Program
# Schedule

**Tuesday, December 12**

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<td>Jaideep Pathak (University of Maryland, College Park, USA)</td>
<td>Model free replication of chaotic attractors from data: A reservoir computing approach</td>
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<td>Peter Ashwin (University of Exeter, UK)</td>
<td>Fast and slow domino regimes for transient escapes on networks</td>
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<td>Juan Restrepo (University of Colorado, Boulder, USA)</td>
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<td>Yuanzhao Zhang (Northwestern University, USA)</td>
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*All times Central Standard Time (CST; GMT-6)*
Faculty Speakers

**Peter Ashwin**
*University of Exeter, UK*

**Fast and slow domino regimes for transient escapes on networks**
Dec 13, 9:00 CST

We discuss the problem of sequential escapes of a number of coupled units where there is a “quiescent” and an “active” attractor, and one can escape from the quiescent to the active state under the influence of noise. We examine the influence of the coupling strength on such networks, and make the case that there are various regimes of spreading escape, including fast and slow “domino” regimes depending on the degree of synchronization of the escapes.

*Co-authors: J. Creaser and K. Tsaneva-Atanasova*

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**Christian Bick**
*University of Oxford, UK*

**Beyond Kuramoto phase oscillator networks: Global dynamics through generalized interactions**
Dec 12, 13:10 CST

The function of many real-world systems that consist of interacting oscillatory units depends on their collective dynamics. The Kuramoto model, which has been widely used to study the dynamics of oscillator networks, assumes that interactions between oscillators is determined by the sine of the differences between pairs of oscillator phases. We show that more general interactions between identical phase oscillators allow for global dynamical phenomena such as dynamic switching between chimeras as localized frequency synchrony patterns.

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**Pietro-Luciano Buono**
*University of Ontario Institute of Technology, Canada*

**The interaction of averaging and symmetry for the study of coupled oscillators**
Dec 12, 11:10 CST

In this talk, I will present new theoretical results on the appearance of periodic solutions in networks of symmetrically coupled oscillators that are amenable to averaging. The result rests on the idea that steady-states of the averaged systems lead to periodic solutions of the full system. We show that given a mild symmetry of the oscillators, the averaged system inherits an $O(2)$ symmetry along with the symmetry group $G$ of the network. We are able to show that steady-states with symmetry group $H$ subset of $G \times SO(2)$ lead to periodic orbits with spatio-temporal symmetry group $H$ subset of $G \times S^1$ where $S^1$ now is the phase shift group on autonomous periodic orbits. This approach leads to the same bifurcating branches as using the Equivariant Hopf bifurcation theorem. I will discuss an application to coupled crystal oscillator system and timing networks.
Nonlinear dynamics in multiplex networks
Dec 13, 13:10 CST

We will show some of the recent results in our group concerning dynamics in multiplex networks. On the one hand, we consider multiplex networks as a set of nodes in different layers. At each layer, the set of nodes is the same but the connections among the nodes can be different in the layers. Furthermore, the connections among the layers are described by a “network of layers.” We have studied different processes across the layers (diffusion) and between the layers (reaction) [1]. In this case, Turing patterns appear as an effect of different average connectivities in different layers [2]. We also show that a multiplex construction where the layers correspond to contexts in which agents make different sets of connections can make a model of opinion formation to show stationary states of coexistence that are not observed in simple layers [3]. Finally, as a particular case of multiplex networks, one can also analyze networks that change in time, since in this case each layer of the multiplex corresponds to a snapshot of the interaction pattern. For this situation, we have shown that there are different mechanisms that dominate the diffusion of information in the system depending on the relative effect of mobility and diffusion among the nodes [4,5].

References:

Patterns of phase-shift synchrony
Dec 13, 12:10 CST

A hyperbolic $T$-periodic solution to an $n$-node system $X(t) = (x_1(t),...,x_n(t))$ has phase-shift synchrony if there are two nodes $i$ and $j$ and a phase-shift $\theta$ such that $x_i(t) = x_j(t+\theta T)$. That phase-shift is rigid if every small $n$-node system perturbation leads to a perturbed $T$-periodic solution $Y(t) = (y_1(t),...,y_n(t))$ such that $y_i(t) = y_j(t+\theta T)$. I will discuss the following theorem: Rigid phase-shift synchrony occurs only when that synchrony is forced by a symmetry on a quotient network. Remark: Only some of these patterns of phase-shift synchrony can be obtained by Hopf bifurcation.

The theorem was proved over a five-year period in a sequence of papers by Ian Stewart and Martin Parker (2007, 2008) and David Romano, Yunjiao Wang, and me (2010, 2012).

Network structure induced nontrivial synchronization patterns with electrochemical oscillators
Dec 13, 10:00 CST

For some networks, the dynamics can be inferred from generalization of the behavior of oscillator pairs (through direct stability analysis of the solutions) or populations (through mean field approaches). Here we consider synchronization patterns in networks of oscillators, whose behavior is fundamentally different from a pair or population of elements. A network of two groups of two oscillators is considered, where the all-to-all inter-group coupling is weaker than the intragroup coupling. With simple delayed difference (linear) interactions, it is shown that the network can produce nearly anti-phase
synchronization patterns between the elements, when pairs (or a population) of oscillators can exhibit only nearly in-phase synchronized patterns. The patterns are interpreted with collective phase sensitivity description. With carefully designed nonlinear interactions, it is shown that the network interactions can produce very robust chimera states with localized frequency clusters, where pairs or globally coupled oscillators produce only phase locked states. The results show that an experiment-based phase model description of oscillatory processes is essential in the description and design of chemical pattern formation.

Katharina Krischer
TU München, Germany

From Kuramoto-type oscillators to experimental pattern recognition with oscillatory networks
Dec 12, 9:40 CST

Globally coupled phase oscillators of similar frequencies may synchronize at a phase difference close to zero or π, depending on the sign and strength of the coupling. There have been different ideas in the literature on how to use such a network for pattern recognition by modifying individual couplings between the oscillators, some of them using time-modulated coupling functions. We have engineered the coupling modulation and introduced a mirrored network structure, so that the network gains the following properties: a) the memorized patterns are attractors; b) coupling modulations are internally generated; c) it has a low number of physical connections, allowing for experimental implementation. In this talk, we first present the so-called MONACO (Mirrored Oscillator Networks for Autoassociative COmputation) network architecture and its mathematical properties. Then, we demonstrate its experimental realization, which includes an automatic frequency annealing mechanism and an easy way to read out phase differences.
Co-author: D. Heger

Adilson Motter
Northwestern University, USA

Network cascades: Unfolding, modeling, and control
Dec 13, 11:30 CST

A characteristic property of networks is their ability to propagate influences, such as infectious diseases, behavioral changes, and failures. An especially important class of such contagious dynamics is that of cascading processes. These processes include, for example, cascading failures in infrastructure systems, extinctions cascades in ecological networks, and information cascades in social systems. In this presentation, I will discuss recent progress and challenges associated with the modeling, prediction, detection, and control of cascades in networks. In particular, I will present new mathematical and computational models for cascading blackouts in power-grid networks that are both realistic and amenable to rigorous analysis.

Peter Mucha
University of North Carolina, Chapel Hill, USA

Post-processing partitions to identify domains of modularity optimization
Dec 12, 10:50 CST

We introduce the Convex Hull of Admissible Modularity Partitions (CHAMP) algorithm to prune and prioritize different network community structures identified across multiple runs of possibly various computational heuristics. Given a set of partitions, CHAMP identifies the domain of modularity optimization for each partition—i.e., the parameter-space domain where it has the largest modularity relative to the input set—discarding partitions with empty domains to obtain the subset of partitions that are “admissible” candidate community structures that remain potentially optimal over indicated parameter domains. Importantly, CHAMP can be used for multi-
dimensional parameter spaces, such as those for multilayer networks where one includes a resolution parameter and interlayer coupling. Using the results from CHAMP, a user can more appropriately select robust community structures by observing the sizes of domains of optimization and the pairwise comparisons between partitions in the admissible subset. We demonstrate the utility of CHAMP with several example networks. In these examples, CHAMP focuses attention onto pruned subsets of admissible partitions that are 20-to-1785 times smaller than the sets of unique partitions obtained by community detection heuristics that were input into CHAMP.

This work has appeared as Algorithms 10, 93 (2017), doi:10.3390/a10030093.

Co-authors: W. Weir, S. Emmons, R. Gibson, and D. Taylor

The network analog of the butterfly effect
Dec 13, 9:20 CST

The relation between network structure and dynamics is determinant for the behavior of complex systems in numerous domains. An important long-standing problem concerns the properties of the networks that optimize the dynamics with respect to a given performance measure. Here, we show that such optimization can lead to sensitive dependence of the dynamics on the structure of the network. Specifically, using diffusively coupled systems as examples, we demonstrate that the stability of a dynamical state can exhibit sensitivity to unweighted structural perturbations (i.e., link removals and node additions) for undirected optimal networks and to weighted perturbations (i.e., small changes in link weights) for directed optimal networks. As mechanisms underlying this sensitivity, we identify discontinuous transitions occurring in the complement of undirected optimal networks and the prevalence of eigenvector degeneracy in directed optimal networks. These findings establish a unified characterization of networks optimized for dynamical stability, which we illustrate using Turing instability in activator-inhibitor systems, synchronization in power-grid networks, network diffusion, and several other network processes. Our results suggest that the network structure of a complex system operating near an optimum can potentially be fine-tuned for a significantly enhanced stability compared to what one might expect from simple extrapolation. On the other hand, they also suggest constraints on how close to the optimum the system can be in practice. Finally, the results have potential implications for biophysical networks, which have evolved under the competing pressures of optimizing fitness while remaining robust against perturbations.


Antonio Palacios
San Diego State University, USA

On the synchronization phenomenon of spin torque nano-oscillators
Dec 13, 12:50 CST

Synchronization of Spin Torque Nano Oscillators (STNOs) has been a subject of extensive research as various groups try to harness the collective power of STNOs to produce a strong enough microwave signal at the nanoscale. Achieving synchronization has proven to be, however, rather difficult for even small arrays while in larger ones the task of synchronization has eluded theorists and experimentalists altogether. In this talk, we discuss recent work in which we solved the synchronization problem, analytically and computationally, for networks of STNOs connected in series. The procedure combines group theory and equivariant bifurcation theory in systems with symmetry. More importantly, the results are valid for networks of arbitrary size and they are readily extendable to other network topologies. These results should help guide future experiments and, eventually, lead to the design and fabrication of a nanoscale microwave signal generator.
Effects of structural perturbations on the synchronizability of diffusive networks  
Dec 13, 12:30 CST

We investigate the effects of structural perturbations of both undirected and directed diffusive networks on their ability to synchronize. We establish a classification of directed links according to their impact on synchronizability. We focus on adding directed links in weakly connected networks having a strongly connected component acting as driver. When the connectivity of the driver is not stronger than the connectivity of the slave component, we can always make the network strongly connected while hindering synchronization. On the other hand, we prove the existence of a perturbation which makes the network strongly connected while increasing the synchronizability. Under additional conditions, there is a node in the driving component such that adding a single link starting at an arbitrary node of the driven component and ending at this node increases the synchronizability.

Experiments with arbitrary networks in time-delayed systems (with Joseph Hart)  
Dec 12, 9:20 CST

We report a new experimental approach using an optoelectronic feedback loop to investigate the dynamics of oscillators coupled on large complex networks with arbitrary topology. Our implementation is based on a single optoelectronic feedback loop with time delays. We use the space-time interpretation of systems with time delay to create large networks of coupled maps. Others have performed similar experiments using high-pass filters to implement the coupling; this restricts the network topology to the coupling of only a few nearest neighbors.

In our experiment, the time delays and coupling are implemented on a field-programmable gate array, allowing the creation of networks with arbitrary coupling topology. This system has many advantages: the network nodes are truly identical, the network is easily reconfigurable, and the network dynamics occur at high speeds. We use this system to study cluster synchronization and chimera states in both small and large networks of different topologies.

Co-authors: J. Hart, D. Schmadel, T. Murphy
Recent results on pulse coupled oscillators synchronization and scheduling
Dec 13, 10:30 CST

Bio-inspired techniques have been advocated by many as fault-tolerant and scalable alternatives to produce self-organization in communication networks. The Pulse Coupled Oscillator (PCO) dynamics in particular have been the source of inspiration for many network synchronization and scheduling protocols. This talk discusses new results that characterize their application and convergence properties in locally connected networks. For synchronization, we provide tight bounds for the synchronization accuracy and for scheduling (or desynchronization) we study the algorithm fixed point, fairness, efficiency, and convergence rate.

Moreover, these noise-induced chimera states are characterized by alternating behavior: coherent and incoherent domains switch periodically their location. We show that this alternating switching can be explained by analyzing the coupling functions. Finally, time-delayed feedback control allows for the control of these chimeras [3].

Co-authors: A. Zakharova, N. Semenova, and V. Anishchenko

References:

Why directedness promotes network synchronization
Dec 12, 12:10 CST

In this talk, we will examine synchronization of heterogeneous coupled oscillators in undirected and directed complex networks. We employ the framework of the Synchrony Alignment Function (SAF), a versatile tool that objectively measures the synchronization properties of networks of heterogeneous oscillators. The SAF framework has been used recently to optimize networks for synchronization, identify important links and nodes in specific networks, and find generic dynamical and structural properties that promote/inhibit synchronization in general networks. Specifically, we use a generalized SAF approach to show that, on average, directed networks synchronize more strongly than undirected networks. We show that this phenomenon is induced by a combination of two effects: a) the alignment of the oscillators’ heterogeneous frequencies with particular singular vectors of the network Laplacian and b) the overall distribution of the singular values of the network Laplacian. Finally, time permitting, we demonstrate the potential impact these results may have in real-world applications such as power grid dynamics.
Resilience of network synchronization against structural and dynamical perturbations
Dec 12, 11:30 CST

Synchronization of network coupled systems is an important research topic, especially given its broad engineering and biological applications, for example, in brain waves, power grids, and animal behavior. In practice, a system almost never operates in the absence of changes or perturbations, and consequently, a central question is how these perturbations might affect synchronization. Existing work through the use of master stability analysis focuses either on a network’s synchronizability (resilience against change of coupling strength) or linear stability of synchronization (resilience against infinitesimal dynamical perturbations). In this work, we focus on general structural and dynamical perturbations, providing analytical tools to measure their effects on network synchronization, and show (through numerical simulations) that an interesting nonlinear correlation seems to exist between a network’s structural and dynamical resilience. To illustrate the importance of our analysis, we show examples of where cospectral networks, whose synchronization properties are identical under master stability analysis, nevertheless exhibits drastically synchronization dynamics: some synchronize slower than the others, and some do not synchronize at all (despite being predicted otherwise using corresponding linearized dynamics).
to implement the coupling; this restricts the network topology to the coupling of only a few nearest neighbors.

In our experiment, the time delays and coupling are implemented on a field-programmable gate array, allowing the creation of networks with arbitrary coupling topology. This system has many advantages: the network nodes are truly identical, the network is easily reconfigurable, and the network dynamics occur at high speeds. We use this system to study cluster synchronization and chimera states in both small and large networks of different topologies.

Co-authors: R. Roy, D. Schmadel, T. Murphy

Jaideep Pathak
University of Maryland, College Park, USA

Model free replication of chaotic attractors from data: A reservoir computing approach
Dec 12, 12:50 CST

Networks of nonlinearly interacting neuron-like units have the capacity to approximately reproduce the dynamical behavior of a wide variety of dynamical systems. We demonstrate the use of such artificial neural networks for reconstruction of chaotic attractors from limited time series data using a machine learning technique known as reservoir computing. The orbits of the reconstructed attractor can be used to obtain approximate estimates of the ergodic properties of the original system. As a specific example, we focus on the task of determining the Lyapunov exponents of a system from limited time series data. Using the example of the Kuramoto-Sivashinsky system, we show that this technique offers an attractive method for estimating a large number of Lyapunov exponents of a high-dimensional spatiotemporal chaotic system. In this example, we find that it is possible to obtain robust estimates of all the positive exponents and a large number of negative Lyapunov exponents of a 15-dimensional attractor from a multivariate time series of a reasonable length.

Co-authors: Z. Lu, B. Hunt, M. Girvan, E. Ott
Network structure induced nontrivial synchronization patterns with electrochemical oscillators (on behalf of István Kiss)
Dec 13, 10:00 CST

For some networks, the dynamics can be inferred from generalization of the behavior of oscillator pairs (through direct stability analysis of the solutions) or populations (through mean field approaches). Here we consider synchronization patterns in networks of oscillators, whose behavior is fundamentally different from a pair or population of elements. A network of two groups of two oscillators is considered, where the all-to-all inter-group coupling is weaker than the intragroup coupling. With simple delayed difference (linear) interactions, it is shown that the network can produce nearly anti-phase synchronization patterns between the elements, when pairs (or a population) of oscillators can exhibit only nearly in-phase synchronized patterns. The patterns are interpreted with collective phase sensitivity description. With carefully designed nonlinear interactions, it is shown that the network interactions can produce very robust chimera states with localized frequency clusters, where pairs or globally coupled oscillators produce only phase locked states. The results show that an experiment-based phase model description of oscillatory processes is essential in the description and design of chemical pattern formation.

Symmetries in the time-averaged dynamics of stochastic models on networks: Reducing unnecessary complexity through minimal network models
Dec 13, 11:10 CST

Complex networks are the subject of fundamental interest from the scientific community at large. Several metrics have been introduced to characterize the structure of these networks, such as the degree distribution, degree correlation, path length, clustering coefficient, centrality measures etc. Another important feature is the presence of network symmetries. In particular, the effect of these symmetries has been studied in the context of network synchronization, where they have been used to predict the emergence and stability of cluster synchronous states. Here we show that network symmetries play a role in a substantially broader class of dynamical models on networks, including epidemics, game theory, communication, and coupled excitable systems. Namely, we see that nodes that are related by a symmetry relation show the same time-averaged dynamical properties. This discovery also allows us to propose reduction techniques for exact, yet minimal, simulation of complex networks dynamics, which we show can be effectively implemented to optimize the use of computational resources, such as computation time and memory.

Identical synchronization of nonidentical oscillators
Dec 13, 10:50 CST

An outstanding problem in the study of networks of heterogeneous dynamical units concerns the development of rigorous methods to probe the stability of synchronous states when the differences between the units are not small. Here, we address this problem by presenting a generalization of the master stability formalism that can be applied to heterogeneous oscillators with large mismatches. Our approach is based on the simultaneous block diagonalization of the matrix terms in the variational equation, and it leads to dimension reduction that simplifies the original equation significantly. This new formalism allows the systematic investigation of scenarios in which the oscillators need to be nonidentical in order to reach an identical state, where all oscillators are completely synchronized. In the case of networks of identically coupled oscillators, this corresponds to breaking the symmetry of the system as a means to preserve the symmetry of the dynamical state—a recently discovered effect termed asymmetry-induced synchronization (AISync). Our framework enables us to identify communication delay as a new and potentially common mechanism giving rise to AISync, which we demonstrate using networks of delay-coupled Stuart-Landau oscillators. The results also have potential implications for control, as they reveal oscillator heterogeneity as an attribute that may be manipulated to enhance the stability of synchronous state.