WIAS Workshop
“Dynamics of Coupled Oscillator Systems”

Weierstrass Institute
for Applied Analysis and Stochastics
November 19 – 21, 2018

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Weierstraß-Institut für
Angewandte Analysis und Stochastik

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Dear Participant,

Welcome to the Weierstrass Institute for Applied Analysis and Stochastics in Berlin. We wish you a pleasant stay at the Institute and in Berlin. For your convenience, you can find more information below:

Entrance to the building will be provided showing your participants badge. Please make sure to wear it anytime you want to enter the building. Otherwise the porter won't let you access the building.

Lectures are given in the Erhard-Schmidt lecture room on the ground floor.

Poster session will be held in room 405/406 in the 4th floor. We provide snacks and drinks.

Smoking in the building is not allowed. As your coffee breaks take place on the ground floor, please use this opportunity to smoke outside of the building.

Computer facilities are provided for your use in the graphics room on the ground floor to the right-hand side coming from the doorkeeper's. Any workstation in this room may be used. For login, please enter the following:

User name	**dcos**	OK
Password	**dC=EKXK8**	OK

For logout, you can use the Log out -selection on the K-menu (left down corner).

Please be aware that this account is used by all workshop participants. Therefore, do not leave any confidential data in its home directory. All remaining files will be deleted after the workshop.

Additionally, there is the possibility to use a WiFi connection with your own laptop.
Please ask Laura Wartenberg for your personal WiFi card.

Lunch can be taken in a number of restaurants and snack bars near the institute, see the extra sheet "Places to have lunch".

Workshop dinner will be held in the restaurant MAXIMILIANS, FRIEDRICHSTR. 185–190, 10117 BERLIN on Tuesday November 20, 2018 at 6:30 p. m. The menu is covered by the conference fee, consisting of starter (salat or soup), main course, dessert and drinks.

Assistance in case of questions will be given by anybody of the WIAS staff participating in the workshop (wearing blue badges).

Yours sincerely,
Organizers

Monday, 19.11.2018

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09:00	**Arkady Pikovsky** Solitary synchronization waves in distributed oscillators populations
09:45	**Diego Pazó** Kuramoto model for excitation-inhibition-based oscillations
10:30 – 11:00	Coffee break
11:00	**Tiago Pereira** Frequency synchronisation induced by large delay
11:45	**Benjamin Lindner** Analysis of the asynchronous state in networks of randomly coupled oscillators
12:30 – 14:00	Lunch break
14:00	**Vladimir Klinshov** Pulse coupled oscillators: Routs to complex dynamics
14:45	**Oleksandr Burylko** Winner-take-all in a phase oscillator system with adaptation
15:15	**Michael Zaks** Is synchronization compatible with homoclinicity?
15:45 – 16:15	Coffee break
16:15	**Sindre Haugland** Cluster-halving cascades from intensive to extensive dynamics: Chimera states and fractensivity
16:45	**Sebastian Eydam** Bifurcations of mode-locked solutions
17:15	**Rico Berner** Multi-cluster structures in networks of adaptively coupled oscillators
18:00 – 20:00	**Poster session** Iva Bačić, Denis Goldobin, Aida Hajizadeh, Marcus Hauser, David Hering, Maria Mikhaylenko, Jakub Sawicki, Jan-Hendrik Schleimer, Isabelle Schneider, Nataliya Stankevich, Max Thiele, Matthias Wolfrum, Chunming Zheng

Tuesday, 20.11.2018

09:00	**Katharina Krischer** Emerging dynamics in globally coupled Stuart–Landau oscillators: Cluster singularities and symmetries of chimera states
09:45	**Oleh Omel'chenko** Traveling chimera states
10:30 – 11:00	Coffee break
11:00	**Igor Belykh** When three is a crowd: Chaos from clusters in networks of Kuramoto oscillators with inertia
11:45	**Simona Olmi** Ageing of chimera states
12:30 – 14:00	Lunch break
14:00	**Michael Rosenblum** Dynamical disentanglement approach to data analysis
14:45	**Rok Cestnik** Inferring the phase response curve from observation of a continuously perturbed oscillator
15:15	**Florian Spreckelsen** Synchronization of viscoelastically coupled excitable oscillators
15:45 – 16:15	Coffee break
16:15	**Janina Hesse** Symmetry-breaking of phase susceptibility enhances synchronization in coupled neural oscillators
16:45	**Robert Ronge** Clustering in systems of repulsively coupled Morris–Lecar neurons
17:15	**Jan Totz** Synchronization transitions in a large network of chemical oscillators
18:30	Workshop Dinner

Wednesday, 21.11.2018

09:00	**Oleksandr Popovych** Adaptive delivery of continuous and delayed feedback deep brain stimulation
09:45	**Igor Franović** Switching dynamics in two adaptively coupled excitable systems
10:30 – 11:00	Coffee break
11:00	**Thomas Lilienkamp** Features of transient chaos in coupled oscillators and extended systems
11:45	**Lutz Schimansky-Geier** Coupled stochastic active particles
12:30	**Anna Zakharova** Coherence resonance in multiplex neural networks
13:00 – 13:10	Closing

Inverse stochastic resonance in a system of active rotators with adaptive coupling

Iva Bačić

Institute of Physics Belgrade

Inverse stochastic resonance is a phenomenon where an oscillating system shows a nonlinear response to noise, displaying a minimal oscillation frequency at an intermediate noise level. Such an effect has been indicated to play important functional roles in neuronal systems, contributing to reduction of spiking frequency in the absence of neuromodulators or to triggering of the on-off tonic spiking activity. We demonstrate a novel generic scenario for such an effect in a multi-timescale system, considering the example of emergent oscillations in two adaptively coupled active rotators with excitable local dynamics. The fast-slow analysis we carry out indicates that the plasticity plays a facilitatory role by guiding the fast-flow dynamics to parameter domains where the stable equilibria change character from nodes to focuses, which ultimately enhances the influence of noise. The described scenario persists for different plasticity rules, underlying its robustness in light of potential application to neuronal systems.

When three is a crowd: Chaos from clusters in networks of Kuramoto oscillators with inertia

Igor Belykh

Department of Mathematics & Statistics and Neuroscience Institute, Georgia State University

In this talk, we discuss the emergence and co-existence of stable patterns of synchrony in two- and three-population networks of identical Kuramoto oscillators with inertia. The populations have different sizes and can split into clusters where the oscillators synchronize within a cluster while there is a phase shift between the dynamics of the clusters. Due to the presence of inertia, which increases the dimensionality of the oscillator dynamics, this phase shift can oscillate periodically or chaotically, inducing a chaotically breathing cluster pattern. We derive analytical conditions for the co-existence of stable patterns with constant and oscillating phase shifts in two- and three-population networks. We demonstrate that the multistable, and possibly, chaotic dynamics of the phase shifts in the three-population network is governed by two coupled driven pendulum equations. We also discuss the implications of our stability results to the stability of chimeras.

Multi-cluster structures in networks of adaptively coupled oscillators

Rico Berner

Technische Universität Berlin

Dynamical systems on networks with adaptive couplings appear naturally in real-world systems such as power grid networks, social networks as well as neuronal networks. We investigate collective behaviour in a paradigmatic network of adaptively coupled phase oscillators. The coupling topology of the network changes slowly depending on the dynamics of the oscillators. We show that such a system gives rise to numerous complex dynamics, including relative equilibria and hierarchical multi-cluster states. An analytic treatment for equilibria and multi-cluster solutions as well as the existence of continuous families of these states is presented and parameter regimes of high multi-stability are found. In addition, we give an interpretation for equilibria as functional units which are building blocks in multi-cluster structures. Our results contribute to the understanding of mechanisms for pattern formation in adaptive networks, such as the emergence of multi-layer structure in neural systems.

Winner-take-all in a phase oscillator system with adaptation

Oleksandr Burylko

Institute of Mathematics of National Academy of Sciences of Ukraine

We consider a system of generalized phase oscillators with a central element and radial connections. In contrast to conventional phase oscillators of the Kuramoto type, the dynamic variables in our system include not only the phase of each oscillator but also the natural frequency of the central oscillator, and the connection strengths from the peripheral oscillators to the central oscillator. With appropriate parameter values the system demonstrates winner-take-all behavior in terms of the competition between peripheral oscillators for the synchronization with the central oscillator. Conditions for the winner-take-all regime are derived for stationary and non-stationary types of system dynamics. Bifurcation analysis of the transition from stationary to non-stationary winner-take-all dynamics is presented. A new bifurcation type called a Saddle Node on Invariant Torus (SNIT) bifurcation was observed and is described in detail. Computer simulations of the system allow an optimal choice of parameters for winner-take-all implementation.

Inferring the phase response curve from observation of a continuously perturbed oscillator

Rok Cestnik

Universität Potsdam

Phase response curves are important for analysis and modeling of oscillatory dynamics in various applications, particularly in neuroscience. Standard experimental technique for determining them requires isolation of the system and application of a specifically designed input. However, isolation is not always feasible and we are compelled to observe the system in its natural environment under free-running conditions. To that end we propose an approach relying only on passive observations of the system and its input. We illustrate it with simulation results of an oscillator driven by a stochastic force.

Bifurcations of mode-locked solutions

Sebastian Eydam

WIAS Berlin

We investigate the dynamics of a Kuramoto-type system of globally coupled phase oscillators with equidistant natural frequencies and a coupling strength below the synchronization threshold. In such cases one can observe a stable regime of sharp pulses in the mean-field amplitude which is also known as mode locking. We discuss the emergence of this particular type of solution as well as the typical bifurcation scenarios that are found along their stability boundaries. In large ensembles, where the natural frequencies follow a multi-modal distribution, mode-locked solutions are observed and the breakup of the pulsation due to the broadening of the modal width is explored.

Switching dynamics in two adaptively coupled excitable systems

Igor Franović

Institute of Physics Belgrade

We consider slow stochastic fluctuations in a system of two adaptively coupled active rotators with excitable intrinsic dynamics. Depending on the adaptation rate, the interplay of plasticity and noise is demonstrated to give rise to two qualitatively different types of switching behavior. For slower adaptation, one finds alternation between the two modes of noise-induced oscillations, distinguished by the different order of successive spiking of the two units. For intermediate adaptation rates, the deterministic dynamics involves multistability between the stationary and oscillatory regimes. In presence noise, the phases then exhibit a bursting-like behavior, mediated by switching between the metastable states associated to coexisting attractors of the deterministic system. Once the switching dynamics for intermediate adaptation rates becomes strongly biased toward the stationary states, one observes the effect of inverse stochastic resonance, where the oscillation frequency displays a non-linear dependence on noise, characterized by a minimum at a preferred noise level. Applying the fast-slow analysis and the averaging approach, we analyze the mechanisms behind the two types of switching dynamics and explain the scenario by which plasticity enhances the effect of inverse stochastic resonance.

Collective mode reductions for populations of coupled noisy oscillators

Denis Goldobin

Institute of Continuous Media Mechanics, Ural Branch of RAS

Synchrony of large ensembles of coupled elements can be characterised by the order parameters—the mean fields. Quite often the evolution of these collective variables is surprisingly simple, which makes a description with only a few order parameters feasible. Thus, one tries to construct accurate closed low-dimensional mathematical models for the dynamics of the first few order parameters. These models represent useful tools for gaining insight into the underlaying mechanisms of some more sophisticated collective phenomena: for example, one describes coupled populations by virtue of coupled equations for the relevant order parameters. A regular approach to the construction of closed low-dimensional systems is also beneficial for dealing with phenomena, which are beyond the applicability scope of these models; for instance, with such an approach, one can determine constrains on clustering in populations. There are two prominent types of situations, where the low-dimensional models can be constructed:
(i) for a certain class of ideal paradigmatic systems of coupled phase oscillators, the Ott–Antonsen ansatz yields an exact equation for the main order parameter [E. Ott, T.M. Antonsen, Chaos **18**, 037113 (2008)];
(ii) the Gaussian approximation for the probability density of the phases, also yielding a low-dimensional closure, is frequently quite accurate (e.g., see [K.M. Hannay, D.B. Forger, V. Booth, Sci. Adv. **4**, e1701047 (2018)]).
In this work, we compare applications of these two model reductions for situations, where neither of them is perfectly accurate. Furthermore, on the basis of the recently suggested "circular cumulant" approach [I.V. Tyulkina *et al.*, Phys. Rev. Lett. **120**, 264101 (2018)], we construct a new reduction approach [D.S. Goldobin *et al.*, Chaos **28**, 101101 (2018)] which practically works as a first-order correction to the best of the two basic approximations.

The work was supported by Russian Science Foundation (Grant Nr. 14-21-00090).

Frequency repulsion for a general class of limit-cycle oscillators synchronized by common noise in the presence of desynchronizing global coupling

Denis Goldobin, Anastasiya V. Dolmatova

Institute of Continuous Media Mechanics, Ural Branch of RAS

We construct an analytical theory of interplay between synchronizing effects by common noise and by global coupling for a general class of smooth limit-cycle oscillators. Both the cases of attractive and repulsive coupling are considered. The derivation is performed within the framework of the phase reduction, which fully accounts for the amplitude degrees of freedom. Firstly, we consider the case of identical oscillators subject to intrinsic noise, obtain the synchronization condition, and find that the distribution of phase deviations always possesses lower-law heavy tails. Secondly, we consider the case of nonidentical oscillators. For the average oscillator frequency as a function of the natural frequency mismatch, limiting scaling laws are derived; these laws exhibit the nontrivial phenomenon of frequency repulsion accompanying synchronization under negative coupling. The analytical theory is illustrated with examples of Van der Pol and Van der Pol–Duffing oscillators and the neuron-like FitzHugh–Nagumo system; the results are also underpinned by the direct numerical simulation for ensembles of these oscillators. The work was supported by the Russian Science Foundation (Grant No. 14-21-00090).

Auditory event-related fields emerging from the network structure of the auditory cortex

Aida Hajizadeh[1], **Artur Matysiak**[1], **Asim H. Dar**[1], **Nina Härtwich**[1], **Patrick May**[1,2], **Reinhard König**[1]

[1] *Leibniz Institute for Neurobiology, Magdeburg*
[2] *Lancaster University*

Auditory stimuli evoke a series of peaks and troughs in the event-related fields (ERF) of the magnetoencephalogram (MEG). These deflections reflect not only stimulus properties but also the subject-specific cortical topogra- phy. While the general biophysics of the generation of the MEG signal is well understood, what the ERF represents has remained obscure. The com- mon view suggests that the ERF waveform is a linear combination of the activity of spatially distributed generators in the brain. However, this view might just reflect the limitations of current imaging techniques rather than the actual state of affairs. Here, we introduce a computational model of the auditory cortex (AC) which addresses this issue. Our starting point is an already existing nonlinear model which is based on the anatomical core-belt-parabelt structure of the AC. The computational unit is a simpli- fied description of the cortical column comprising one excitatory and one inhibitory cell population, each characterized by a mean spiking rate. The dynamics of the model are described by two sets of 240 coupled non-linear differential equations. We developed analytical solutions for this system by linearizing the equation for the spiking rate and by introducing symmetric connections between the columns. The latter allowed us to simultaneously diagonalize the matrices determining the decay constant and angular fre- quency. Our analytical model captures the dynamics of the AC in terms of uncoupled damped harmonic oscillators (normal modes). In this view, ERFs are characterized by coupling of normal modes, whereby each depending di- rectly on the entire set of connection pattern and connection strength of the system. The novelty of our approach is that ERFs are no longer determined by discrete response generators in the AC but, rather, the ERF emerges as a network property of the entire AC. Acknowledgment: DFG: HE1721/10-1 & 10-2; SFB-TRR 31. Ruropean Union's Horizon 2020 research and innovation programme (grant agreement 763959).

Cluster-halving cascades from intensive to extensive dynamics: Chimera states and fractensivity

Sindre Haugland

Nonequilibrium Chemical Physics, Technische Universität München

An ensemble of globally coupled oscillators can exhibit both intensive dynamics, whose dimensionality is independent of the overall dimensionality of the system, and extensive dynamics, whose dimensionality grow linearly with the system size. A stable two-cluster state is an example of the former, while a state of only incoherent oscillators is an example of the latter. In a system exhibiting both kinds of dynamics for different parameter values, the transition between the two can either take place in a single bifurcation transversal to the two-cluster manifold or through a greater number of steps. Here, we study the latter case in an ensemble of Stuart-Landau oscillators with nonlinear global coupling, where a periodic two-cluster state, stable for any ensemble size, transitions towards a fully incoherent state in a cascade of cluster-halving period-doubling bifurcations as a control parameter is varied. Inspired by the concept of information entropy, we develop a measure for quantifying he relative disorder of the intermediate states.

Partial synchronisation in yeast cell populations

Marcus Hauser

Institute of Physics, Otto-von-Gurricke-Universität Magdeburg

The mechanism of the transition between synchronized and desynchronized behaviour of intact yeast cells of the strain Saccharomyces carlsbergenis was investigated. In cell colonies of intermediate cell density, all cells remain oscillatory, in addition, a partially synchronized and a desynchronized state are accessible for experimental studies. In the partially synchronized state, the mean oscillatory period is shorter than that of the cells in a desynchronized state. This implies that synhronisation occurs due to entrainment to the cells that oscillate more rapidly. This is typical for synchronisation due to phase advancement. However, the cells do not synchronize completely, as the distribution of the oscillatory frequencies only narrows but does not collapse to a single frequency. The desynchronisation is characterized by a broadening of the distribution of oscillation frequencies of the cells. Chimera states, i.e., the coexistence of a synchronized and a desynchronized parts of the population, could not be observed.

Application of equivariant Pyragas control to networks of chemical oscillators

David Hering

Technische Universität Berlin, Institut für theoretische Physik

Networks of coupled oscillators can exhibit various types of spatio-temporal patterns. Here we investigate networks of locally coupled chemical BZ-oscillators and subject them to equivariant Pyragas control and a variant of the well-known time-delayed feedback scheme which also takes the desired spatio-temporal pattern into account. Without control, we observe synchronization. With control, we can explicitly target, select and stabilize spatio-temporal patterns. The control will be implemented into an experimental set-up of coupled BZ-oscillators.

Symmetry-breaking of phase susceptibility enhances synchronization in coupled neural oscillators

Janina Hesse

Institute for Theoretical Biology, Humboldt-Universität zu Berlin

We investigate the ability of coupled oscillator systems to dynamically synchronize and desynchronize depending on single-unit properties. Our focus lies on the nervous system, where synchronization can have both negative and positive effects, from memory networks to pathophysiology [1][2].

A large set of neuron models (called type I) switch their spike onset bifurcation from a SNIC bifurcation to a HOMoclinic orbit bifurcation in response to an increase in temperature. This happens at the codimension-2 saddle-node loop (SNL) bifurcation [3]. The present work shows that the SNL bifurcation induces a symmetry breaking in the phase susceptibility of a single neuron with drastic consequences for network dynamics. Around the bifurcation, even small variations in relevant parameters substantially change the neuron's synchronization ability.

Network simulations with inhibitory coupling lead to an increase in classical in-phase synchronization when passing the SNL point. A population of conductance-based neuron models, when weakly coupled with excitatory synapses, increases in phase synchronization. In this case, the network enters a splay state, where the different neurons' phases are equally distributed. In summary, internal, single cell parameters can substantially change network properties.

References:

[1] N. Axmacher, F. Mormann, G. Fernández, C. E. Elger, and J. Fell. Memory formation by neuronal synchronization, *Brain Research Reviews* 52 pp. 170-182, 2006.

[2] P. J. Uhlhaas, and W. Singer. Neural Synchrony in Brain Disorders: Relevance for Cognitive Dysfunctions and Pathophysiology, *Neuron*, 52 (1), pp. 155-168, 2006.

[3] J. Hesse, J.-H. Schleimer, and S. Schreiber. Qualitative changes in phase-response curve and synchronization at the saddle-node loop bifurcation, *Physical Reviews E*, 95(5):052203, 2018.

Pulse coupled oscillators: Routs to complex dynamics

Vladimir Klinshov

Institute of Applied Physics, Nizhny Novgorod

I will present analytic results on the dynamics of pulse coupled oscillators with delayed coupling. In such systems the basic and simplest regime is periodic emission of pulses, the so-called regular spiking. Due to the interaction between the units this regime may destabilize and give rise to more complex activity patterns characterized by time-varying inter-spike intervals. I will derive the conditions for the regular spiking destabilization and describe the scenarios of the complex dynamics emergence. The work is supported by the Russian Foundation for Basic Research under Project No. 17-02-00904.

Emerging dynamics in globally coupled Stuart–Landau oscillators: Cluster singularities and symmetries of chimera states

Katharina Krischer

Technische Universität München, Physik-Department

Globally coupled Stuart-Landau oscillators are a generic model system for the study of collective behavior in oscillatory systems beyond the weak coupling limit. In this talk we will address two fundamental questions concerning emergent behavior in globally coupled oscillatory networks: 1) How is clustering behavior in minimal networks linked to clustering dynamics in large ensembles of oscillators. 2) Which symmetries are realized in states with partially broken symmetry, also called chimera states. In both cases, we start out by considering a minimal system of four globally coupled Stuart-Landau oscillators. To answer the first question, we elaborate how 2-cluster states crowd when increasing the number of oscillators. Furthermore, using persistence, we discuss how this crowding leads to a continuous transition from balanced cluster states to synchronized solutions via the intermediate unbalanced 2-cluster states. These cascade-like transitions emerge from what we call cluster singularities. As for the second question, we demonstrate that when the four mean-coupled Stuart-Landau oscillators form states with partially broken symmetry, states with different set-wise symmetries in the incoherent oscillators may arise, some of which are and some are not invariant under a permutation symmetry on average. We conclude our report with a discussion of how the results apply to spatially extended systems.

Features of transient chaos in coupled oscillators and extended systems

Thomas Lilienkamp

Universitätsmedizin Göttingen, Max Planck Institute for Dynamics and Self-Organization

Many (high dimensional) dynamical systems, including networks of oscillators and excitable media, exhibit chaotic dynamics which is not persistent but transient. For extended systems the length of the transient typically grows exponentially with the system size (supertransients) and for a large class of systems the chaotic phase terminates abruptly, without any obvious precursors in commonly used observables. By probing the state space using perturbed trajectories we show the existence of a terminal transient phase, which occurs prior to the abrupt collapse of chaotic dynamics [1,2]. During this phase the impact of perturbations is significantly different from the earlier transient and particular patterns of (non)susceptible regions in state space occur close to the chaotic trajectories. We therefore hypothesize that even without perturbations proper precursors for the collapse of chaotic transients exist, which might be highly relevant for coping with spatiotemporal chaos in cardiac arrhythmias or brain functionality, for example.

References:

[1] T. Lilienkamp and U. Parlitz, Phys. Rev. Lett. 120, 094101 (2018)

[2] T. Lilienkamp and U. Parlitz, Phys. Rev. E 98, 022215 (2018)

Analysis of the asynchronous state in networks of randomly coupled oscillators

Benjamin Lindner

Humboldt-Universität zu Berlin, Institute of Physics, Bernstein Center for Computational Neuroscience Berlin

Although many studies of coupled oscillators have focussed on their synchronization, some systems of interest (the neural networks in the brain) remarkably show an asynchronous activity with nontrivial temporal correlations. The corresponding correlation functions are determined by a self-consistency condition. As I will discuss in my talk, in some cases (rotator network with random coupling coefficients) this self-consistency condition leads us to an explicit differential equation for the correlation function, in others (e.g. networks of spiking neurons) to an iterative scheme for the determination of power spectra.

Weak multiplexing in neural networks: Switching between chimera and solitary states

Maria Mikhaylenko

Institut für Theoretische Physik, Technische Universität Berlin, ITMO University, St.Petersburg

Using the model of a FitzHugh-Nagumo system in the oscillatory regime, we study spatio-temporal patterns occurring in a two-layer multiplex network, where each layer is represented by a non-locally coupled ring [1]. We show that weak multiplexing, i.e., when the coupling between the layers is smaller than that within the layers, can have a significant impact on the dynamics of the neural network. We develop control strategies based on weak multiplexing and demonstrate how the desired state in one layer can be achieved without manipulating its parameters, but only by adjusting the other layer. We find that for coupling range mismatch weak multiplexing leads to the appearance of chimera states with different shapes of the mean velocity profile for parameter ranges where they do not exist in isolation. Moreover, we show that introducing a coupling strength mismatch between the layers can suppress chimera states with one incoherent domain (one-headed chimeras) and induce various other regimes such as in-phase synchronization or two-headed chimeras. Interestingly, small intra-layer coupling strength mismatch allows to achieve solitary states throughout the whole network.

References:

[1] M. Mikhailenko, L. Ramlow, S. Jalan and A. Zakharova, Weak multiplexing in neural networks: Switching between chimera and solitary states, arXiv:1809.07148 (2018)

Ageing of chimera states

Simona Olmi

Inria Sophia Antipolis Mediterranee Research Centre, MathNeuro Team

We consider a network of identical Kuramoto oscillators with inertia, subject to global mean field coupling. Depending on the phase-shift value we observe a transition from synchronized state to cluster synchronization and finally to chimera states. In particular, chimera states are formed by a coherent part, i.e. a stable cluster of oscillators frequency synchronized, plus an incoherent part, i.e. a free cloud of oscillators with different average frequencies. Numerical simulations have shown that such chimera states are transient phenomena subjected to ageing evolution. During this evolutionary process we can observe many small clusters forming, exchanging oscillators, breaking up and reforming in addition to the stable cluster of oscillators that is still present. The formation of short-lived minor clusters induces instability in the main cluster that tends to absorb other oscillators until the chimera state collapses in a cluster synchronized state with few solitary asynchronous oscillators still present. This novel phenomenon of reconfiguration and ageing of chimera states strongly depends on system size and initial conditions.

Traveling chimera states

Oleh Omel'chenko

Universität Potsdam, Institute of Physics and Astronomy

In this talk we will describe recent work on traveling chimera states in a one-dimensional ring of nonlocally coupled phase oscillators. In the continuum limit such chimera states appear as traveling wave solutions of the corresponding Ott-Antonsen equation. We will derive asymptotic formulas for slowly moving chimera states and show how to perform numerical continuation of such solutions and analyze their stability. Finally, we will outline some unsolved mathematical problems concerned with the analysis of non-stationary chimera states.

Kuramoto model for excitation-inhibition-based oscillations

Diego Pazó

Instituto de Física de Cantabria, Universidad de Cantabria

The Kuramoto model (KM) is a theoretical paradigm for investigating the emergence of rhythmic activity in large populations of oscillators. A remarkable example of rhythmogenesis is the feedback loop between excitatory (E) and inhibitory (I) cells in large neuronal networks. Yet, although the EI-feedback mechanism plays a central role in the generation of brain oscillations, it remains unexplored whether the KM has enough biological realism to describe it. In this contribution we present a two-population KM that is analytically solvable to a large extent, and describes the main features of the EI-based rhythms.

Frequency synchronisation induced by large delay

Tiago Pereira

University of Sao Paulo

We study how introducing a large delay feedback can induce a synchronisation phenomenon in a neighbourhood of a stable periodic orbit. The synchronisation is made by frequency-locking, which means that any trajectory close to the stable periodic orbit will adjust its rhythm to lock frequency with the delay. We develop a theory of invariant manifold to tackle this problem and discuss applications of these results to networks of lasers.

Solitary synchronization waves in distributed oscillators populations

Arkady Pikovsky

Universität Potsdam, Department of Physics and Astronomy

We demonstrate existence of solitary waves of synchrony in one-dimensional arrays of oscillator populations with Laplacian coupling. Characterizing each subpopulation with its complex order parameter, we obtain lattice equations similar to those of the discrete nonlinear Schrödinger system. Close to full synchrony, we find solitary waves for the order parameter perturbatively, starting from the known phase compactons and kovatons; these solution are extended numerically to the full domain of possible synchrony levels. For non-identical oscillators, existence of dissipative solitons is demonstrated.

Adaptive delivery of continuous and delayed feedback deep brain stimulation

Oleksandr Popovych

Institute of Neuroscience and Medicine - Brain & Behaviour (INM-7), Research Centre Juelich

Adaptive deep brain stimulation (aDBS) is a closed-loop method, where high-frequency (HF) DBS is turned on and off according to a feedback signal, whereas the conventional continuous HF DBS (cDBS) is delivered permanently. Using a computational model of subthalamic nucleus and external globus pallidus, we extend the concept of adaptive stimulation by adaptively controlling not only continuous HF DBS, but also demand-controlled stimulation. Apart from aDBS and cDBS, we consider continuous pulsatile delayed feedback stimulation specifically designed to induce desynchronization. Additionally, we combine adaptive on-off delivery with continuous delayed feedback modulation of HF pulse train by introducing adaptive pulsatile delayed feedback stimulation, where the stimulation is turned on and off using pre-defined amplitude thresholds. By varying the stimulation parameters we obtain optimal parameter ranges and reveal a simple relation between the thresholds of the local field potential and the extent of the stimulation-induced desynchronization as well as the integral stimulation time required. We find that adaptive stimulation can be more efficient in suppressing abnormal synchronization than continuous simulation, and delayed feedback still remains more efficient and also causes a stronger reduction of the beta burst length. Hence, adaptive on-off delivery may further improve the intrinsically demand-controlled delayed feedback stimulation.

Clustering in systems of repulsively coupled Morris–Lecar neurons

Robert Ronge

Humboldt-Universität zu Berlin, Institut für Physik

We study systems of identical Morris-Lecar neurons with repulsive all-to-all coupling. System parameters are chosen such that for the decoupled case each neuron is at rest, giving rise to a stable synchronous fixed point, but close to a saddle-node on invariant circle bifurcation, a scenario that is known in neurscience as class I excitability. We find that for sufficiently repulsive coupling strength the neurons form in general two or three clusters of spiking neurons of approximately equal size. However, for suitable initial conditions the system may split in three groups, two small spiking clusters in anti-phase and one large cluster of nearly resting neurons whose activity is apparently suppressed by the smaller clusters. Additionally, for coupling strengths close to the bifurcation of the synchronous fixed point we find a transient outlier dynamics in which all neurons for some time spike one after another in a regular fashion before forming two or three large clusters. We investigate how this transient behavior can be related to apparently stable dynamics of the same kind for an active rotator model which obeys Watanabe-Strogatz theory.

Dynamical disentanglement approach to data analysis

Michael Rosenblum

Universität Potsdam, Department of Physics and Astronomy

A typical problem in data analysis is to eliminate a particular component of a given time series, e.g. to remove noise, trend, oscillation in a certain frequency band, etc. A whole variety of techniques has been designed to tackle this task by means of filtering in the frequency domain, smoothing in a running window, subtracting a fitted polynomial, and soon. Furthermore, a number of modern methods - principal mode decomposition, independent mode decomposition, empirical mode decomposition - represent a signal of interest as a sum of modes such that (at least) dominating modes are assumed to represent certain dynamical processes. Correspondingly, some of these modes can be analyzed separately or, on the contrary, if they are considered as irrelevant, they can be subtracted from the original data, so that the cleansed signal is processed. Here we elaborate on a technique, designed for analysis of signals, generated by coupled oscillatory systems. The technique is based on reconstruction of phase dynamics of the analyzed unit. The obtained equation is then used for generation of new, cleansed, data by excluding one, or, generally, several inputs to the system. For example, if only the deterministic part of the model is used, i.e. the noise term is omitted, then the simulated data represents the dynamics of noise-free system. This disentanglement procedure is neither the standard filtering (because the preserved and eliminated components can overlap in frequency domain) nor the mode decomposition (because the sum of preserved and eliminated components does not yield the original signal). Here we consider application of this approach to analysis of cardio-respiratory interaction in humans.

Interplay of adaptivity and symmetry in multiplex networks

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Research on multilayer networks has recently opened up new aspects, providing a description of systems interconnected through different types of links. One class of interactions are within the layers, and ad- ditionally other types of interactions occur between the network nodes from different layers. In addition, dynamical systems on networks with time dependent topology have attracted a lot of attention in studies of neural networks, power grids as well as social groups. We investigate the impact of multiplexing on the collective dynamics in adaptive lay- ers. Building on these results the analysis of dynamics on self-organized emergent symmetric networks is lifted to multiplex structures.

Coupled stochastic active particles

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Stochastic active particles aim to describe the dynamics of self-propelled particles. The activity stands for an internal propulsive mechanism whereas the random character of motion is due to the smallness of the particles as well as due to internal errors in the propulsive mechanism. Both aspects of the particle's dynamics yield a description similarly to a noise driven phase oscillators.

In the talk I will concentrate on systems of particles coupled mutually and locally by alignment forces. I show how to derive 2d-hydrodynamic equations for the flows of the coupled stochastic particles. The qualitative dynamics of certain systems is discussed by various examples.

Reconstructed and theoretical predictions coupling functions in Drosophila's wing motor-circuit

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Swimming, crawling, flying, brachiating or running are but some examples of locomotor behaviours based on oscillations [1]. All of these are controlled by nerve activity in motocircuits. In some examples, one and the same circuit has to produce several distinct activation patterns to create multiple motor actions.

In the present study this is exemplified by a circuit of 5 motoneurons (MN1-5) which is involved in at least three distinct motor behaviours of *Drosophila*: (i) It powers flight, and produces (ii) sine song and (iii) pulse song. Based on the kinetics of indirect flight, optimal activity pattern is a splay-state configuration which ensures a steady application of force onto the thoracic wing resonator. It has been postulated that this network dynamics is due to an inhibitory coupling between neurons [2]. However, our recent experimental findings have indicated the involvement of gap-junctions.

Based on insight from coupled phase-oscillator theory [3][4], the present work resolves this problem by deriving the possible neuronal phase-susceptibilities and predicting coupling functions and global network states from them. It is shown that a splay-state ins indeed possible with gap-junction coupling.

These predictions are corroborated with reconstructed coupling functions from *in vivo* spike recordings of the wing motor circuit. Two algorithms a employed for the reconstruction, one based on Fourier decomposition [5] and a new strategy based on least-squares optimisation. The performance is evaluated on simulated data and then applied to electrophysiological recordings.

The results of this study will contribute to a better understanding of how single cell properties [6] shape the activity patterns in small networks.

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Application of equivariant Pyragas control to networks of chemical oscillators

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Networks of coupled oscillators can exhibit various types of spatio-temporal patterns. Here we investigate networks of locally coupled chemical BZ-oscillators and subject them to equivariant Pyragas control – a variant of the well-known time-delayed feedback scheme which also takes the desired spatio-temporal pattern into account. Without control, we observe synchronization. With control, we can explicitly target, select and stabilize spatio-temporal patterns. The control will be implemented into an experimental set-up of coupled BZ-oscillators.

Synchronization of viscoelastically coupled excitable oscillators

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Viscoelastically coupled excitable oscillators exhibit an interesting range of synchronization patterns due to the interplay of autonomous oscillation and refractory period following an excitation. The viscoelastic coupling effectively introduces a delay to the coupling of such oscillators. As an example of this class of coupled oscillators we study individually beating spatially separated cardiomyocytes surrounded by an extracellular matrix via numerical simulations. We investigate the synchronization of a linear chain of two or more coupled cells. Depending on the viscoelastic properties of the coupling different synchronization patterns (asynchrony, in- or anti-phase, 1:1, n:n) occur.

Synchronization of coupled quasiperiodic generators

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A problem of synchronization of quasiperiodic oscillations is discussed in application to an example of coupled models of radiophysical generators with autonomous quasiperiodic dynamics. Charts of Lyapunov exponents are presented that reveal characteristic domains on the parameter plane: oscillator death, complete synchronization, phase synchronization of quasiperiodic oscillations, broadband synchronization, broadband quasiperiodicity. The features of each type of dynamical behavior are discussed. Analysis of corresponding bifurcations is presented, including quasiperiodic Hopf bifurcations, saddle-node bifurcations of invariant tori of different dimensions, and bifurcations of torus doublings. Both the case of dominance of quasiperiodic oscillations in one of the generators and the case of pronounced periodic resonances embedded in the region of quasiperiodicity are considered.

Dynamics of two adaptively coupled phase oscillators

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We investigate the dynamics of two non-identical adaptively coupled phase oscillators using geometric singular perturbation theory. The flow on the critical manifold gives rise to different states including isolated and invariant families of equilibria as well as limit cycles. We introduce a new dynamical transformation which allows us to show the existence and stability of equilibria and limit cycles. Different bifurcation scenarios and the influence of frequencies mismatch are studied. The analytic findings are verified using numerical simulations.

Synchronization transitions in a large network of chemical oscillators

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Synchronization is a ubiquitous theme in nature. Examples range from flashing fireflies, chirping crickets, firing neurons, beating heart cells, and circadian rhythms in biology to pendula, lasers, Josephson junctions, computer chips, power grids, and bridge-crossing pedestrians in engineered systems and beyond [1]. It is well known that synchronization in an ensemble of oscillators occurs once the interaction between them is sufficiently strong [2,3]. However, the particular character of the synchronization transition is determined by the network topology and frequency distribution [3]. Here we will show our latest experimental results on synchronization transitions utilizing a versatile setup based on optically coupled chemical micro-particles, that allows for the study of synchronization dynamics in very large networks of relaxation oscillators. In the past we employed this setup to experimentally verify the elusive spiral wave chimera [5] that was predicted theoretically by Kuramoto in 2002 [6]. Furthermore, the setup allows for reproducible experiments under laboratory conditions on networks with N>2000 oscillators. It facilitates the free choice of network topology, coupling function, coupling strength, range, and time delay, all of which can even be chosen as time-dependent. These experimental capabilities open the door to a broad range of future experimental inquiries into pattern formation and synchronization on large networks, which were previously out of reach.

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Phase-sensitive excitability of a limit cycle

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The classical notion of excitability refers to an equilibrium state that shows under the influence of perturbations a nonlinear threshold-like behavior. We extend this concept by demonstrating how periodic orbits can exhibit a specific form of excitable behavior where the nonlinear threshold-like response appears only after perturbations applied within a certain part of the periodic orbit, i.e the excitability happens to be phase-sensitive. As a paradigmatic example of this concept we employ the classical FitzHugh-Nagumo system. The relaxation oscillations, appearing in the oscillatory regime of this system, turn out to exhibit a phase-sensitive nonlinear threshold-like response to perturbations, which can be explained by the nonlinear behavior in the vicinity of the canard trajectory. Triggering the phase-sensitive excitability of the relaxation oscillations by noise we find a characteristic non-monotone dependence of the mean spiking rate of the relaxation oscillation on the noise level. We explain this non-monotone dependence as a result of an interplay of two competing effects of the increasing noise: the growing efficiency of the excitation and the degradation of the nonlinear response.

Coherence resonance in multiplex neural networks

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Using the model of a FitzHugh-Nagumo system in the excitable regime, we study the impact of multiplexing on coherence resonance in a two-layer network [1]. We show that multiplexing allows for the control of the noise-induced dynamics. In particular, we find that multiplexing induces coherence resonance in networks that do not demonstrate this phenomenon in isolation. Examples are provided by deterministic networks and networks where the strength of interaction between the elements is not optimal for coherence resonance. In both cases, we show that the control strategy based on multiplexing can be successfully applied even for weak coupling between the layers. Moreover, for the case of deterministic networks, we obtain a counter-intuitive result: the multiplex-induced coherence resonance in the layer which is deterministic in isolation manifests itself even more strongly than that in the noisy layer.

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Is synchronization compatible with homoclinicity?

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In many applications of coupled oscillators the desired dynamics is synchronized: instantaneous states of all ensemble elements coincide. For globally coupled identical units, synchronous behavior in such cases is governed by the low-dimensional system that may depend on external parameters and exhibit bifurcations when those parameters are varied. To be physically observable, synchronous states should be robust: stable with respect to perturbations that split the ensemble and provoke the departure of separate units from the synchronous cluster. We demonstrate that the situations when the low-dimensional system possesses a saddle equilibrium and undergoes a homoclinic bifurcation, feature a generic mode of instability that leads to the destruction of the cluster state and breakdown of synchrony. We briefly discuss the possibilities for reversal of this effect with the help of the specially tailored non-generic schemes of coupling to the global field.

Stochastic bursting in delay-coupled noisy systems

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We study the mutually delay-coupled oscillators (neurons) in noisy environment. An idealized point process is used to describe the statistics of the spike patterns, such as the interspike interval distribution (ISI) and power spectrum. The phenomenon of stochastic bursting is also discussed in all-to-all delay-coupled case.

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