SOE 13: Networks: From Topology to Dynamics (joint session SOE/CPP/BP/DY)

Time: Wednesday 9:30–12:15 Location: MA 001

SOE 13.1 Wed 9:30 MA 001

Dynamics of interacting tipping elements on complex networks — •Jonathan F. Donges[1,2], Ann-Kristin Klose[1], and Ricarda Winkelmann[1] — [1]Earth System Analysis, Potsdam Institute for Climate Impact Research, Potsdam, Germany — [2]Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden

In recent years, an increasing number of potential tipping elements have been identified in ecological, climatic and social systems. Tipping elements are defined by their ability to undergo large qualitative change that is caused by a small perturbation in a parameter or state variable. We investigate the emergent nonlinear dynamics of pairs, chains and networks of generalized tipping elements. Understanding the dynamics of systems of interacting tipping elements on complex networks is relevant for assessing the resilience and transformative capacity of complex systems such as the Earth's climate system and the World's energy system in the context of decarbonization transformation for meeting the Paris climate agreement.

SOE 13.2 Wed 9:45 MA 001

The interdependent network of gene regulation and metabolism is robust where it needs to be — •Marc Hütt[1], David Klosik[2], Anne Grimbs[1], and Stefan Bornholdt[2] — [1]Jacobs University, Bremen, Germany — [2]Institute for Theoretical Physics, University of Bremen, Bremen, Germany

Despite being highly interdependent, the major biochemical networks of the living cell – the networks of interacting genes and of metabolic reactions, respectively – have been approached mostly as separate systems so far. Recently, a framework for interdependent networks has emerged in the context of statistical physics. In a first quantitative application of this framework to systems biology, here we study the interdependent network of gene regulation and metabolism for the model organism *Escherichia coli* in terms of a biologically motivated percolation model [1]. Particularly, we approach the system's conflicting tasks of reacting rapidly to (internal and external) perturbations, while being robust to minor environmental fluctuations. Considering its response to perturbations that are localized with respect to functional criteria, we find the interdependent system to be sensitive to gene regulatory and protein-level perturbations, yet robust against metabolic changes. We expect this approach to be applicable to a range of other interdependent networks.

[1] Klosik, D. F., Grimbs, A., Bornholdt, S., and Hütt, M.-T. (2017). Nature Communications, 8(1):534.

SOE 13.3 Wed 10:00 MA 001

Robust connectivity in networks with groups of vulnerable nodes — •Sebastian M. Krause[1,2], Michael M. Danziger[3], and Vinko Zlatić[2] — [1]Faculty of Physics, University of Duisburg-Essen, Lotharstr. 1, 47048 Duisburg, Germany — [2]Theoretical Physics Division, Rudjer Bošković Institute, Bijenicka c. 54, 10000 Zagreb, Croatia — [3]Department of Physics, Bar-Ilan University, Ramat Gan 5290002, Israel

In many networked systems there are large groups of similar nodes which are vulnerable to the same failure or adversary. For example, servers in a communication network running the same software will fail together, if this software has a bug. Therefore, we are often faced with networks where all nodes of a group can fail together. Further, many different vulnerabilities can cover the whole network. This structural weakness has so far been overlooked in studies of network robustness. Here we discuss, how multiple redundant paths enable a high level of robustness, even if no node is trusted [1,2]. With each vulnerability described as a color, we discuss "color-avoiding percolation". We present a fast numerical algorithm for real world networks and analytical results for random network ensembles.

[1] Sebastian M. Krause, Michael M. Danziger, and Vinko Zlatić, Hidden Connectivity in Networks with Vulnerable Classes of Nodes, Phys. Rev. X 6, 041022 (2016).

[2] S. M. Krause, M. M. Danziger, and V. Zlatić, Color-avoiding percolation, Phys. Rev. E 96 022313 (2017).

SOE 13.4 Wed 10:15 MA 001

When is a network a network? Multi-order graphical model selection in time series data on networks — •Ingo Scholtes — Chair of Systems Design, ETH Zürich, Zürich, Switzerland

We introduce a novel framework for the modeling of time series data on networks. Such data are important, e.g., when studying click streams of users in the Web, travel patterns of passengers in transportation systems, information cascades in social networks, biological pathways, or time-stamped social interactions. While it is common to apply graph analytics and network analysis to such data, recent works have shown that temporal correlations can invalidate the results of such methods. This raises a fundamental question: When is a network abstraction of time series data justified?

Addressing this open question, we propose a framework that combines Markov chains of multiple, higher orders into a multi-layer network model that captures temporal correlations at multiple length scales simultaneously. We develop a model selection technique to infer the optimal number of layers of such a model and show that our method outperforms baseline Markov order detection techniques.

An application to eight real-world data sets capturing causal paths in time series data on networks shows that the inferred models provide an optimal summarization of the causal topologies of real-world complex systems. Our work highlights fallacies of network-based modelling techniques and provides a principled answer to the open question when they are justified. Generalizing networks to optimal multi-order models, it opens perspectives for the study of complex systems.

SOE 13.5 Wed 10:30 MA 001

Exact expected cluster sizes for bond percolation in finite networks — Joan Pont Serra and •Konstantin Klemm — IFISC (CSIC-UIB), Mallorca, Spain

Bond percolation describes the statistical ensemble generated by randomly deleting edges from a given network. Traditionally studied on grids (lattices), bond percolation forms a crucial part of modern network theory with implications for epidemic spreading and network robustness under failures. For quenched systems of size well above 20 nodes, the computation of percolation quantities relies on heuristics (e.g. by the graph spectrum) or Monte Carlo sampling. Here we introduce an exact computational method that is time-efficient when the network has certain separation properties. Specifically, we work with a branch decomposition of low width. Then the network is recursively separable by removing a small number of nodes in each step. For several test networks, we present exact results for the first time. We find that the computational cost of our exact method is lower than that of Monte Carlo runs required to reach an acceptable precision.

SOE 13.6 Wed 10:45 MA 001

Controlling percolation with limited resources — •Malte Schröder[1], Nuno Araújo[2], Didier Sornette[3], and Jan Nagler[3] — [1]Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany — [2]Universidade de Lisboa, Lisboa, Portugal — [3]ETH Zürich, Zurich, Switzerland

Connectivity - or the lack thereof - is crucial for the proper functioning of many essential socio-economic processes, from financial and economic networks over epidemic spreading in social networks to technical infrastructure. Often, connections are deliberately established or removed by various parties to induce, maintain, or destroy global connectivity. Thus, there has been a great interest in understanding how to control percolation, the transition to large-scale connectivity. Previous work studied control strategies implicitly assuming unlimited resources, leading to a large number of models of "explosive" and discontinuous percolation. Realistically, however, such control is often subject to a limited budget. We derive an efficient control strategy to delay percolation under the constraint of limited resources and study its implications. We show that the transition can be significantly delayed even with scarce resources but remains smooth and in the same universality class as random percolation. In particular, the transition never becomes "explosive". We derive an approximation for the optimal control parameters and show how resource optimal delay of percolation leads to a sudden, discontinuous transition. Thus, the percolation transition becomes effectively uncontrollable as an unintended consequence of optimal control.

SOE 13.7 Wed 11:00 MA 001

Discrete reaction-diffusion models of innovations using multi-

particles in networks. — •Yuki Kawasaki and Hirotada Ohashi — The University of Tokyo, Tokyo, Japan

Reaction-diffusion is a fundamental process underlying many social and economic phenomena. This process has been widely studied in continuous physical space. Different from physical and chemical phenomena, social and economic processes occur in networks connecting individuals, firms and organizations. In this study, we model reaction-diffusion processes of innovations in structured networks employing multi-particles that represent innovations and some kind of enzymes. The reaction process is that several particles react on nodes according to reaction rules and the diffusion process is that particles travel randomly to neighboring nodes. This model is able to reproduce macroscopic behaviors of systems taking account of microscopic relationships between individual particles. Simulation results are obtained for various network structures including small-world and scale-free networks. Next we extend our model to deal with simultaneous reaction and diffusion of different kinds of particles. This model can describe competition and cooperation between innovations in networks including predator-prey processes.

SOE 13.8 Wed 11:15 MA 001

Probabilistic Quantifiers for Deterministic Spreading — •Justine Wolter[1,2], Benedict Lünsmann[3], Xiaozhu Zhang[1,2], Malte Schröder[1,2], and Marc Timme[1,2,3] — [1]Chair for Network Dynamics, Institute for Theoretical Physics and Center for Advancing Electronics Dresden (cfaed), TU Dresden, Dresden, Germany — [2]Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen — [3]Max Planck Institute for the Physics of Complex Systems, 01069 Dresden

How do signals spread across dynamical systems? Spreading may be stochastic, e.g., during epidemic outbreaks or deterministic, e.g., in electrical or other supply networks. Due to mathematical challenges, it remains unknown how to robustly quantify even simple characteristics such as peak times or amplitudes of a spreading signal propagating across a network. Here we change the perspective and propose to analyze deterministic spreading dynamics employing concepts of probability theory. We characterize generic spreading dynamics by expectation values to work out a theory explicitly quantifying when and how strongly a perturbation initiated at one unit of a network impacts any other [1]. The theory provides this information as a function of the relative position of initially perturbed and responding unit as well as on the entire network topology. Furthermore, asymptotically exact approximation schemes enable to well predict previously inaccessible peak times and amplitudes. These insights may open up a new realm of quantifying characteristics of deterministic processes through probability theory. Ref.: [1] J. Wolter et al., http://arXiv.org/abs/1710.09687

SOE 13.9 Wed 11:30 MA 001

Perturbation spreading on diffusively-coupled networks and power grids — •Xiaozhu Zhang[1,2], Dirk Witthaut[3], and Marc Timme[1,2] — [1]Chair for Network Dynamics, Institute for Theoretical Physics and Center for Advancing Electronics Dresden (cfaed), TU Dresden, Dresden, Germany — [2]Network Dynamics, Max Planck Institute for Dynamics and Self-organization, 37077 Göttingen — [3]Institute for Energy and Climate Research - Systems Analysis and Technology Evaluation (IEK-STE), Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

Spreading phenomena on networks essentially underlie the collective dynamics of systems across physics, biology and engineering. Yet, how local changes dynamically spread in such networked systems is still far from fully understood. Here we analyze the spreading dynamics for diffusively-coupled networks close to given operating points. We provide analytical solutions of transient nodal responses via linear response theory and approximate the perturbation arrival times via Taylor expansion. In homogeneous networks, we find the spreading speed based on the estimated arrival times decreases and converges to a constant at large distance. Intriguingly, the asymptotic spreading speed is essentially determined by the network topology, i.e. the limiting behavior of the number of shortest paths at large distance. These results shed light on the qualitatively universal asymptotic spreading behavior in networks and its quantitative dependence on the underlying network topology.

SOE 13.10 Wed 11:45 MA 001

Temporal networks with geometric constraints and protein folding — •Nora Molkenthin[1], Marc Timme[2,1], and Steffen Mühle[3] — [1]Network Dynamics, Max Planck Institute for Dynamics and Self-Organization, 37077 Göttingen — [2]Chair for Network Dynamics, Center for Advancing Electronics Dresden (cfaed) and Institute for Theoretical Physics, TU Dresden, 01062 Dresden — [3]Physics Department III, University of Göttingen, D-37077 Göttingen, Germany

The structure of many complex networks is highly constrained by geometric factors, affecting a broad range of systems from polymer aggregates to traffic and supply networks. On the microscopic scale, folding proteins constitute paradigmatic systems for spatial network formation. They are well characterized as Protein Residue Networks (PRN) yet their statistical properties seem to be diverse and general rules are largely unknown. Here, advancing a recent graph-theoretical mapping [1], we develop a temporal network model for the aggregation of connected, spatially extended units, thereby reproducing key features of PRN*s. In stark contrast to network models without geometric constraints, we observe algebraic scaling of the network diameter with system size and predict the characteristic link length distribution, both features fitting with those experimentally observed in PRN*s.

[1] Molkenthin & Timme, Scaling Laws in Spatial Network Formation, Phys. Rev. Lett. 117:168301 (2016)

SOE 13.11 Wed 12:00 MA 001

Non-inertial reference frames for inferring networks from dynamics — •Jose Casadiego[1,2] and Marc Timme[1,2] — [1]Chair for Network Dynamics, Institute of Theoretical Physics and cfaed - Center for Advancing Electronics Dresden, Technical University of Dresden, Dresden, Germany — [2]Network Dynamics, Max Planck Institute for Dynamics and Self-Organization (MPIDS), Goettingen, Germany

The dynamics of complex networks are determined to a great extent by the connectivity of their units. Given that measuring the connectivity by direct methods is often infeasible, researchers typically apply inverse approaches to infer links between units from the collective dynamics. Current state-of-the-art methods rely on either (i) quantifying functional links through statistical dependencies, or (ii) approximating the possibly nonlinear interactions between units via modeling of differential equations. Yet, functional links frequently do not match physical links, and finding an appropriate model may be computationally demanding and also require a prior knowledge about the interactions. Here we develop a model-independent theory to reconstruct the connectivity of networks from transients states to stable dynamics. Specifically, we demonstrate that representing these transients with respect to non-inertial reference frames provides simple linear mappings between network connectivity and dynamics. Furthermore, we show the robustness of our framework by reconstructing the full connectivity of different network dynamical systems exhibiting phase-locking, periodic orbits and collective synchronization.