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Network Science Institute
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NETS 7976: Directed Study
Network Reconstruction and
Inference from Dynamics

Spring 2024; 2 credits
Wednesday: 1:00-2:30pm
Jan 8 – Apr 26, 2024
177 Huntington, #1005

Summary

This class is an introduction to network reconstruction techniques using time series data. Using time series data derived from underlying network dynamics to reconstruct said networks is an open field of study combining network science, time series analysis, and statistics. The course will focus on the mathematical foundation behind multivariate time series analysis, information theory, and network dynamics and how each interplay to reconstruct networks. This course is especially relevant as networks are frequently presented using time series data, e.g., neuron's firing, stock price fluctuations, climate changes, etc., where each node has a time series which is affected by it's neighbors based on underlying network dynamics. Hence, there is an increasing need to understand how to use these time series to reconstruct the true network. Students will leave the class with an understanding of the tools used in multivariate time series analysis and have experience using these tools to reconstruct networks. This class is designed in collaboration with **Cory Glover**, a third-year PhD student in Network Science.

Coursework, Class Structure, Grading

The course adopts a flipped classroom concept: Students are exposed to the relevant material through pre-recorded video lectures, readings, and exercises that involve both analytic calculation and coding. The in-class hours are dedicated to recapitulation of the most important points, clarification of questions, as well as open discussion. The grading of the course is based on active participation in discussions and continual work on exercises. In a typical class students will summarize the main points of the lectures in their own words. The weekly exercises and questions, that students prepare prior to class, structure the in class discussion. Discussions will remain open and allow to explore topics deeper as needed.

Learning Objectives and Outcomes

By the end of this course students should have a deep familiarity with common used techniques of multivariate time series analysis and how to apply them to network reconstruction. In particular, they will develop an understanding of the strengths and pitfalls, similarities and dissimilarities of common multivariate analysis methods. They will learn how information theory and Bayesian statistics combine with these methods in order to reconstruct networks. Lastly, they will combine this knowledge with data to practice implementation of these approaches and explore how network topology and network dynamics influence the reconstruction of said networks. Students should leave the course able to reconstruct networks using multivariate time series data and have an understanding of the strengths and pitfalls of the methods chosen. This course will achieve these objectives while being:

- *Current*: Through the discussion of research papers and textbook chapters in the course, students should learn to identify concepts from multivariate time series analysis, information theory, and network science and recognize how they can be combined in order to reconstruct networks.
- *Practical*: The course will include implementing the methods learned and analyzing their performance when used for network reconstruction. It will also has mathematical exercises where applicable from the course reading in order to understand the derivation of said techniques.

- *Actionable*: The open structure of in-class discussion encourages students to explore the application of the course material to their own area of research as well as exploring open questions within the topic of network reconstruction.

Evaluation

The course evaluation is based on two components:

1. Active participation in the weekly meetings: This includes active participation in discussions through posing relevant questions, engaging in discussion around the assigned readings and presenting solved porblems, relevant code and any aditional exploratory research.
2. Completion and presentation of a final project: The project gives students a chance to show their ability to reconstruct networks from multivariate time series and exhibit deep understanding of the methods used. It can take the form of a research paper, literature review, etc.. The presentation of the results in the final week of the semester is part of the evaluation.

Materials

This course will primarily use current, published research papers as the readings for the course. These papers are categorized into (i) multivariate time-series analysis papers and (ii) network reconstruction papers. For the study of multivariate time-series analysis, we will use *Cliff, Oliver M., et al. "Unifying pairwise interactions in complex dynamics." Nature Computational Science 3.10 (2023): 883-893.* as a basis of study as it provides a framework unifying many techniques commonly used. For the topic of network reconstruction, we will learn reconstruction methods from both information theoretical and Bayesian statistic approaches. The informational theoretical readings will come from *An Introduction to Transfer Entropy* (2016) by Bossomaier et. al. as well as revelant papers. The Bayesian statistic approach will be taught from Tiago Peixoto's 2019 paper *Network Reconstruction and Community Detection from Dynamics*. Course materials can be found at `https://www.dropbox.com/scl/fo/b8mm9tiiz2se4ifq96wd0/h?rlkey=7areggqk1r9lgf4w9owwfebj1&dl=0`.

Instructor

Brennan Klein is an associate research scientist at the Network Science Institute, with a joint affiliation at the Institute for Experiential AI. He is the director of the Complexity & Society Lab. His research spans two broad topics: 1) Information, emergence, and inference in complex systems — developing tools and theory for characterizing dynamics, structure, and scale in networks, and 2) Public health and public safety — creating and analyzing large scale datasets that reveal inequalities in the United States, from epidemics to mass incarceration. Dr. Klein received a PhD in Network Science in 2020 from Northeastern University and got his BA in Cognitive Science & Psychology from Swarthmore College in 2014. Website: brennanklein.com.

Schedule

Week 1: January 8, 2024 – Course Introduction and Multivariate Time Series Analysis

- Primary reading: Cliff, Oliver M., et al. "Unifying pairwise interactions in complex dynamics." Nature Computational Science 3.10 (2023): 883-893.

- Supplementary reading: Klein, Brennan. "A consolidated framework for quantifying interaction dynamics." Nature Computational Science 3.10 (2023): 823-824.

Week 2: January 15, 2024 – Basic/Distance/Casual Time Series Analysis Methods

- Primary reading: Cliff, Oliver M., et al. "Unifying pairwise interactions in complex dynamics." Nature Computational Science 3.10 (2023): 883-893. Supp. 1.1-.3
- Primary reading: Associated references for methods defined in Supplement above.
  - Supplementary reading: Cliff, O. M. DynamicsAndNeuralSystems/pyspi (Zenodo, 2023); `https://doi.org/10.5281/zenodo.8223340`

Week 3: January 22, 2024 – Spectral and Misc. Approaches

- Primary reading: Cliff, Oliver M., et al. "Unifying pairwise interactions in complex dynamics." Nature Computational Science 3.10 (2023): 883-893. Supp. 1.5-.6
- Primary reading: Associated references for methods defined in Supplement above.
  - Supplementary reading: Cliff, O. M. DynamicsAndNeuralSystems/pyspi (Zenodo, 2023); `https://doi.org/10.5281/zenodo.8223340`

Week 4: January 29, 2024 – Information Theoretical Approaches

- Primary reading: Primary reading: Cliff, Oliver M., et al. "Unifying pairwise interactions in complex dynamics." Nature Computational Science 3.10 (2023): 883-893. Supp. 1.4
- Primary reading: Associated references for methods in Supplement above.
- Primary reading: *An Introduction to Transfer Entropy* Chap. 4.1-.2
  - Supplementary reading: `https://www.youtube.com/@JosephLizier`

Week 5: February 5, 2024 – Transfer Entropy and Granger Causality

- Primary reading: *An Introduction to Transfer Entropy* Chap. 4.3-.7
  - Supplementary reading: `https://www.youtube.com/@JosephLizier`

Week 6: February 12, 2024 – Reconstruction w/ Transfer Entropy & Granger Causality

- Primary reading: *An Introduction to Transfer Entropy* Chap. 7
- Primary reading: Novelli, Leonardo, et al. "Deriving pairwise transfer entropy from network structure and motifs." Proceedings of the Royal Society A 476.2236 (2020): 20190779.
- Primary reading: Borge-Holthoefer, Javier, et al. "The dynamics of information-driven coordination phenomena: A transfer entropy analysis." Science advances 2.4 (2016): e1501158.
  - Supplementary reading: Siggiridou, Elsa, et al. "Evaluation of Granger causality measures for constructing networks from multivariate time series." Entropy 21.11 (2019): 1080.

Week 7: February 19, 2024 – BK OUT OF TOWN, NO CLASS

Week 8: February 26, 2024 – Detecting Casuality for Network Reconstruction

- Primary reading: Sugihara, George, et al. ”Detecting causality in complex ecosystems.” science 338.6106 (2012): 496-500.
- Primary reading: Runge, Jakob, et al. ”Detecting and quantifying causal associations in large nonlinear time series datasets.” Science advances 5.11 (2019): eaau4996.
- Primary reading: Sun, Jie, Dane Taylor, and Erik M. Bollt. ”Causal network inference by optimal causation entropy.” SIAM Journal on Applied Dynamical Systems 14.1 (2015): 73-106.
  – Supplementary reading: Runge, Jakob. ”Causal network reconstruction from time series: From theoretical assumptions to practical estimation.” Chaos: An Interdisciplinary Journal of Nonlinear Science 28.7 (2018).

Week 9: March 4, 2024 – Spring Break – NO CLASS

Week 10: March 11, 2024 – Existing Packages for Reconstructing Networks

- Primary reading: Cliff, O. M. DynamicsAndNeuralSystems/pyspi (Zenodo, 2023); `https://doi.org/10.5281/zenodo.8223340`
- Primary reading: McCabe, Stefan, et al. ”netrd: A library for network reconstruction and graph distances.” arXiv preprint arXiv:2010.16019 (2020).

Week 11: March 18, 2024 – Bayesian Approach to Network Reconstruction

- Primary reading: Peixoto, Tiago P. ”Network reconstruction and community detection from dynamics.” Physical review letters 123.12 (2019): 128301.
  – Supplementary reading: Peixoto, Tiago P. ”Scalable network reconstruction in subquadratic time.” arXiv preprint arXiv:2401.01404 (2024).

Week 12: March 25, 2024 – Update on Final Project

- No readings. In lieu of readings there will be a presentation of current work accomplished towards final presentation.

Week 13: April 1, 2024 – Higher-Order Interactions

- Primary reading: Battiston, Federico, et al. ”The physics of higher-order interactions in complex systems.” Nature Physics 17.10 (2021): 1093-1098.
- Primary reading: Santoro, Andrea, et al. ”Higher-order organization of multivariate time series.” Nature Physics 19.2 (2023): 221-229.
  – Supplementary reading: Majhi, Soumen, Matjaž Perc, and Dibakar Ghosh. ”Dynamics on higher-order networks: A review.” Journal of the Royal Society Interface 19.188 (2022): 20220043.

Week 14: April 8, 2024 – Limitations and Applications of Network Reconstruction

- Primary reading: Angulo, Marco Tulio, et al. ”Fundamental limitations of network reconstruction from temporal data.” Journal of the Royal Society Interface 14.127 (2017): 20160966.
- Primary reading: Korhonen, Onerva, Massimiliano Zanin, and David Papo. ”Principles and open questions in functional brain network reconstruction.” Human Brain Mapping 42.11 (2021): 3680-3711.
- Primary reading: Faust, Karoline, et al. ”Signatures of ecological processes in microbial community time series.” Microbiome 6.1 (2018): 1-13.
  - Supplementary reading: Freilich, Mara A., et al. ”Reconstructing ecological networks with noisy dynamics.” Proceedings of the Royal Society A 476.2237 (2020): 20190739.
  - Supplementary reading: Fath, Brian D., et al. ”Ecological network analysis: network construction.” Ecological modelling 208.1 (2007): 49-55.

Week 15: April 15, 2024 – BK OUT OF TOWN, NO CLASS

Week 16: April 22, 2024 – Review week

- Final presentation due.
