12. Networks of neurons and ecosystems
    - Network construction via reverse engineering and from correlations
    - Changes in brain default networks during aging and disease
    - Ecological networks: keystone species and prediction of ecosystem damage
13. Networks and drug design
    - Human disease and drug-target networks
    - Determination of drug binding sites in amino acid networks
    - Prediction of novel drug targets by network topology and dynamics

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

Homework:
Smaller homework assignments are given weekly on the practical sessions.
Download the homework assignments for 2012

Tests:

A 70 minutes written test is taken at midterm.
Download the test questions for 2012

Term projects:
A longer term project has to be fulfilled during the semester. The students can choose between simple projects (usually corresponding to numerical studies of one of the problems discussed in the course) and research projects (aimed at involving the student in ongoing network research). A short presentation summarizing the achieved results is expected on the last lecture of the course.
Download the project descriptions for 2012

Optional Textbooks:

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)

P. Csermely: *Weak Links: The Universal Key to the Stability of Networks and Complex Systems*, Springer (2009).

Instructors' bio:

Gergely Palla (born 1975) is a senior research associate at the Statistical and Biological Physics Research Group of the Hungarian Academy of Sciences (MTA). He received his Ph.D from the Eötvös University (ELTE) in 2002, the topic of his thesis was related to quantum chaos, semiclassical approximation and mesoscopic physics. His main field of interest concerns complex networks, with a special focus on topological phase transitions, community finding , the time evolution of communities and the studies of tagged networks. He has 37 publications in peer reviewed journals (including 2 papers in Nature), his independent citations are above 4000. During his scientific carrier he received the following prizes:Young Scientist Prize of the Hungarian Academy of Sciences (2006), Bolyai Scholarship (2008), Imre Bródi Award (2009) and Junior Prima Award (2009).

Daniel Abel (born 1983) obtained his degree in physics from Eötvös Lorand University, where he studied complex networks and collective behaviour. He is a cofounder of Maven Seven Ltd, a Hungarian startup company applying network science in sociometry, marketing and business, where he works on building tools and web interfaces in Java and Python for doing data analysis and visualization.