DY 10: Nonlinear Dynamics, Synchronization and Chaos

Time: Monday 15:00–18:30 Location: BH-N 128

DY 10.1 Mon 15:00 BH-N 128

Biochemical pH oscillators in giant lipid vesicles — Arthur Straube[1,2], •Guillermo Olicón-Méndez[2], Maximilian Engel[3,2], Felix Höfling[2,1], and Stefanie Winkelmann[1] — [1]Zuse Institute Berlin — [2]Fachbereich Mathematik und Informatik, Freie Universität Berlin — [3]Korteweg-de Vries Institute, University of Amsterdam

We study pH oscillators confined to giant lipid vesicles serving as an open reactor [1]. In contrast to conventional pH oscillators in closed reactors, the exchange with the vesicle exterior periodically resets the pH clock that switches the system from acid to basic, resulting in self-sustained oscillations. We analyze the structure of the limit cycle, which controls the dynamics for giant vesicles and dominates the strongly stochastic oscillations in small vesicles of submicrometer size [2]. Based on an accurate reduced two-variable model [1], we further apply geometric singular perturbation theory [3] to rigorously analyze the structure underlying the limit cycle. Insights into the mechanism of pH oscillations for a single oscillator is crucial for rationalizing experiments and understanding communication of vesicles and synchronization of rhythms.

[1] A.V. Straube, S. Winkelmann, F. Höfling, J. Phys. Chem. B. 127, 2955 (2023). [2] A.V. Straube, S. Winkelmann, C. Schütte, F. Höfling, J. Phys. Chem. Lett. 12, 9888 (2021). [3] M. Engel, G. Olicón-Méndez, accepted by Contemp. Math. (preprint arXiv:2305.18021).

DY 10.2 Mon 15:15 BH-N 128

Artificial homeostatic temperature regulation via bio-inspired feedback mechanisms — Petro Feketa[1], Tom Birkoben[2], •Maximiliane Noll[2], Alexander Schaum[3], Thomas Meurer[4], and Hermann Kohlstedt[2,5] — [1]School of Mathematics and Statistics, Victoria University of Wellington, New Zealand — [2]Chair for Nanoelectronics, Kiel University, Germany — [3]Chair for Process Analytics, University Hohenheim, Stuttgart, Germany — [4]Digital Process Engineering Group, Institute for Mechanical Process Eng. and Mechanics, Karlsruhe Institute of Technology, Germany — [5]Kiel NanoSurface and Interface Science KiNSIS, Kiel University, Germany

Homeostasis enables living organisms to maintain robust functioning by adapting to a changing environment. An instance of homeostatic behavior is the thermoregulation in mammals where a stable internal temperature is kept. In this work we present an electronic realization of a temperature regulation based on a single-effector regulation system. The electronic system contains two thermosensitive neurons, a summation unit processing the spikes and a feedback loop which leads to heating or cooling of the neurons via a Peltier element. The spiking trains of thermosensitive neurons can be processed to stabilize an a priori unknown system-inherent set-point. As important parameters for the set-point the feedback control gain and the activity patterns of the thermosensitive artificial neurons are investigated.

DY 10.3 Mon 15:30 BH-N 128

A Sufficient Synchronization Criterion for Memristively Coupled FitzHugh-Nagumo Oscillators — •Jonas Röhrig[1], Robin Lautenbacher[2], Bakr Al Beattie[1], Karlheinz Ochs[1], and Ralf Köhl[2] — [1]Ruhr-University, Bochum, Germany — [2]Christian-Albrechts-University, Kiel, Germany

Moving towards computational hardware that mimics efficient computation schemes from biological nervous systems, oscillator networks are an abstraction level of biological neuronal nets that is of great interest to study. A key question in that regard is to understand the occurrence of synchronization in oscillator networks whose topology adapts over time. We study electrical implementations of such networks, consisting of FitzHugh-Nagumo oscillators (FNOs) and memristive couplings between them. The latter implement growth and learning of the network. For such networks, we propose a sufficient synchronization criterion. This criterion is formulated in terms of the connectivity of the coupling graph and the maximal absolute negative differential resistance of the FNOs nonlinearity such that it is readily applicable for practitioners. Wave digital emulations of memristively coupled FNO networks demonstrate the application of the criterion.

DY 10.4 Mon 15:45 BH-N 128

A Sensory Driven Adaptive Central Pattern Generator — •Jonas Röhrig, Sebastian Jenderny, Bakr Al Beattie, and Karlheinz Ochs — Ruhr-University, Bochum, Germany

Contributing to the ongoing effort to integrate our understanding of biological neuronal systems into the next generation of computational hardware, we propose an ideal electrical circuit to model a central pattern generator (CPG). A CPG is a fundamental neuronal circuit that can autonomously generate rhythmic muscle contractions that may be modulated by external inputs. Concretely, we consider a CPG that consists of inhibitorily coupled, alternatingly firing pacemaker neurons that are excitatorily coupled with motor neurons. As a technologically and biologically plausible neuron model we use the FitzHugh-Nagumo oscillator. We let some sources and components depend on a sensory signal to achieve varying oscillation frequencies and synchronization patterns. Moreover, we present a wave digital model of the proposed circuit that can be used to emulate the CPGs behavior, demonstrating switching between synchronization patterns and frequency changes.

DY 10.5 Mon 16:00 BH-N 128

Complex state space in high dimension - Impact on chimera dynamics? — •Seungjae Lee[1,2] and Katharina Krischer[2] — [1]Chair for Network Dynamics (cfaed) and Institute of Theoretical Physics, Technische Universität Dresden, Dresden, Germany — [2]Department of Physics, Technische Universität München, Garching bei München, Germany

Chimeras, states of coexisting coherence and incoherence, constitute intriguing collective dynamics of coupled oscillators and arise from symmetry-breaking. Past research focussed on systems of (Abelian) Kuramoto-Sakaguchi (KS) phase oscillators. Recent generalizations studied ensembles of higher-dimensional non-Abelian Kuramoto oscillators moving on the surface of a D-dimensional unit sphere, rather than being confined to a unit circle. Here, we discuss observable chimera dynamics in a system of higher-dimensional KS oscillators in two-population networks. Exploiting a generalized Watanabe-Strogatz transformation and the higher-dimensional Ott-Antonsen ansatz, we explore the macroscopic collective dynamics. For 2-dimensional complex spaces, we find diverse dynamics of the order parameter vectors, depending on the strength of intra-population coupling. We in particular observe both stationary and breathing chimeras. We furthermore show the transition of the chimera state into a component-wise aperiodic dynamics as the coupling strength weakens sufficiently. The emergence of aperiodic chimera dynamics is attributed to the breaking of conserved quantities that are preserved in trajectories of stationary, breathing, and alternating chimera states.

DY 10.6 Mon 16:15 BH-N 128

Emergence of limit cycle in Lindblad dynamics — •Shu Zhang[1], Shovan Dutta[1,2], and Masudul Haque[1,3] — [1]Max-Planck-Institut für Physik Komplexer Systeme, Dresden, Germany — [2]Raman Research Institute, Bangalore, India — [3]Technische Universität Dresden, Dresden, Germany

Among the most iconic features of classical nonlinear dynamics are persistent limit-cycle oscillations and critical slowing down at the onset of such oscillations, where the system relaxes purely algebraically in time. On the other hand, quantum systems subject to generic Markovian dissipation decohere exponentially in time, approaching a unique steady state. Here we show how coherent limit-cycle oscillations and algebraic decay can emerge in a quantum system governed by a Markovian master equation as one approaches the classical limit. We illustrate these general mechanisms using a single-spin model and a two-site lossy Bose-Hubbard model, contrasting with the scenario of a classical fixed point. In particular, we demonstrate that the fingerprint of a limit cycle is a slow-decaying branch with vanishing decoherence rates in the Liouville spectrum, while a power-law decay is realized by a spectral collapse at the bifurcation point.

DY 10.7 Mon 16:30 BH-N 128

The Dynamics of Future Power Grids - Bridging Theory and Application — •Anna Büttner and Jakob Niehues — Potsdam Institute for Climate Impact Research (PIK), 14412 Potsdam, Germany

Renewable energy sources such as wind turbines and solar cells are connected to the power grid via inverters. As we move towards a fully renewable grid, there is a growing need for so-called grid-forming inverters (GFIs) that can contribute to grid stability and synchronization. This shift presents a significant challenge as GFIs are a relatively new and complex technology, of which there is a limited practical and theoretical understanding. The so-called normal form of GFIs is a formulation that does not depend on the technology of the grid-forming actors and can be estimated from data.

In this talk, we show recent results from the validation of the normal form via system identification. The normal form can accurately model the dynamic behavior of a large class of GFIs. We present these results for lab measurements as well as complex simulation data.

We also show novel analytical results on the linear stability of the synchronous state of general power grid dynamics. Using the novel small-phase theorem we have shown that the stability can be analyzed in terms of a network component and the local dynamics, given by the normal form.

We are thus for the first time able to show stability results for validated power grids thereby bridging the gap between theoretical calculations and real-world application.

15 min. break

DY 10.8 Mon 17:00 BH-N 128

Chaos Control in Cardiac Dynamics: A novel approach to low-energy defibrillation — •Daniel Suth and Thomas Lilienkamp — Computational Physics for Life Science, Nuremberg Institute of Technology Georg Simon Ohm, Nuremberg, Germany

Various dynamical systems exhibit chaotic states with spiral wave-like patterns. Control schemes for chaotic patterns aim to terminate or synchronize such states, by applying a single or multiple stimuli to the system. One possible application is the use of multiple low-energy pulses to terminate ventricular and atrial fibrillation, with the advantage of avoiding negative side effects associated with singular high-energy defibrillation shocks.

This study demonstrates that sequences of well-timed stimuli provide high success rates at low amplitudes to terminate chaotic dynamics in numerical simulations of cardiac tissue. Therefore, we propose a simple and robust approach to calculate the pulse timings derived directly from simple characteristic features of the associated state variables.

We demonstrate this method using numerical simulations with four different 2D computational models of cardiac dynamics that vary in complexity and target species. Therefore, a detailed statistical analysis of the proposed approach, the results that can be achieved with it and a comparison with multiple existing methods is provided.

Furthermore, we investigate fundamental mechanisms of cardiac dynamic models that can be utilised to terminate chaotic states in such systems.

DY 10.9 Mon 17:15 BH-N 128

Pulse Optimization for Activation of Virtual Electrodes — •Justine Wolter[1,2], Ulrich Parlitz[1,2], and Stefan Luther[1,2,3] — [1]MPI for Dynamics and Self-Organization, Göttingen — [2]University Medical Center, Göttingen — [3]Deutsches Zentrum für Herz-Kreislauf-Forschung, Partner Site Niedersachsen, Göttingen, Germany

Cardiac arrhythmias represent one of the major causes of mortality worldwide. In case of cardiac arrhythmias, the normal heart beat is disturbed, affecting the heart's pumping function. Life-threatening cases such as ventricular fibrillation are commonly treated with a single high-energetic shock that causes traumatic pain, tissue damage and a worsening prognosis. Low-energy defibrillation techniques that apply a sequence of weak electrical pulses reduce the necessary energy while still being able to control the fibrillation. These methods use virtual electrodes which consist of heterogeneities in cardiac tissue acting as wave emitters in the presence of an external electrical field.

In this study, we present numerical simulations of two dimensional excitable media in a mono- and a bidomain model, showing the impact and dynamics of such virtual electrodes.

For different sizes of heterogeneities we find that by optimizing the pulse duration and form, the necessary energy for activation is significantly reduced. With our work, defibrillation protocols that apply sequences of weak, energetic electrical pulses can be further optimized. Therefore, we provide valuable insights for the further development of improved defibrillation techniques.

DY 10.10 Mon 17:30 BH-N 128

Toward Better Defibrillation through Genetic Optimisation — •Marcel Aron[1,2,3,4], Ulrich Parlitz[1,3,4], and Stefan Luther[2,1,3,4] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Institute of Pharmacology and Toxicology, University Medical Center Göttingen, Germany — [3]Institute for the Dynamics of Complex Systems, Georg-August-Universität Göttingen, Germany — [4]German Center for Cardiovascular Research (DZHK e.V., partner site Niedersachsen), Göttingen, Germany

Cardiac fibrillation results in the lethal, chaotic disruption of the heart's electricity-coordinated contraction mechanism. Its current standard treatment, defibrillation, may damage tissue and even lead to (e.g.) elevated fibrillation susceptibility long-term. This has motivated research into alternative, less intrusive (i.e. low-energy) defibrillation schemes beyond the usual singular, potent shock.

The search for better defibrillation schemes has proven difficult largely due to the sheer amount of possible shock sequences to consider. We sought to reduce the number of candidate low-energy shock sequences through the design and application of an optimisation heuristic inspired by evolutionary biology. To guide this heuristic, we consulted simplified defibrillation simulations.

This talk covers our quantification of "better" in the context of defibrillation schemes and an outline of our optimisation heuristic. We also show our findings in its application to optimising multi-shock defibrillation, including the discovery of a potentially global optimum.

DY 10.11 Mon 17:45 BH-N 128

Dynamics of transient chaos in excitable media — Melvin Dix[1,2], Paula Luttermann[1,2], Thomas Lilienkamp[3], Stefan Luther[1,2,4,5], and •Ulrich Parlitz[1,2,5] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Institute for the Dynamics of Complex Systems, Georg-August-Universität Göttingen, Germany — [3]Computational Physics for Life Science, Nuremberg Institute of Technology Georg Simon Ohm, Nuremberg, Germany — [4]Institute of Pharmacology and Toxicology, University Medical Center Göttingen, Göttingen, Germany — [5]German Center for Cardiovascular Research (DZHK e.V., partner site Niedersachsen), Göttingen, Germany

Chaotic spatio-temporal dynamics in excitable media such as cardiac tissue is often not permanent but limited in time. In this contribution, we discuss the influence of heterogeneities and stochastic perturbations on the mean lifetime of such chaotic transients. Using simulations with the Aliev-Panfilov and the Fenton-Karma model, we show that both forms of perturbationss can (significantly) prolong the duration of chaotic transients.

DY 10.12 Mon 18:00 BH-N 128

Patched patterns and emergence of chaotic interfaces: a new paradigm in coupled excitable systems — •Igor Franovic[1] and Sebastian Eydam[2] — [1]Institute of Physics Belgrade, Serbia — [2]RIKEN Center for Brain Science, Wako, Japan

While coherence-incoherence patterns have been extensively explored for coupled oscillators, much less is known about onset mechanisms and finite-size effects associated with such patterns in coupled excitable systems. Here we present a new class of patterns, called patched patterns, in non-locally coupled arrays of excitable units with attractive and repulsive interactions. Their self-organization involves the formation of patches, the spatial domains of units locked by their average spiking frequencies. Depending on the prevalence of attraction vs repulsion, patched patterns can be temporally periodic, quasiperiodic or chaotic, whereby in contrast to chimeras, chaos is not spatially localized. Chaotic patterns may develop interfaces where the units display a slow alternation between epochs of locking to adjacent patches and epochs of increased variability. We demonstrate typical bifurcation scenarios giving rise to chaos, showing that adapting the coupling range may change the character of the transition to chaos. Unlike chimeras, the maximal Lyapunov exponent for chaotic patched patterns converges to a finite value with system size. Nevertheless, interfaces may undergo an unpinning transition, which leads to diffusive motion similar to that of the incoherent part of chimeras.

Reference: I. Franović and S. R. Eydam, Chaos 32, 091102 (2022), https://doi.org/10.1063/5.0111507

DY 10.13 Mon 18:15 BH-N 128

Self-similar growth patterns in 2-dimensional von Neumann elementary cellular automata: a complete exploration of all outer-totalistic rules — •Kian Siadat and Jens Christian

Claussen — School of Computer Science, University of Birmingham, UK

Growth patterns of cellular automata emerging from a localized single seed initial condition have intrigued the nonlinear dynamics community through the identification of two universality (sub)classes within the Wolfram class IV cellular automata [1], where rule 90 (Sierpinski) and rule 150 are representatives of these classes. In this work, we perform an exhaustive exploration of all 2-dimensional cellular automata rules which in addition obey the criterion of outer-totalistic, i.e., the output depends on the number of active neighbour cells, but not about their spatial pattern. While being a subset of all possible 2-dim CA rules, this is the most central class of CA rules as they retain a maximum of symmetries. We identify several distinct time series related to the growth patterns, and beside the 1-dim and 2-dim versions of rule 90, we also identify a rule providing a triple replication, and generating a 2-dim spatial Sierpinski pattern.

Our findings indicate that despite the large number of possible cellular automata rules, we observe only a few self-similar growth patterns and associated time series.

[1] Nagler, J. Claussen, J. (2005) $1/f^\alpha$ spectra in elementary cellular automata and fractal signals, Phys. Rev. E 71, 067103 (2005)