# DY 34: Nonlinear Dynamics, Synchronization, and Chaos

Time: Thursday 11:30–13:00 Location: H43

DY 34.1 Thu 11:30 H43

**Hierarchical Clustering in Mean-Field Coupled Stuart-Landau Oscillators** — •Nicolas Thomé and Katharina Krischer — Technische Universität München

Coupled oscillator networks are fundamental in many physics, chemistry, and biology fields, representing a captivating subject of study in nonlinear science. A persistent challenge is understanding the transition from a coherent synchronous solution to a completely incoherent one. This work explores this transition using globally coupled Stuart-Landau oscillators under mean-field interactions. We show that a cascade of codimension-2 points, coined Type-II cluster singularities, organizes the transition from two- to three-cluster solutions. These Type-II cluster singularities naturally induce a hierarchal structure to the clustering behavior and pave the way for the formation of chimera and incoherent solutions. Based on numerical bifurcation and Floquet multiplier analyses, our findings offer new insights into intermediate synchronization states and their role in complex oscillator systems.

DY 34.2 Thu 11:45 H43

**Synchronization in the Fully Disordered Kuramoto Model of Coupled Oscillators** — •Axel Prüser, Sebastian Rosmej, and Andreas Engel — Carl von Ossietzky University Oldenburg, Institut für Physik, D26111 Oldenburg, Germany

We investigate the dynamics of phase oscillators in fully disordered Kuramoto networks with defined degree of asymmetry. Both disordered couplings and disordered phases are considered. Employing the dynamical cavity method, the mean-field dynamics is reduced to a self-consistent stochastic single-oscillator problem which we analyze perturbatively and by numerical simulations. We elucidate the influence of the disorder characteristics on the correlation and response function of the system, together with their impact on the distribution of the order parameter. The mechanism of the so-called volcano transition and its relation to the existence of an oscillator glass phase is clarified.

DY 34.3 Thu 12:00 H43

**Training of neuromorphic systems based on coupled phase oscillators via equilibrium propagation: effects of network architecture** — •Qingshan Wang[1], Clara Wanjura[1], and Florian Marquardt[1,2] — [1]Max Planck Institute for the Science of Light, Staudtstrasse 2, Erlangen, Germany — [2]Department of Physics, University of Erlangen-Nuremberg, 91058 Erlangen, Germany

The increasing scale and resource demands of machine learning applications have driven research into developing more efficient learning machines that align more closely with the fundamental laws of physics. A key question in this field is whether both inference and training can exploit physical dynamics to achieve greater parallelism and acceleration. Equilibrium propagation, a learning mechanism for energy-based models, has shown promising results in physical systems with energy functions more complex than Hopfield-like models.

In this study, we focus on equilibrium propagation training of coupled phase oscillator systems. We investigate the influence of different experimentally feasible network architectures on the training performance. We analyze lattice structures, convolutional networks, and autoencoders, examining the effects of network size and other hyperparameters. Our findings lay the ground work for future experimental implementations of energy-based neuromorphic systems for machine learning, encompassing systems such as coupled laser arrays, CMOS oscillators, Josephson junction arrays, coupled mechanical oscillators, and magnetic systems

DY 34.4 Thu 12:15 H43

**Stability of Grid-Following Inverters Under Forced Oscillations and Sequential Load Switching** — •Benedikt Grüger and Florian Steinke — Technical University of Darmstadt, Darmstadt, Germany

The growing integration of renewable energy sources has led to a proliferation of inverter technologies in modern distribution grids. This shift introduces new dynamic stability challenges, particularly during periodic fluctuations in demand or generation caused by equipment malfunctions or cyber-physical attacks. Our work investigates the dynamic stability of grid-following inverters subjected to periodic grid voltage fluctuations. While forced oscillations in high-voltage grids have been widely studied, related research at the low-voltage level has primarily focused on bifurcations in inverter dynamics (e.g., Ma et al., 2020) or the impact of current limits (Zhang et al. 2024). However, the behavior of inverter-dominated distribution grids under forced oscillations remains largely unexplored. Our study employs a dynamic grid model that includes control mechanisms operating on time scales comparable to load switching, such as direct voltage control and phase-locked loop. This approach results in a fourth-order differential-algebraic system, akin to that proposed by Ma et al. (2023). We show that periodic grid voltage fluctuations can destabilize controllers, leading to inverter failures. By varying internal controller time scales, we identify different stability regimes and destabilizing effects are characterized. In sum, these findings highlight dynamic vulnerabilities in inverters and point out cyber-physical risks in inverter-dominated grids.

DY 34.5 Thu 12:30 H43

**Shrimp structure as a test bed for ordinal pattern measures** — Yong Zou[1], Norbert Marwan[2,3], Xiujing Han[4], •Reik V. Donner[2,5], and Jürgen Kurths[2] — [1]East China Normal University, Shanghai, China — [2]Potsdam Institute for Climate Impact Research, Potsdam, Germany — [3]University of Potsdam, Germany — [4]Jiangsu University, Zhenjiang, China — [5]Magdeburg-Stendal University of Applied Sciences, Magdeburg, Germany

Identifying complex periodic windows surrounded by chaos in the two or higher dimensional parameter space of certain dynamical systems is a challenging task for time series analysis. This holds particularly true for the case of shrimp structures, where different bifurcations occur when crossing different domain boundaries. Here we propose to use ordinal pattern transition networks (OPTN) to characterize shrimp structures. Our results demonstrate that among different ordinal characteristics, the OPTN out-link transition entropy exhibits better classification accuracy between chaotic and periodic time series than other existing measures like permutation entropy. This improved performance results from the fact that the transition behavior between ordinal patterns encodes additional dynamical information that is not captured by traditional ordinal measures that are solely based on pattern occurrence frequencies. Ultimately, the new OPTN based entropy measure also outperforms previously used measures based on recurrences in phase space.

DY 34.6 Thu 12:45 H43

**Designing Robust Edge Oscillations with Topological Protection in Nonlinear Coupled Systems** — •Sayantan Nag Chowdhury and Hildegard Meyer-Ortmanns — School of Science, Constructor University, 28759 Bremen, Germany

Topological protection, a powerful concept in physics, ensures robust states across quantum and classical systems. While topological insulators exemplify its applications in quantum systems with electric currents protected along the edges, an example from classical physics is provided by topoelectrical circuits with stable signal transduction. However, the role of topological protection in the context of classical oscillatory systems has been much less explored. Our study applies tools from band theory of condensed matter physics to systems with nonlinear dynamics to achieve robust edge oscillations. This means that oscillations are restricted to the edge of a two-dimensional grid, while those in the bulk settle into near-steady-state dynamics. This pattern is resilient to parameter mismatches, structural defects, and blockages. By calculating the Zak phase as topological characteristic for this phenomenon, we explain edge-localized oscillations through bulk-boundary correspondence. We further analyze the collective behavior by examining the limiting case of weak coupling strength in our directed network, which alternates between strong and weak values. We validate our findings for different prototypical oscillator models with possible applications in biochemical systems. Our findings establish a robust design for controlling the state of oscillation of units that are attached to a spatial grid.