SOE 17: Networks: From Topology to Dynamics (joint session SOE/DY)

Time: Wednesday 15:00–18:30 Location: TC 006

SOE 17.1 Wed 15:00 TC 006

Implicit models, latent compression, intrinsic biases, and cheap lunches in community detection in networks — •Tiago Peixoto — Central European University, Vienna, Austria

The task of community detection, which aims to partition a network into clusters of nodes to summarize its large-scale structure, has spawned the development of many competing algorithms with varying objectives. Some community detection methods are inferential, explicitly deriving the clustering objective through a probabilistic generative model, while other methods are descriptive, dividing a network according to an objective motivated by a particular application, making it challenging to compare these methods on the same scale. In this talk I present a solution to this problem that associates any community detection objective, inferential or descriptive, with its corresponding implicit network generative model. This allows us to compute the description length of a network and its partition under arbitrary objectives, providing a principled measure to compare the performance of different algorithms without the need for ground truth labels. Our approach also gives access to instances of the community detection problem that are optimal to any given algorithm, and in this way reveals intrinsic biases in popular descriptive methods, explaining their tendency to overfit. Using our framework, we compare a number of community detection methods on artificial networks, and on a corpus of over 500 structurally diverse empirical networks.

[1] Tiago P. Peixoto, Alec Kirkley, Phys. Rev. E 108, 024309 (2023)

SOE 17.2 Wed 15:15 TC 006

ESABO Co-Abundance Analysis: cases where the binarization threshold matters — •Devi Chandran and Jens Christian Claussen — School of Computer Science University of Birmingham, UK

Population dynamics including their complex interactions lead, in societies and microbial populations, to rich co-abundance patterns, and often only the (co)abundance pattern data is measured – whereby the precise interactions remain unknown. Here, ESABO [1] has been introduced to grasp interactions that remain unseen especially for low-abundant species. In [1], using ESABO we have recovered positive and negative interactions between agents (or species) within the population based on co-abundance data. However, in the medium abundance region, instead of a binarization threshold of 1, might it be worth to consider larger binarization thresholds? We investigate, based on two datasets, whether higher thresholds can lead to a higher information gain (in the sense of ESABO), and demonstrate cases of higher information gain for higher thresholds, but also confirm that the original threshold of 1 can be optimal for other datasets.

[1] J.C.Claussen at al., PlosCB (2017) 13(6): e1005361.

SOE 17.3 Wed 15:30 TC 006

Interplay of synchronization and cortical input in models of brain networks — •Eckehard Schöll[1,2,3] and Jakub Sawicki[2] — [1]Technische Universität Berlin — [2]Potsdam Institute for Climate Impact Research (PIK) — [3]Bernstein Center for Computational Neuroscience (BCCN) Berlin

It is well known that synchronization patterns and coherence have a major role in the functioning of brain networks, both in pathological and in healthy states. In particular, in the perception of sound, one can observe an increase in coherence between the global dynamics in the network and the auditory input. In this work, we show that synchronization scenarios are determined by a fine interplay between network topology, the location of the input, and frequencies of these cortical input signals [1]. To this end, we analyze the influence of an external stimulation in a network of FitzHugh-Nagumo oscillators with empirically measured structural connectivity, and discuss different areas of cortical stimulation, including the auditory cortex. [1] J. Sawicki and E. Schöll: Europhys. Lett. (2024), invited Perspective.

SOE 17.4 Wed 15:45 TC 006

Neuronal avalanches in weakly coupled FitzHugh-Nagumo oscillators — Max Contreras[1], Everton Medeiros[2], Igor Franović[3], and •Philipp Hövel[4] — [1]Technische Universität Berlin, Germany — [2]Carl von Ossietzky University Oldenburg, Germany — [3]University of Belgrade, Serbia — [4]Saarland University, Germany

The activity in the brain cortex remarkably shows a simultaneous presence of robust collective oscillations and neuronal avalanches, where intermittent bursts of pseudo-synchronous spiking are interspersed with long periods of quiescence. The mechanisms allowing for such coexistence are still a matter of an intensive debate. Here, we demonstrate that avalanche activity patterns can emerge in a rather simple model of an array of diffusively coupled neural oscillators with multiple timescale local dynamics in the vicinity of a canard transition. The avalanches coexist with the fully synchronous state where the units perform relaxation oscillations. We show that the mechanism behind the avalanches is based on an inhibitory effect of interactions, which may quench the spiking of units due to an interplay with the maximal canard. The avalanche activity bears certain heralds of criticality, including scale-invariant distributions of event sizes. Furthermore, the system shows increased sensitivity to perturbations, manifested as critical slowing down and reduced resilience.

Reference: Max Contreras, Everton S. Medeiros, Anna Zakharova, Philipp Hövel, and Igor Franović: *Scale-free avalanches in arrays of FitzHugh-Nagumo oscillators*, Chaos **33**, 093106 (2023).

SOE 17.5 Wed 16:00 TC 006

On the inadequacy of nominal assortativity for assessing homophily in networks — •Fariba Karimi[1] and Marcos Oliveira[2] — [1]Graz University of Technology — [2]Exeter University

Nominal assortativity (or discrete assortativity) is widely used to characterize group mixing patterns and homophily in networks, enabling researchers to analyze how groups interact with one another. Here we demonstrate that the measure presents severe shortcomings when applied to networks with unequal group sizes and asymmetric mixing. We characterize these shortcomings analytically and use synthetic and empirical networks to show that nominal assortativity fails to account for group imbalance and asymmetric group interactions, thereby producing an inaccurate characterization of mixing patterns. We propose the adjusted nominal assortativity and show that this adjustment recovers the expected assortativity in networks with various level of mixing. Furthermore, we propose an analytical method to assess asymmetric mixing by estimating the tendency of inter- and intra-group connectivities. Finally, we discuss how this approach enables uncovering hidden mixing patterns in real-world networks.

SOE 17.6 Wed 16:15 TC 006

Unveiling homophily beyond the pool of opportunities — •Sina Sajjadi[1,2], Samuel Martin-Gutierrez[1], and Fariba Karimi[1,3] — [1]Complexity Science Hub Vienna, Vienna, Austria — [2]Central European University, Vienna, Austria — [3]Graz University of Technology, Graz, Austria

We introduce a robust methodology for quantifying and inferring choice homophily, reflecting individuals' preferences for connecting with similar others beyond structural factors that determine the pool of opportunities. Our approach employs statistical network ensembles to estimate and standardize homophily measurements. We control for group size imbalances and activity disparities by counting the number of possible network configurations with a given number of inter-group links using combinatorics. Our framework is suitable for undirected and directed networks, and applicable in scenarios involving multiple groups. Tested on synthetic networks, our approach outperforms traditional metrics, accurately capturing generative homophily despite additional tie-formation mechanisms. Preferential attachment has no effect on our measure, and triadic closure's impact is minor, especially in homophilic scenarios. We apply our model to scientific collaboration and friendship networks, demonstrating its effectiveness in unveiling underlying gender homophily. Our method aligns with traditional metrics in networks with balanced populations, but we obtain different results when the group sizes are imbalanced. This finding highlights the importance of considering structural factors when measuring choice homophily in social networks.

15 min. break

SOE 17.7 Wed 16:45 TC 006

Nonequilibrium Nonlinear Dynamics I: Nonlinear Shift and Tipping — Julian Fleck[1], Moritz Thümler[1], Malte

Schröder[1], Seungjae Lee[1], and •Marc Timme[1,2] — [1]Center for Advancing Electronics Dresden (cfaed) and Institute for Theoretical Physics, Technische Universität Dresden, 01062 Dresden, Germany — [2]Lakeside Labs, 9020 Klagenfurt am Wörthersee, Austria

The collective nonlinear dynamics and reliable function of complex networked systems fundamentally underlie our daily lives, whether in biological cells, in power grids or in ecosystems. Most complex systems from the natural and engineering sciences are externally driven, and may exhibit intrinsically nonlinear state shifts or undergo tipping that disrupt the systems* intended or desired functionality. While state-of-the-art theoretical concepts and method development have focused on linear responses suitable for weak driving signals, it is far less understood how to characterize, predict and design complex systems responding to strong perturbations, that e.g., may ultimately lead to tipping. Here we report average response offsets that scale nonlinearly at asymptotically small amplitudes. At some critical driving amplitude, responses cease to stay close to a given operating point and may diverge. Standard response theory fails to predict these amplitudes even at arbitrarily high orders. We propose an integral self-consistency condition that captures the full nonlinear response dynamics. We illustrate our approach for a minimal one-dimensional model and capture the nonlinear shift of voltages in the response dynamics of AC power grid networks.

SOE 17.8 Wed 17:00 TC 006

Nonequilibrium Nonlinear Dynamics II: Strong Perturbations — •Julian Fleck, Moritz Thümler, Malte Schröder, Seungjae Lee, and Marc Timme — Institute for Theoretical Physics, Technische Universität Dresden, 01062 Dresden, Germany

Analytical studies of driven nonlinear dynamical systems often focus on linear response theory or extensions thereof in the asymptotic limit of small driving amplitudes. However, standard perturbation series are incapable of faithfully describing driving-induced system disruptions such as driving-induced tipping. In recent work (see part I: Nonlinear Shift and Tipping), we have proposed a self-consistency condition to estimate at which driving amplitudes non-equilibrium nonlinear system dynamics may tip. Here we propose to predict the tipping point by a large-perturbation expansion evaluated inside the self-consistency condition. We compare small-amplitude with the novel large-amplitude ansatz. The approach we propose may help to quantitatively predict intrinsically nonlinear response dynamics as well as bifurcations emerging at large driving amplitudes in non-autonomous dynamical systems.

SOE 17.9 Wed 17:15 TC 006

Transport networks with dynamical metric: when noise is advantageous — •Frederic Folz[1], Kurt Mehlhorn[2], and Giovanna Morigi[1] — [1]Theoretische Physik, Universität des Saarlandes, 66123 Saarbrücken, Germany — [2]Algorithms and Complexity Group, Max-Planck-Institut für Informatik, Saarland Informatics Campus, 66123 Saarbrücken, Germany

The interplay of nonlinear dynamics and noise is at the basis of coherent phenomena, such as stochastic resonance, synchronization, and noise-induced phase transitions. While the effect of noise in these phenomena has been partially analyzed, the impact of the specific form of the nonlinear dynamics on noise-induced phase transitions is unknown. In this work, we analyze transport on a noisy network where the nonlinearity enters through a dynamical metric, which depends nonlinearly on the local current. We determine network selforganization for different functional forms of the metric in a geometry of constraints simulating the network of metro stations of the city of Tokyo. We consider Gaussian noise and show that the resulting dynamics exhibits noise-induced resonances for a wide range of the model parameters, which manifest as selforganization into the most robust network with a resonant response to a finite value of the noise amplitude. We analyze in detail the specific features and perform a comparative assessment. Our study sheds light on the interplay between nonlinear dynamics and stochastic forces, highlighting the relevance of their mutual interplay in determining noise-induced coherence.

SOE 17.10 Wed 17:30 TC 006

Crossword puzzle percolation — •Alexander K. Hartmann — University of Oldenburg, Germany

Games are a popular subject, also for physicists. Many games have a lattice or network representation. A crossword puzzle consists of *black* (blocked) and *white* sites, the latter can be *empty* or *occupied* with letters. A word is *known* in the puzzle if a complete horizontal or vertical segment of white sites, usually between two black sites, is occupied (periodic boundary conditions are used, words may also take a full column or row).

Here the crossword puzzle is considered as percolation problem: Two known words are *connected* if they are perpendicular to each other and share one occupied site. A configuration is considered as *percolating* if there exists a path of connected words around the system, in either direction.

Numerical simulations for two-dimensional crosswords up to size 1000×1000 are performed. For uncorrelated occupation with probability p for the white sites, percolation transitions at critical thresholds p_c, depending on the fraction of black sites, are found. The results are analyzed by finite-size scaling and indicate that the problem is in the universality class of standard two-dimensional percolation. This changes, when the real game case is considered where full words are known with a probability $p_w(x)$ which depends on the fraction x of already known letters in the word, introducing correlations. The universality class depends on the shape of $p_w(x)$.

SOE 17.11 Wed 17:45 TC 006

Network percolation provides early warnings of abrupt changes in coupled oscillatory systems: An explanatory analysis — Noémie Ehstand[1], •Reik V. Donner[2,3], Cristóbal López[1], and Emilio Hernández-García[1] — [1]IFISC, Palma de Mallorca, Spain — [2]Magdeburg-Stendal University of Applied Sciences, Magdeburg, Germany — [3]Potsdam Institute for Climate Impact Research, Potsdam, Germany

Functional networks are powerful tools to study statistical interdependency structures in spatially extended or multivariable systems. In particular, percolation properties of correlation networks have been employed to identify early warning signals of critical transitions. Here, we further study the potential of percolation measures for the anticipation of different types of sudden shifts in the state of coupled irregularly oscillating systems. For a ring of diffusively coupled noisy FitzHugh-Nagumo oscillators that are nearly completely synchronized, the percolation-based precursors successfully provide very early warnings of the rapid switches between the two states of the system. We clarify the mechanisms behind the percolation transition by separating global trends given by the mean-field behavior from the synchronization of individual stochastic fluctuations. We then apply the same methodology to real-world data of sea surface temperature anomalies during different phases of the El Niño-Southern Oscillation. This leads to a better understanding of the factors that make percolation precursors effective as early warning indicators of incipient El Niño and La Niña events. [N. Ehstand et al., Phys. Rev. E, 108, 054207, 2023]

SOE 17.12 Wed 18:00 TC 006

Bond percolation and tree decompositions of real-world networks — •Konstantin Klemm — IFISC (CSIC-UIB), Palma de Mallorca, Spain

Percolation is a class of models with numerous applications in spreading processes including epidemics and social interactions. For most real-world and model-generated networks, percolation studies rely on Monte-Carlo sampling or approximate calculations such as (heterogeneous) mean-field. The present contribution introduces a method for exact numerical estimates of expected cluster sizes in bond percolation. The method is efficient on networks with a narrow tree-decomposition, a property shared by empirical networks of interest [Klemm, Journal of Physics: Complexity 1, 035003 (2020)]. Generalization of the approach to other processes in statistical physics are discussed [Klemm, arXiv:2111.04766].

SOE 17.13 Wed 18:15 TC 006

Between mechanisms and behaviors in higher-order systems — •Thomas Robiglio[1], Davide Coppes[2], Cosimo Agostinelli[2], Matteo Neri[3], Maxime Lucas[4], Federico Battiston[1], and Giovanni Petri[4,5] — [1]Department of Network and Data Science, Central European University, Vienna, Austria — [2]Department of Physics, University of Turin, Via Pietro Giuria 1, 10125 Turin, Italy — [3]Institut de Neurosciences de la Timone, Aix Marseille Université, UMR 7289 CNRS, 13005, Marseille, France — [4]CENTAI, Corso Inghilterra 3, 10138 Turin, Italy — [5]NPLab, Network Science Institute, Northeastern University London, London, UK

Mechanism and behavior are the two fundamental facets of the study of the dynamical properties of complex systems. Mechanism describes how a system is structured and what the microscopic rules governing its dynamic are while behavior accounts for its emergent properties.

Using tools from information theory, we systematically explore the relationship between higher-order (i.e. beyond pairwise) mechanisms and higher-order behaviors. Considering two dynamical models with group interactions -a simplicial Ising model and the simplicial model of social contagion- we find a region of the parameter space in which higher-order synergistic behaviors and group mechanisms co-occur.

We also apply higher-order information theoretical metrics to characterize the behavior of the stock market across time and show that we can identify periods of economic crisis that are overseen by the corresponding low-order metrics.