Higher-Order Topology & Dynamics in Complex Networks
Satellite Symposium within NetSci2022

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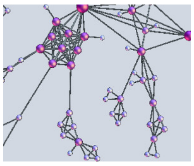

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Abstracts

- **Nuno A. M. Araujo**, ***Optimal nets for self-folding Kirigami***

  Three-dimensional shells can be synthesized from the spontaneous self-folding of two-dimensional templates of interconnected panels, called nets. However, some nets are more likely to self-fold into the desired shell under random movements. The optimal nets are the ones that maximize the number of vertex connections, i.e., vertices that have only two of its faces cut away from each other in the net. Previous methods for finding such nets are based on random search and thus do not guarantee the optimal solution. We proposed a deterministic procedure [1]. Our method allows not only to design the self-assembly of much larger shell structures but also to apply additional design criteria, as a complete catalog of the nets with the maximum number of vertex connections is obtained.
  [1] N. A. M. Araujo, R. A. da Costa, S. N. Dorogovtsev, J. F. F. Mendes, Physical Review Letters 120, 188001 (2018).

- **Ginestra Bianconi**, ***The dynamics of higher-order networks: the effect of topology and triadic interactions***

  Higher-order networks capture the interactions among two or more nodes in complex systems ranging from the brain to chemical reaction networks. Here we show that higher-order interactions are responsible for new dynamical processes that cannot be observed in pairwise networks. We will cover how topology is key to define synchronization of topological signals, i.e. dynamical signal defined not only on nodes but also on links, triangles and higher-dimensional simplices in simplicial complexes. Interesting topological synchronization dictated by the Dirac operator can lead to the spontaneous emergence of a rhythmic phase where the synchronization order parameter displays low frequency oscillations which might shed light on possible topological mechanisms for the emergence of brain rhythms. We will also reveal how triadic interactions can turn percolation into a fully-fledged dynamical process in which nodes can turn on and off intermittently in a periodic fashion or even chaotically leading to period doubling and a route to chaos of the percolation order parameter.

- **Stefano Boccaletti**, ***Structure, processes and dynamics of networks with higher order interactions***

  All the beauty, richness and harmony in the emergent dynamics of a complex system largely depend on the specific way in which its elementary components interact. The last twenty years have seen the birth and development of the multidisciplinary field of Network Science, wherein a variety of distributed systems in physics, biology, social sciences and engineering have been modelled as networks of coupled units, in the attempt to unveil the mechanisms underneath their observed functionality.
  But there is a fundamental limit in such a representation: networks capture only pairwise interactions, whereas the function of many real-world systems not only involves dyadic

connections, but rather is the outcome of collective actions at the level of groups of nodes. For instance, in ecological systems, three or more species may compete for food or territory, and similar multi-component interactions appear in functional and structural brain networks, protein interaction networks, semantic networks, multi-Authors scientific collaborations, offline and online social networks, gene regulatory networks and spreading of consensus or contagious diseases due to multiple, simultaneous, contacts. Such multi-component interactions can only be grasped through either hypergraphs or simplicial complexes, which indeed have recently found a huge number of applications in social and biological contexts, as well as in engineering and brain science.
In my talk, I will describe a series of questions which arise when one goes beyond the limit of pairwise interactions in a networked system. In particular, I will try to focus on some structural issues of these new objects, such as the need of properly redefining centrality and rankings of nodes, as well as on a series of new emerging phenomenologies (such as the setting of synchronization and game equilibria) that occur on top of such new objects.

- **Lucille Calmon**, ***Dirac Synchronization: explosive transition and rhythmic phase***

Recently topology has been shown to be key to capture higher-order network dynamics. In particular, topology provides the mathematical tools to treat the dynamics of topological signals: i.e. dynamical variables defined not only on nodes, but also links and higher-order simplices in a simplicial complexes. Indeed it was found in [1] that topological signals of a given dimension can synchronize, and the dynamics is explosive when the coupling is global and adaptive. This raises several important questions: how can we treat and couple dynamics of signals of different dimensions? Can we define a local and topological coupling between phases associated to simplices of different orders? Here we propose Dirac Synchronization [2], a mathematical framework that uses the recently proposed Dirac operator [3] to couple locally and topologically oscillating phases associated to nodes and to links of a network. This general framework couples topological signals of different dimensions introducing a phase lag in the dynamics of the phases that depends on the upper and lower adjacent neighbouring signals. We find in [2] that the dynamics of Dirac synchronization is explosive for signals on fully connected networks. By investigating numerically and analytically Dirac synchronization, we reveal that the phase diagram contains a discontinuous forward phase transition, and the backward transition is continuous. Our theoretical results are in excellent agreement with our numerical simulations and show that this hysteresis loop is thermodynamically stable. We also find that the coherent phase of this dynamics is non-stationary, and the complex order parameter coherently oscillates at an emergent non-zero frequency. This exotic rhythmic phase is a very special feature of Dirac synchronization dynamics, which can shed light on topological mechanisms for the emergence of brain rhythms. These results will be extended in the future to reveal further interplay between real-world network topology and geometry and dynamics.
[1] A.P Millan, J.J. Torres, and G. Bianconi, Explosive higher-order Kuramoto dynamics on simplicial complexes, Phys. Rev. Let. 124, 218301 (2020).
[2] L. Calmon, J.G. Restrepo, J.J. Torres, and G. Bianconi, Topological synchronization: explosive transition and rhythmic phase, arXiv:2107.05107, (2021).
[3] G. Bianconi, The topological Dirac equation of networks and simplicial complexes, JPhys. Complexity 2, 035022 (2021).

- **Malajaya Chutani, Bosiljka Tadic and Neelima Gupte**, ***Patterns of phase synchronization on high-diemnsional simplicial complexes***

We study the phase synchronization of simple Kuramoto oscillators attached to the nodes in two classes of high-dimensional simplicial complexes. Specifically, we consider (a) simplexes of different orders (up to 14-clique) attached to the brain hubs in the human connectome; (b) mono-clique complex consisting of geometrically assembled 5-cliques. The leading pairwise coupling promotes a continuous synchronization in both systems, leading to complete synchrony for strong positive coupling. In contrast, a partial synchronization occurs, with different order parameter values, when the pairwise coupling is negative. The addition of the triangle-based interactions changes the synchronization curve and opens the hysteresis loop, as shown in [1]. This presentation focuses on the time trajectories of individual phases, which are behind the observed partial synchronization, primarily for the negative pairwise couplings. We have observed co-evolving groups of nodes with partially synchronized phases. Interestingly, these groups of trajectories move around the phase circle at different speeds in the case of the human connectome complexes; consequently, such phase evolution patterns lead to temporal oscillations of the global order parameter. More precisely, the time fluctuations of the order parameter possess multi-scale fractal features and long-range temporal correlations [2]. The oscillatory patterns and the corresponding quantitative indicators of multifractal fluctuations vary with the coupling's strength (and sign), which correlates with the number of partially-synchronized groups and their phase evolution velocity. In contrast, the partial synchrony in the 5-cliques assembly results in a dominant weakly synchronized group of nodes with uniformly moving phases, resulting in steady order-parameter evolution. These results indicate the relevance of the composition of simplicial complexes and how they are embedded into mesoscopic communities and global network architecture, anatomically constrained in the case of the human connectome.

[1]M. Chutani, B. Tadic, N. Gupte: Hysteresis and synchronization processes of Kuramoto oscillators on high-dimensional simplicial complexes with competing simplex-encoded couplings, Phys. Rev. E 104, 034206 (2021)
[2] B. Tadic, M. Chutani, N. Gupte: Multiscale fractality in partial phase synchronization on simplicial complexes around brain hubs, Chaos Solitons and Fractals, (in press) (2022)

- **Sergey Dorogovtsev**, ***Rich phase diagrams for networks with overlapping layers***

I survey a set of percolation problems for multilayer networks having some edges overlapping with edges in other layers. For a mutually connected component problem, it is well understood that the phase transition is discontinuous for any finite fraction of overlapping edges, providing a simple phase diagram. This result was derived by three different techniques. On the other hand, a generalization of the k-core problem to such networks provides a set of more complicated phase diagrams depending on the number of layers and on how these layers are overlapped. These phase diagrams contain the lines of continuous and discontinuous transitions connected in various ways.

[1] G. J. Baxter, G. Bianconi, R. A. da Costa, S. N. Dorogovtsev, and J. F. F. Mendes, Correlated edge overlaps in multiplex networks, Phys. Rev. E 94, 012303 (2016).
[2] N. Azimi-Tafreshi, J. Gómez-Gardenes, and S. N. Dorogovtsev, k-core percolation on multiplex networks, Phys. Rev. E 90, 032816 (2014).
[3] G. J. Baxter, R. A. da Costa, S. N. Dorogovtsev, and J. F. F. Mendes, Weak Multiplex Percolation (Cambridge University Press, Cambridge, 2021).

- **Dibakar Ghosh**, ***Higher-order interactions promote chimera and synchronization states***

We will discuss two collective states, namely chimera and synchronization states, in higher-order interaction networks. Since the discovery of chimera states, the presence of a nonzero phase lag parameter turns out to be an essential attribute for the emergence of chimeras in a nonlocally coupled identical Kuramoto phase oscillators' network with pairwise interactions. Recently, we report the emergence of chimeras without phase lag in a nonlocally coupled identical Kuramoto network owing to the introduction of nonpairwise interactions. The influence of added nonlinearity in the coupled system dynamics in the form of simplicial complexes mitigates the requisite of a nonzero phase lag parameter for the emergence of chimera states. For synchronization state, the interplay between higher-order interactions topology and coupling configurations is not well explored yet. We study the stability for synchronization state in simplicial complexes with multiple interaction layers. Although more recent research has focused on static networks with higher-order interactions, such group interactions have not yet been considered in the context of temporal networks. Recently, we derive the stability for synchronization in time-varying higher-oredr interactions.

1. S Majhi, M Perc, and D Ghosh, Dynamics on higher-order networks: A review, Journal of the Royal Society Interface 19 (188), 20220043 (2022)
2. S Kundu, and D Ghosh, Higher-order interactions promote chimera states, Physical Review E 105 (4), L042202 (2022)
3. MS Anwar, and D Ghosh, Intralayer and interlayer synchronization in multiplex network with higher-order interactions, Chaos: An Interdisciplinary Journal of Nonlinear Science 32 (3), 033125 (2022)

4. MS Anwar and D Ghosh, Stability of synchronization in time-varying simplicial complexes (in preparation) /font>

- **Polina I. Kakin**, ***Self-organized criticality: renormalization group analysis of a simple model that elucidates interplay between intrinsic dynamics and external disturbances***

The Hwa-Kardar model of a "running sandpile" is a stochastic equation for a coarse-grained field that describes evolution of anisotropic system with self-organized criticality [Phys. Rev. Lett. 62, 1813 (1989); Phys. Rev. A 45, 7002 (1992)]. Using the Martin-Siggia-Rose-Janssen-de Dominicis formalism one can cast the equation into a field theory that can be then studied with the renormalization group (RG) analysis. The latter allows one to explore "critical" points (RG equations fixed points) that determine universality classes and related critical exponents. We use this investigative setup to study competition between intrinsic dynamics and external disturbances by adding random motion of the environment modelled by Gaussian velocity ensembles or by the Navier-Stokes stochastic equation. While chaotic external flows are known to dramatically affect critical behaviour, we found that it is a contest between strongly anisotropic intrinsic dynamics and isotropic external disturbances that produce the most interesting results. Isotropic flow may "wash away" the anisotropy of the system altogether but surprisingly it does not always preclude the restoration of original strong anisotropy via highly nontrivial mechanism. New crossover universality class can also appear where the anisotropy survives, but becomes "weakened" in a sense that there is no longer two independent dimensions corresponding to different directions. Anisotropic flow, on the other hand, brings interesting results when Hwa-Kardar model is altered to include a columnar (time-independent or spatially quenched) random noise instead of the white noise. Fixed points in this case turn out to have overlapping stability regions; the situation may be interpreted as a universality violation. It is especially interesting that the same model without external flow does not predict this.

- **Jasper van der Kolk, M. Angeles Serrano, and Marian Boguna**, ***Topological phase transitions in the geometric configuration model***

J The (soft) configuration model (CM) has been extremely successful as a null model for real networks. Given a degree sequence from a real network, the CM is defined as the maximally random graph ensemble with that given (expected) degree sequence. A remarkable property of this model is the fact that interactions among nodes are pairwise. In its soft version, this is equivalent to say that any pair of nodes i,j are connected independently with probability pij ~ κiκj/N, with κi and κj accounting for the expected degrees of nodes i and j. However, the CM model is unable to generate finite clustering in the thermodynamic limit because the connection probability is inversely proportional to the system size. To overcome this problem, we introduced the network geometry paradigm [1], which main hy- pothesis states that the architecture of real complex networks has a geometric origin. The nodes of the complex network can be characterized by their positions in an underlying metric space so that the observable network topology—abstracting their patterns of interactions—is then a reflection of distances in this space. This simple idea led to the development of a very general framework able to explain the most ubiquitous topological properties of real networks, namely, degree heterogeneity, the small-world property, and high levels of clustering. Network geometry is also able to explain in a very natural way other non-trivial properties, like self-similarity and community structure, their navigability properties, and is the basis for the definition of a renormalization group in complex networks. Quite strikingly, these results are achieved with only pairwise interactions among nodes, while higher order structures are naturally induced by the underlying metric space. Within this paradigm, the (soft) geometric configuration model (GCM) is defined as the maximally random ensemble of geometric random graphs able to generate graphs with a given (expected) degree sequence that are simultaneously sparse, small-world, clustered, and without degree-degree correlations [2]. Clustering in the GCM undergoes a phase transition between a geometric phase with finite clustering coefficient in the thermodynamic limit and a non-geometric phase where the clustering coefficient is zero. This transition, however, does not fit within the Landau symmetry breaking paradigm. Instead, it is a topological phase transition between two different topological orders. Upon mapping the network ensemble to a system of noninteracting fermions at temperature β−1, we find an anomalous behavior for the entropy of the ensemble, which diverges at the critical point. This leads to an anomalous scaling behavior for finite systems and to the definition of an effective system size scaling logarithmically with the number of nodes [3].

[1]M. Boguna,I. Bonamassa,M. DeDomenico,S. Havlin, D. Krioukov, and M.Angeles Serrano. Network geometry. Nature Reviews Physics, 3:114–135, 2021.
[2] M. Boguna, D. Krioukov, P. Almagro, and M.Angeles Serrano. Smallworlds and clustering in spatial etworks.Phys.Rev.Research,2:023040,2020.
[3] J. van der Kolk, M. Angeles Serrano, and M. Boguna. An anomalous topological phase transition in spatial random graphs. arXiv.2106.08030, 2021.

- **Jongshin Lee, and B. Kahng** , ***(k,q)-core percolation of hypergraphs***

Selecting a highly-connected subgraph from a hypergraph, analogous to k-core in the ordinary graph with pairwise interactions, is an essential subject. Here, we consider (k, q)-core percolation in hypergraphs. The (k,q)-core is the largest subgraph in which vertices have at least k hypergraph degree, and hyperedges contain at least q vertices. To obtain the dynamic equation for (k,q)-core and the percolation threshold, we construct an analytic framework to understand the (k,q)-core percolation transition. We find that a hybrid phase transition occurs for $k \geq 3$ or $q \geq 3$ at a finite transition point. We also quantify the critical slowing down that appears at this critical point.

- **Matteo Marsili**, ***Simplicity calls for higher order interactions in statistical learning***

Occam razor, as applied to learning, suggests that learning should satisfy principles that are rather different from those on which popular learning machines, such as Restricted Boltzmann Machines, are based. The internal representation of a learning machine trained on a complex dataset should be as parsimonious as possible. Internal states should not be assumed if they are not necessary and features should not be introduced unless they are needed ("Pluralitas non est ponenda sine necessitate"). This entails a hierarchical organisation of features, which is consistent with a recently proposed principle of maximal relevance and that can only be realised only within models going beyond pairwise interactions. I will illustrate this point with two special cases: the inability of Gaussian learning machines to describe complex datasets and a simple (exactly soluble) hierarchical spin model that is consistent with Occam razor. (joint work with Rongrong Xie and Roberto Mulet).

- **Marija Mitrovic Dankulov & Bosiljka Tadic**, ***Higher-distance connectivity portraits and spectral dimension of human connectomes***

Research into the functional architecture of the human connectome has been enabled by massive brain imaging data and the mapping onto brain networks. Evolutionary developments lead to the robust anatomical structure of the human brain but with variations in the number of fibre bundles connecting different anatomical areas in the female and male connectomes, thus supporting the differences in the entire activity, psychology and behaviour. In particular, the quantitative analysis of the female and male consensus connectomes revealed different connectivity in the hidden geometry consisting of higher-order simplicial complexes [1,2] and at the underlying graph level [3]. Here, we present an analysis of the network portraits, a graph invariant independent of the labelling of the nodes. We consider the consensus female connectome (with the edges common to 100 female individuals) and the maile connectome (common to 100 male individuals). Based on the HC imaging data, it is constructed [1] at the Budapest connectome server. The network portrait is particularly suitable for comparing these two anatomically similar structures based on the higher-distance connectivity. Our results revealed that, despite the visually close profiles of the female and male connectomes, the KS distance between them can be substantial and varies with the shortest-path distance across the brain and the weight threshold for the edges. Furthermore, we have found that the female and male connectomes have the same spectral dimension ds~2, based on the 1-distance connections related to the standard diffusion operator in these networks [4]. These findings suggest that the evolutionary developments led to the robustly designed structures of the human connectomes to support fundamental dynamic processes; meanwhile, the nuanced differences may manifest in the collective-dynamic fluctuations.

[1] B. Tadic, M. Andjelkovic, R. Melnik, Functional Geometry of Human Connectomes, Sci. Rep. 9, 12060 (2019)

[2] M. Andjelkovic, B. Tadic, R. Melnik,The topology of higher-order complexes associated with brain hubs in human connectomes, Sci. Rep. 10, 17320 (2020)
[3] B. Szalkai, B. Varga, V. Grolmusz, Graph theoretical analysis reveals: Women's brains are better connected than men's. PLoS One 10(7), 1–30, 07 (2015).
[4] M. Mitrovic Dankulov, B. Tadic, R. Melnik, Spectral properties of hyperbolic nanonetworks with tunable aggregation of simplexes, Phys. Rev. E 100, 012309 (2019)

- **Geza Odor**, ***Higher-order interactions generate mixed order phase transition and Griffiths phases on heterogeneous complex networks***

In d>2 dimensional, homogeneous threshold models discontinuous phase transition emerge, but the mean-field solution provides 1/t power-law activity decay and other power laws, and thus it is called mixed-order or hybrid type. This is in contrast with simple unary reaction spreading models, where continuous transition occur [1]. Quasi-static network heterogeneity can cause dynamical criticality below the transition point if the dimension is d<4 [1]. We provide numerical evidence that even in case of high graph dimensional hierarchical modular networks a Griffiths phase in the K=2 threshold model is present below the hybrid phase transition. This is due to the fragmentation of the activity propagation by modules, which are connected via single links. This delivers a widespread mechanism in the case of the threshold type of heterogeneous systems, modeling the brain, socio or epidemic spreading for the occurrence of dynamical criticality in extended Griffiths phase parameter spaces [3].

[1] G. Odor, Universality classes in nonequilibrium lattice systems Rev. Mod. Phys. 76 (2004) 663. Phase transition classes in triplet and quadruplet reaction-diffusion models, Phys. Rev. E 67 (2003) 056114.
[2] M. A. Munoz, R. Juhasz, C. Castellano, and G, Odor, Griffiths Phases on Complex Networks, Phys. Rev. Lett. 105, 128701 (2010)
[3] Geza Odor and Beatriz de Simoni, Heterogeneous excitable systems exhibit Griffiths phases below hybrid phase transitions, Phys. Rev. Res. 3 (2021) 013106.

- **Gergely Palla**, ***The inherent community structure of hyperbolic networks***

Hyperbolic network models are centred around the idea of placing nodes at random into a hyperbolic space and connecting node pairs according to a probability that is decreasing as a function of the hyperbolic distance. Remarkably, the random graphs generated this way are usually small-world, highly clustered and scale-free, allowing these models to reproduce the most important universal features of real networks in a natural way, without any further exogenous mechanisms. A recently discovered further feature of hyperbolic networks is that they can also display a rather strong community structure in a wide range of the model parameters, in spite any explicit community formation actions built into the network generation procedure. In the talk I will discuss the background and consequences of this intrinsic modular structure, including also analytical results related to the modularity of growing hyperbolic networks.

- **Alexander Shapoval**, ***Random transport of stress to provide the prediction efficiency in sandpiles***

Substantiated explanations of the unpredictability regarding sandpile models of self-organized criticality (SOC) gave way to efficient forecasts of extremes in few models. The appearance of extremes requires a preparation phase which ends up with general overloading of the system and spatial clustering of the local stress. The prediction problem successfully tackled by scholars can be formulated as the identification in advance of short alarm intervals such that extreme events occur within these intervals. The efficiency of the prediction posed with such formulation is naturally estimated with the fail-to-predict and alarm rates. Prediction algorithms designed for practical applications should avoid the information regarding the current amount of stress in the system, as this information is not observable in practice. Historical records back up the prediction instead. According to the-state-of-the-art, a low rate of large events results in overloading. This property is possible to quantify into the precursor of extremes. A few such attempts resulted in efficient predictions in the BTW and Manna sandpiles, which are the fundamental models of SOC producing power-law distributions with the deterministic and random transport of stress respectively. The purpose of this presentation is to exhibit the comparative analysis of the prediction efficiency in the BTW and Manna sandpiles. I will choose a single algorithm predicting the occurrence of extremes in both models. While the system size is small, the efficiency attains similar values. However the algorithm is more efficient with the Manna model as soon as the system volume enlarges. I'll show that the efficiency is characterized by the scaling with respect to the system volume. The exponents describing the scaling are 2.75 and 3 in the thermodynamic limit for the Manna and BTW sandpiles respectively. This result indicates that only the largest events, non-observable within any reasonable time interval, are predictable in the BTW model in the case of a large system volume. On the contrary, all events located to the right of the power-lower segment of events' probability distribution are characterized by the efficient prediction in the Manna model. The efficiency increases with events' size. A small correction to the scaling in the Manna model related to the system volume coincides with that required to collapse the power-law segment of events' probability distribution over sizes. The mechanism, responsible for a more efficient prediction in the Manna than BTW sandpile, is yet unknown. The presentation is based on results obtained with D. Savostianova (Gran Sasso Sci- ence Institute), D. Sapozhnikov (HSE University), M. Shnirman (Institute of Earthquake Prediction Theory and Mathematical Geophysics).

- **Deborah Sulem, Henry Kenlay, Mihai Cucuringu, Xiaowen Dong**, ***Graph similarity learning for change-point detection in dynamic networks***

Dynamic networks are ubiquitous for modelling sequential graph-structured data, e.g., brain connectome, population flows and messages exchanges. In this work, we consider dynamic networks that are temporal sequences of graph snapshots, and aim at detecting abrupt changes in their structure. This task is often termed network change-point detection and has numerous applications, such as fraud detection or physical motion monitoring. Leveraging a graph neural network model, we design a method to perform online network change-point detection that can adapt to the specific network domain and localise changes with no delay. The main novelty of our method is to use a siamese graph neural network architecture for learning a data-driven graph similarity function, which allows to effectively compare the current graph and its recent history. Importantly, our method does not require prior knowledge on the network generative distribution and is agnostic to the type of change-points; moreover, it can be applied to a large variety of networks, that include for instance edge weights and node attributes. We show on synthetic and real data that our method enjoys a number of benefits: it is able to learn an adequate graph similarity function for performing online network change-point detection in diverse types of change-point settings, and requires a shorter data history to detect changes than most existing state-of-the-art baselines.

[1] Yu Y, Padilla OHM, Wang D, et al (2021) Optimal network online change point localisation. arxiv.2101.05477
[2] Ktena SI, Parisot S, Ferrante E, et al (2017) Distance metric learning using graph convolu- tional networks: Application to functional brain networks. In: International Conference on Medical Image Computing and Computer- Assisted Intervention, Springer, pp 469–477

- **Michael Small**, ***Link prediction and fault detection for structured engineered networks***

This is joint work with **KeKe Shang**. We address the problem of applying measures of network structure to networks that have been deliberately engineered to serve some purpose. Often, network design rules are microscopic - such as preferential attachment. We consider the situation where a network is deliberately designed to serve some large scale purpose - and fit some macroscopic objective function. Engineered transport networks are an example of such system, and we specifically focus our attention on the metropolitan potable and sewage water distribution networks for Perth, Western Australia. First, we observe that cliques and higher-rder structures in the network and useful predictors of assortative component failure in the network . Second, we show that a randomised comparison of microscopic networks structures in the engineered network and idealised proxies can be used to predict nascent component failure in the system. Third, we introduce link prediction algorithm tailored for networks with inherent large-scale structures - either large loopy networks, or tree-like networks. We show how this can be applied to engineered networks to learn about how best to improve the robustness and efficiency of these networks.

- **Hanlin Sun**, ***Higher-order percolation processes on multiplex hypergraphs***

Abstract: Higher-order interactions are increasingly recognised as a fundamental aspect of complex systems ranging from the brain to social contact networks. Hypergraph as well as simplicial complexes capture the higher-order interactions of complex systems and allow to investigate the relation between their higher-order structure and their function. In this work, we establish a general framework for assessing hypergraph robustness and we characterize the critical properties of simple and higher-order percolation processes. This general framework builds on the formulation of the random multiplex hypergraph ensemble where each layer is characterized by hyperedges of given cardinality. We reveal the relation between higher-order percolation processes in random multiplex hypergraphs, interdependent percolation of multiplex networks and K-core percolation. The structural correlations of the random multiplex hypergraphs are shown to have a significant effect on their percolation properties. The wide range of critical behaviors observed for higher-order percolation processes on multiplex hypergraphs elucidates the mechanisms responsible for the emergence of discontinuous transition and uncovers interesting critical properties which can be applied to the study of epidemic spreading and contagion processes on higher-order networks.

[1] Hanlin Sun and Ginestra Bianconi, Higher-order percolation processes on multiplex hypergraphs, Phys. Rev. E 104, 034306 (2021)

- **Bosiljka Tadic**, ***Spin-reversal dynamics on simplicial complexes: Impact of the geometric frustration and higher-order couplings***

Geometric frustration effects often occur in the magnetization reversal driven by the external magnetic field on nano-assemblies with complex architecture. We study the collective magnetization fluctuations on model systems grown by the geometric aggregation of cliques of different sizes [1] and Ising spins attached to nodes. Then the antiferromagnetic pairwise couplings among spins ideally support the geometric frustration on the triangle faces of the embedded cliques. Moreover, these structures can support the higher-order spin couplings based on the exact topology faces of all orders up to the highest clique (the order of the simplicial complex). Considering the spin-reversal process on an assembly with distributed cliques order in the range from 1 to 9, we show that this topology, in conjunction with the antiferromagnetic pairwise interactions, leads to a characteristic slim hysteresis loop with multiple plateaus. The transition between these plateaus is characterized by collective fluctuations with a multifractal structure and magnetization avalanches. The scale-invariant distributions of the avalanches are observed, characteristic of the self-organized critical dynamics [2]. Furthermore, we consider competition between the antiferromagnetic pairwise and tri-spin interactions embedded on exact triangles on an assembly consisting of the aggregated triangles [3]; We show how the higher-order coupling changes the shape of the hysteresis loop. However, the collective fluctuations and avalanches are robustly present, with the scaling exponents and the multifractal spectra depending on the parameter that balances these competing interactions. These findings suggest that, while the topology descriptors (clique sizes) are relevant to the hysteresis-loop shape, the long-range effects of the geometric frustration induced by the leading antiferromagnetic interactions are critical for the collective fluctuations.

[1] M. Suvakov, M. Andjelkovic, B. Tadic, Hidden geometry of networks arising from cooperative self-assembly, Sci.Rep. 8, 1987 (2018)
[2] B. Tadic, R. Melnik: Self-organized criticality as a key feature for complexity in physical, biological, and social networks, Dynamics 1(2), 181-197 (2021)
[3] B. Tadic, N. Gupte: Hidden geometry and dynamics of complex networks: spin reversal in nanoassemblies with pairwise and triangle-based interactions, Europhys. Lett. 132, 60008 (2021)