Spring 2022 Syllabus

Complex Networks

Prof. Dr. Dr. Frank Schweitzer
Chair of Systems Design
ETH Zurich
fschweitzer@ethz.ch

Lecture: Tuesday, 10:15–11:55 (V), ML E 12 Exercise: Tuesday, 09:15–10:00 (U), ML E 12

Exercises are predominantly programming assignments that can be solved using `python`*. Sample programs and code skeletons will be provided. During the exercise sessions, students are expected to present their solutions, which will then be discussed. Sample solutions are provided after the exercise session.*

1. Introduction to Networks: Basic and Advanced Metrics

Lecture 01 — Motivation *22.02.2022*

Educational Objective: In this lecture, participants will get an overview of the course and will learn the differences between an agent-based modeling and a complex networks perspective.

- Administrative issues and overview of the course
- Introduction: Agent-based modeling vs. a network approach
- Motivation: The role of network structures in complex systems
- Illustrative examples of complex networks in nature, society, economy and technology

Exercise 01: Introduction to `pathpy` *and* `python` *due 01.03.2022*

Lecture 02 — Introduction to Networks *01.03.2022*

Educational Objective: In this lecture, students will learn how to mathematically represent complex networks and how to quantitatively analyse the importance of nodes.

- Basic definitions: graph, network, adjacency matrix, path, cut, degree
- Importance of nodes: betweenness, closeness and degree centrality
- Modules and clusters: clustering coefficient and modularity
- Example: Open Source collaboration network

Exercise 02: Paths, Centralities, and Community Structure *due 08.03.2022*

2. Stochastic Models of Complex Networks

Lecture 03 — Clustering and Small-world networks *08.03.2022*

Educational Objective: In this lecture, participants will learn how to generate networks that reproduce the small diameter and large clustering coefficient observed in a number of real-world networks.

- Degree distribution and clustering coefficient
- Navigability and funnelling in small-world networks
- Watts-Strogatz model: average shortest path length and clustering coefficient

Exercise 03: Empirical Networks and Random Graphs *due 15.03.2022*

Lecture 04 — Ensemble Perspective on Complex Networks *15.03.2022*

Educational Objective: In this lecture, participants will learn how networks can be represented and analysed from a statistical point of view.

- Graph theory vs. network science: macro- vs. microscopic perspective
- Ensemble perspective of complex networks
- Random graph models: degree distribution, diameter and clustering coefficient of random network

Exercise 04: Random Graphs and Small World Networks *due 22.03.2022*

Lecture 05 — Generating Functions and the Friendship Paradox *22.03.2022*

Educational Objective: In this lecture, students will learn how to make statements about the properties of a network if we only know the distribution of node degrees. Furthermore, they learn how to specify network ensembles with fixed degree distributions.

- The generating functions framework
- Properties of generating functions
- Application to the friendship paradox

Exercise 05: Ensembles with fixed degree sequences and the Friendship Paradox due 29.03.2022

Lecture 06 — Generating Functions: the giant connected component *29.03.2022*

Educational Objective: In this lecture, participants will learn how the framework of generating functions can be applied to study the emergence of a giant connected component in complex networks with arbitrary degree distributions.

- Reminder: generating functions and complex networks
- friendship paradox and sampling biases
- emergence of a giant connected component
- the Molloy-Reed criterion

Exercise 06: Robustness and Scale Free Networks *due 05.04.2022*

Lecture 07 — Scale-Free Networks and Limitations of Ensemble Studies *05.04.2022*

Educational Objective: In this lecture, participants will learn what fallacies one encounters when applying findings from ensemble studies to real-world networks.

- Analyzing robustness with generating functions
- Robustness of Scale-free networks
- Limitations of ensemble-based approaches
- Example: AS-level Internet topology

Exercise 07: Limitations of Ensemble Studies *due 12.04.2022*

3. Dynamical Processes on Complex Networks

Lecture 08 — Random Walks and Diffusion in Complex Networks *12.04.2022*

Educational Objective: In this lecture, students will learn how we can model diffusion in complex networks by means of random walks.

- Dynamical processes in networks
- Diffusion processes in networks
- Random walks as model for diffusion processes
- Markov chain convergence theorem

Exercise 08: Simulating diffusion with `pathpy` *due 26.04.2022*

Easter break *19.04.2022*

Lecture 09 — Spectral Properties of Complex Networks *26.04.2022*

Educational Objective: In this lecture, students will learn how the influence of a network on diffusion processes is captured in the eigenvalues of matrix representations and how eigenvectors of these representations can be used to define feedback centrality measures.

- Stationary distributions of random walks
- Feedback centrality measures
- Diffusion speed in complex networks
- Eigenvalue gap of transition matrices

Exercise 09: Spectral analysis using `numpy` *and* `scipy` *due 03.05.2022*

4. Generative Models and Statistical Inference

Lecture 10 — Learning in Networks: Statistical Inference *03.05.2022*

Educational Objective: In this lecture, students will learn how the ensemble perspective on complex networks can be used to infer community structures in relational data.

- Statistical ensembles and statistical inference
- Maximum likelihood approach and stochastic models of networks
- Stochastic block model and community detection
- Minimum description length approach

Exercise 10: Inferring communities with `pathpy` *due 10.05.2022*

Lecture 11 — Learning in Networks: Model Selection *10.05.2022*

Educational Objective: n this lecture, students will learn how information-theoretic concepts can be used to avoid an overfitting of community structures.

- Motivation: overfitting and model selection
- Entropy of statistical ensembles
- Stochastic block model: minimising description length
- Flow compression: InfoMap

Exercise 11: Statistical inference with `pathpy` *due 17.05.2022*

5. Dynamic Networks

Lecture 12 — Time Series Data on Networks *17.05.2022*

Educational Objective: In this lecture, students will get an overview of limitations of network-based methods for the modeling of time-stamped and sequential relational data.

- Motivation: Limitations of the network perspective
- Network evolution and dynamical processes
- Temporal networks: Basics
- A novel perspective on temporal networks

Exercise 12: Time Series Network Data *due 24.05.2022*

. . . . . .

6. Finding Patterns in Network

. . . . . .

Lecture 13 — Structure formation in growing networks *24.05.2022*

Educational Objective: In this lecture, students will learn that feedback phenomena in the growth of networks can lead to the formation of broad degree distributions and complex structures.

- growth models for complex networks
- growth of random networks: uniform attachment
- feedback in network growth: preferential attachment
- preferential attachment and node fitness

Exercise 13: Simulating network growth models *due 31.05.2022*

. . . . . .

Lecture 14 — Knowledge Discovery with Network Ensembles *31.05.2022*

Educational Objective: In this lecture, students will learn how network ensembles can be used to model and analyze relational data on complex systems.

- Generative models of complex networks
- Exponential Random Graph Models
- Generalized Hypergeometric Ensemble of Random Graphs

. . . . . .

Session Examination

. . . . . .