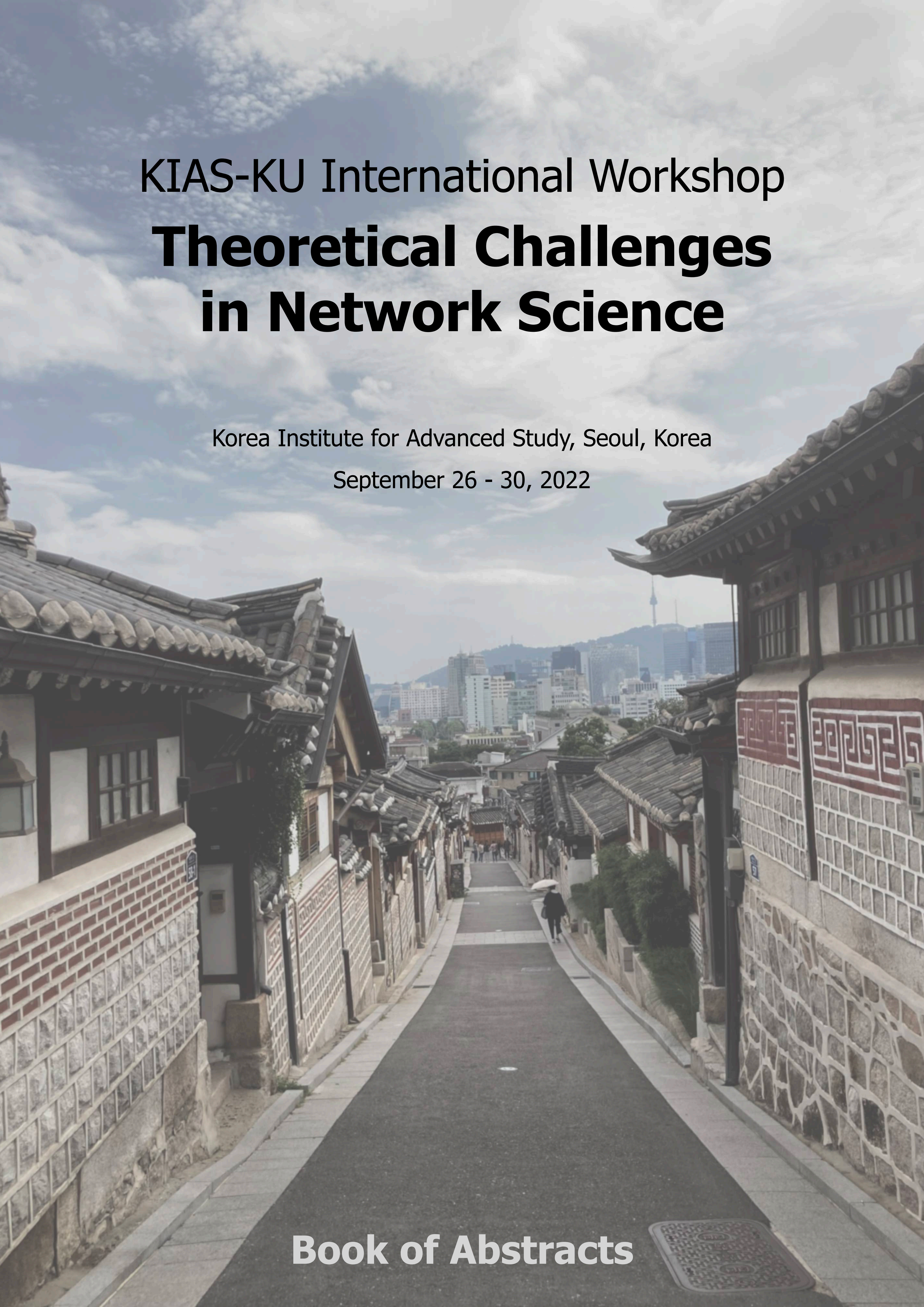

KIAS-KU International Workshop

Theoretical Challenges in Network Science

Korea Institute for Advanced Study, Seoul, Korea

September 26 - 30, 2022

Book of Abstracts

KIAS-KU International Workshop: Theoretical Challenges in Network Science

	9/26 Monday	9/27 Tuesday	9/28 Wednesday	9/29 Thursday	9/30 Friday	10/1 Saturday
09:00 - 09:30	Registration, coffee & sandwiches					
09:30 - 10:30	Chair H. Jeong **N. Masuda** Long-tailed distributions of inter-event times as mixtures of exponentials	Chair G.F. de Arruda **M. Boguñá** Topological phase transitions in the geometric configuration model	Chair M. Boguña **M. Pósfai** Physical networks	Chair M. Pósfai **L. Hébert-Dufresne** Advances in the analytical modeling of complex networks using network compression	Chair B. Kahng **J.F.F. Mendes** Multiplex networks: an overview	**Round table**
10:30 - 10:45	Q&A/break	Q&A/break	Q&A/break	Q&A/break	Q&A/break	
10:45 - 11:45	**B. Kahng** Mitigation of Nonlocal Cascading Failures and Universal Hybrid Percolation Transitions	**S.-H. Yook** Information diversity and anomalous scaling of the information landscape	**J. Park** Probalistic Reference Network and Creativity: Perspectives for human creativity in the Post-AI era	**S.-W. Son** Phase transition of growing complex networks and its application	**B. Min** Effect of heterogeneous adoptability and adaptation in complex contagions on networks	
11:45 - 12:00	Q&A	Q&A	Q&A	Q&A	Q&A	
12:00 - 14:15	Lunch					
14:15- 15:15	Chair N. Masuda **B.J. Kim** Defense strategies against network failures	Chair L. Hébert-Dufresne **G.F. de Arruda** Social contagion models on hypergraphs: Multistability, intermittency, and hybrid transitions	**Excursion**	Chair Y. Moreno **S.H. Lee** Scale-dependent landscape of semi-nested community structures of 3D chromosome contact networks	Chair J.F.F. Mendes **Y.-H. Eom** Revealing the role of flow network organization in the global efficiency of urban traffic flows	
15:15 - 15:30	Q&A/break	Q&A/break		Q&A/break	Q&A/break	
15:30 - 16:30	**H. Jeong** Understanding Complex Systems via D.N.A.(Data, Networks, AI)	**H. Kim** Challenges in studying the synchronization stability of power grids		**Y.S. Cho** Dynamics of clusters in synchronization and percolation models	**Y. Moreno** A critical revision of spreading dynamics on single, multilayer, and higher-order networks	
16:30 - 16:45	Q&A	Q&A/break		Q&A/break	Q&A	
16:45-17:45	**Poster**	**H.-H. Jo** Bursty time series analysis for temporal networks		**S. Havlin** Interdependent Networks (online)	Closing	
17:45 - 18:00		Q&A		Q&A		
18:00 - 20:00		**Banquet**				

Aim

Anticipating the silver jubilee since its modern reincarnation, the network science is still vigorous in compelling theoretical ideas and challenges. The aim of the Workshop is, after the long forced hiatus due to global pandemic, to summon the leading experts in the frontiers of theoretical network science and to promote the focused and active discourse about the current challenges and future perspectives in network science with emphasis on theoretical aspects. We hope this in-person workshop will provide a timely opportunity to solidify and expand the theoretical foundation of network science.

Topics

Major outstanding theoretical issues and challenges, including but not limited to: Higher-order networks, multiplex networks, network geometry and renormalizations, physical networks, time-varying networks and dynamics, network robustness, complex dynamic processes such as contagions, etc.

Invited speakers

Guilherme Ferraz de Arruda (CentAI)
Marián Boguñá (Barcelona)
Young Sul Cho (Jeonbuk Nat'l Univ.)
Young-Ho Eom (U. of Seoul)1
Shlomo Havlin (Bar-Ilan)
Laurent Hébert-Dufresne (Vermont)1
Hawoong Jeong (KAIST)
Hang-Hyun Jo (CUK)
Byungnam Kahng (KENTECH)
Beom Jun Kim (SKKU)
Heetae Kim (KENTECH)1
Sang Hoon Lee (GNU)
Naoki Masuda (Buffalo)
José F.F. Mendes (Aveiro)
Byungjoon Min (CBNU)

Yamir Moreno (Zaragoza)
Juyong Park (KAIST)
Márton Pósfai (CEU)
Seung-Woo Son (Hanyang)
Soon-Hyung Yook (Kyung Hee)

Organizers

Deok-Sun Lee (KIAS)
Kwang-Il Goh (Korea University)
Yamir Moreno (Zaragoza)

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Program

9/26 Monday

[Morning] Chair: Hawoong Jeong (KAIST)

09:30 - 10:30 José F.F. Mendes (Aveiro) Multiplex networks: an overview

10:45 - 11:45 Byungnam Kahng (KENTECH) Mitigation of Nonlocal Cascading Failures and Universal Hybrid Percolation Transitions

[Afternoon] Chair: Naoki Masuda (Buffalo)

14:15 - 15:15 Beom Jun Kim (SKKU) Defense strategies against network failures

15:30 - 16:30 Hawoong Jeong (KAIST) Understanding Complex Systems via D.N.A.(Data, Networks, AI)

[Posters] 16:45 - 18:00

[P1] Role of Geometric Correlations in Mutual Percolation: Multiscale Nature and Topological Explanation by Gangmin Son (KAIST)

[P2] Universal mechanism underlying in hybrid percolation transitions by Hoyun Choi (SNU)

[P3] Higher-order components in hypergraphs by Jung-Ho Kim (Korea U.)

[P4] Structure of international trade hypergraphs by Sudo Yi (KIAS)

[P5] A simple and realistic growing hypergraph models by Dahae Roh (Korea U.)

[P6] (k,q)-core pruning process of hypergraphs by Jongshin Lee (KENTECH)

[P7] Effective control of nonlocal cascading failures in complex networks using graph neural networks by Bukyoung Jhun (SNU)

[P8] A generalized model for wealth exchange in heterogeneous networks by Hyun Gyu Lee (KIAS)

[P9] The heterogeneity of complex network affects on the phase diagram of the AT model with a repulsive interaction by Cook Hyun Kim (KENTECH)

[P10] Optimal strategy for enhancing synchronization in growing coupled oscillators by Jong-Min Park (KIAS)

[P11] Energy-threshold-based stability analysis of power-grid systems by Daekyung Lee (KENTECH)

[P12] A Bifurcation and Numerical Continuation approach to selective extinction in Complex Mutualistic Networks by Andrus Giraldo (KIAS)

[P13] Identifying influential subpopulations in metapopulation epidemic models using message-passing theory by Jeehye Choi (CBNU)

[P14] Contagion dynamics on hypergraphs with nested hyperedges by Jihye Kim (Korea U.)

[P15] Lattice structure and spatial network models incorporated into simulating human-assisted invasion of a forest pest population by Tae-Soo Chon (Ecology and Future Research Institute, Pusan Nat'l University)

[P16] Evolution of Social media activity-financial market network Relationship by Jinjoo Yoon (Chosun U.)

9/27 Tuesday

[Morning] Chair: José F.F. Mendes (Aveiro)
09:30 - 10:30 Marián Boguñá (Barcelona) Topological phase transitions in the geometric configuration model
10:45 - 11:45 Soon-Hyung Yook (Kyung Hee) Information diversity and anomalous scaling of the information landscape

[Afternoon] Chair: Laurent Hébert-Dufresne (Vermont)
14:15 - 15:15 Guilherme Ferraz de Arruda (CentAI) Social contagion models on hypergraphs: Multistability, intermittency, and hybrid transitions
15:30 - 16:30 Heetae Kim (KENTECH) Challenges in studying the synchronization stability of power grids
16:45 - 17:45 Hang-Hyun Jo (CUK) Bursty time series analysis for temporal networks

9/28 Wednesday

[Morning] Chair: Marián Boguñá (Barcelona)
09:30 - 10:30 Márton Pósfai (CEU) Physical networks
10:45 - 11:45 Juyong Park (KAIST) Probabilistic Reference Networks and Creativity: Perspectives for human creativity in the Post-AI era

[Afternoon] Excursion

9/29 Thursday

[Morning] Chair: Márton Pósfai (CEU)
09:30 - 10:30 Laurent Hébert-Dufresne (Vermont) Advances in the analytical modeling of complex networks using network compression
10:45 - 11:45 Seung-Woo Son (Hanyang) Phase transition of growing complex networks and its application

[Afternoon] Chair: Yamir Moreno (Zaragoza)
14:15 - 15:15 Sang Hoon Lee (GNU) Scale-dependent landscape of semi-nested community structures of 3D chromosome contact networks
15:30 - 16:30 Young Sul Cho (Jeonbuk Nat'l Univ.) Dynamics of clusters in synchronization and percolation models
16:45 - 17:45 Shlomo Havlin (Bar-Ilan) Interdependent Networks

9/30 Friday

[Morning] Chair: Guilherme Ferraz de Arruda (CentAI)

09:30 - 10:30 Naoki Masuda (Buffalo) Long-tailed distributions of inter-event times as mixtures of exponentials

10:45 - 11:45 Byungjoon Min (CBNU) Effect of heterogeneous adoptability and adaptation in complex contagions on networks

[Afternoon] Chair: Byungnam Kahng (KENTECH)

14:15 - 15:15 Young-Ho Eom (U. of Seoul) Revealing the role of flow network organization in the global efficiency of urban traffic flows

15:30 - 16:30 Yamir Moreno (Zaragoza) A critical revision of spreading dynamics on single, multilayer, and higher-order networks

9/26 Monday
09:30 - 10:30

Multiplex networks: an overview

José F.F. Mendes (Aveiro)

The realization that many complex systems cannot be understood by representing them as a single network, has led to an explosion of interest in multilayer and multiplex (multiple types of edges) networks. To properly study multilayer systems, it is essential to understand the fundamental properties of such structures. In many cases, the generalization of concepts from single networks, for example, the meaning of "giant connected component", is not straightforward, and introduces a new dimension to the problem. For example, if we want to understand the robustness of critical infrastructures it is necessary to characterize the complex interdependencies between them. Critical phenomena in multilayer structures show surprising new features. It has been recently shown that when we consider several interdependent networks, the system as a whole might be much more fragile than single networks taken in isolation, and that the interdependencies between different networks can trigger cascading failure events of dramatic impact. For a sufficiently large number of layers, say, greater than 3, the complex structure of interconnections makes the problem of the mutually connected component principally richer than for a pair of interdependent networks. I will show that in the case of weak percolation for multiplex networks with overlapping edges turns out to be opposite to that on the giant mutually connected component. While for the giant mutually connected component, overlaps do not change the critical phenomena, our theory shows that in two layers any (nonzero) concentration of overlaps drives the weak percolation transition to the ordinary percolation universality class. Without overlaps, in two layers, the giant component emerges with a continuos phase transition, but with quadratic growth above the critical threshold. In three or more layers, a discontinuous hybrid transition occurs, similar to that found in the giant mutually connected component. In this talk I will give an overview of some of most recent results and mention some of the challenges for future in the topic.

invited talk

9/26 Monday
10:45 - 11:45

Mitigation of Nonlocal Cascading Failures and Universal Hybrid Percolation Transitions

Byungnam Kahng (KENTECH)

The prediction and control of cascading failures in complex networks is a central topic of research in network science. Cascading failures may propagate locally or nonlocally. Whereas conventional epidemic processes based on local contact process have been well understood as branching processes, cascading failures that propagate nonlocally. Most studies of nonlocal cascading failures have been limited to numerical simulations and enumeration. In this study, computational complexity becomes an important issue. Here, using the machine learning approach, we study a cascading failure dynamics that propagates nonlocally using the model proposed by Motter and Lai. This study reduces the computation time as short at O(N), making it possible to understand the propagation of cascading failure in detail and how to mitigate the cascading failures effectively.

A hybrid percolation transition (HPT) exhibits both discontinuity of the order parameter and critical behavior at the transition point. Such dynamic transitions can occur in two ways: by cluster pruning with suppression of loop formation of cut links or by cluster merging with suppression of the creation of large clusters. While the microscopic mechanism of the former is understood in detail, a similar framework is missing for the latter. By studying cluster merging models, we uncover the universal mechanism of the features of HPTs at a microscopic level. Our results provide a unified theoretical framework of the HPT.

9/26 Monday
14:15 - 15:15

Defense strategies against network failures

Beom Jun Kim (SKKU)

"Too-big-to-fail (TBTF)" is a controversial approach to reducing the risk of cascading failures in the financial systems. In the TBTF defense strategy, most financial supports are provided to very big companies in order to avoid the complete breakdown of the entire system. We also consider "too-small-to-fail (TSTF)" as a comparative defense strategy, in which financial supports are more focused on small companies instead. We use two types of model network and a real network based on inter-industry Input-Output Table as underlying structures for cascading failures, and examine the validity of both defense strategies with two types of bailout policy, indirect (node capacity is increased) and direct (node load is decreased). We evaluate and compare the performances of TBTF and TSTF strategies in preventing cascading failures, and demonstrate that TSTF performs better when the node capacity is increased whereas TBTF works better when the node load is decreased.

9/26 Monday
15:30 - 16:30

Understanding Complex Systems via D.N.A.(Data, Networks, AI)

Hawoong Jeong (KAIST)

In this presentation, I will briefly walk through what our lab has been doing for the last couple of years. Our lab, "the complex systems and statistical physics lab," aims to understand complex systems by employing statistical physics techniques such as network science, data science, and, more recently, artificial intelligence (AI). A few examples we studied include big-data analysis on art paintings, analyzing collaboration networks between scientists, and doing "physics" using machine learning techniques, especially deep neural networks.

[1] B. Lee, M.K. Seo, D. Kim, I.-s. Shin, M. Schich, H. Jeong, and, S. Han, "Dissecting landscape art history with information theory", Proc. Nat. Acad. Sci. USA (2020)
[2] G. Son, J. Yun, and H. Jeong, "Quantifying team chemistry in scientific collaboration" (submitted) [arXiv:2202.07252]
[3] D.-K. Kim, Y. Bae, S. Lee, and H. Jeong, "Learning entropy production via neural networks", Phys. Rev. Lett. 125 140604 (2020)
[4] S. Ha, and H. Jeong, "Discovering invariants via machine learning", Phys. Rev. Res. 3 L042035 (2021)
[5] S. Ha, and H. Jeong, "Unraveling hidden interactions in complex systems with deep learning", Sci. Rep. 11 12804 (2021)
[6] G. Kim, D.-K. Kim, and H. Jeong, "Spontaneous emergence of music detectors in a deep neural network" (submitted) [bioRxiv/2021.10.27.466049]

9/27 Tuesday
09:30 - 10:30

Topological phase transitions in the geometric configuration model

Marián Boguñá (Barcelona)

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 $p_{ij} \sim N^{-1} k_i k_j$, with k_i and k_j 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 hypothesis 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] Marián Boguñá, Ivan Bonamassa, Manlio De Domenico, Shlomo Havlin, Dmitri Krioukov, and M. Ángeles Serrano, Network geometry. Nature Reviews Physics, 3:114–135, 2021.

[2] Marián Boguñá, Dmitri Krioukov, Pedro Almagro, and M. Ángeles Serrano. Small worlds and clustering in spatial networks. Phys. Rev. Research, 2:023040, Apr 2020.

[3] Jasper van der Kolk, M. Ángeles Serrano, and Marián Boguñá. An anomalous topological phase transition in spatial random graphs. arXiv.2106.08030, 2021.

9/27 Tuesday
10:45 - 11:45

Information diversity and anomalous scaling of the information landscape

Soon-Hyung Yook (Kyung Hee)

The spreading of information on a social network is taken place through social contagion processes with the competition. To understand how competition affects the diversity of information, we study the social contagion model introduced by Halvorsen-Pedersen-Sneppen (HPS) [Phys. Rev. E {\bf 103} (2021)] on 1-d and 2-d static networks. By mapping the information value into the height of the interface, we find that the width, $W(N,t)$, does not satisfy the well-known Family-Viscek finite-size scaling ansatz. From the numerical simulations, we find that the dynamic exponent, z, should be modified for HPS model. For 1-d static networks, the numerical results show that the information landscape is always rough with an anomalously large growth exponent, β. Based on the analytic derivation of $W(N,t)$, we show that updating information by sparsely distributed influencers and recruiting new followers are responsible for the anomalous values of β and z. Furthermore, we also find that the information landscape on 2-d static networks undergoes a roughening transition, and the metastable state emerges only in the vicinity of the transition threshold.

9/27 Tuesday
14:15 - 15:15

Social contagion models on hypergraphs: Multistability, intermittency, and hybrid transitions

Guilherme Ferraz de Arruda (CENTAI)

Although ubiquitous, interactions of groups of individuals (e.g., modern messaging applications, group meetings, or even a parliament discussion) are not yet thoroughly studied. Frequently, single groups are modeled as critical-mass dynamics, which is a widespread concept used not only by academics but also by politicians and the media. However, less explored questions are how a collection of groups will behave and how the intersection between these groups might change the global dynamics. Here, we follow our initial formulation in terms of binary state dynamics on hypergraphs, which generalizes both the SIS epidemic spreading process and the simplicial complex contagion. We show that our model has a rich and unexpected behavior beyond discontinuous transitions, as initially expected for higher-order networks. In particular, we might have multistability and intermittency due to bimodal state distributions. Furthermore, by using artificial random models, we demonstrated that this phenomenology could be associated with community structures. Specifically, we might have multistability or intermittency by controlling the number of bridges between two communities with different densities. The introduction of bridges (hyperedges connecting different communities) destroys multistability but creates an intermittent behavior. Furthermore, we provide an analytical formulation showing that the observed pattern for the order parameter and susceptibility are compatible with hybrid phase transitions. Our findings open new paths for research, ranging from physics, on the formal calculation of quantities of interest, to social sciences, where new experiments can be designed.

9/27 Tuesday
15:30 - 16:30

Challenges in studying the synchronization stability of power grids

Heetae Kim (KENTECH)

A power grid is one of the world's largest networked systems. In a power-grid network. To supply quality electricity, the voltage and frequency of the electricity are supposed to be stabilized in a power grid. Recently, researchers have been investigating the synchronization stability of power grids based on the second-order Kuramoto model called the Swing equation [1,2] with the numerical estimation method called Basin stability [3]. The Basin stability has been successfully applied to understand the relationship between the topology of a power grid and the synchronization stability of the power-grid nodes [4-12]. However, it requires overcoming some technical and practical challenges to go beyond the topological understanding of the power-grid dynamics. In this talk, we will briefly look at what kinds of challenges—namely, promising research topics—should be considered.

[1] Filatrella, G., Nielsen, A. H. & Pedersen, N. F. Analysis of a power grid using a Kuramoto-like model. Eur. Phys. J. B 61, 485–491 (2008).
[2] Rodrigues, F. A., Peron, T. K. D., Ji, P. & Kurths, J. The Kuramoto model in complex networks. Phys. Rep. 610, 1–98 (2016).
[3] Menck, P. J., Heitzig, J., Marwan, N. & Kurths, J. How basin stability complements the linear-stability paradigm. Nat. Phys. 9, 89–92 (2013).
[4] Menck, P. J., Heitzig, J., Kurths, J. & Schellnhuber, H. J. How dead ends undermine power grid stability. Nat. Commun. 5, 3969 (2014).
[5] Kim, H., Lee, S. H. & Holme, P. Community consistency determines the stability transition window of power-grid nodes. New J. Phys. 17, 113005 (2015).
[6] Kim, H., Lee, S. H. & Holme, P. Building blocks of the basin stability of power grids. Phys. Rev. E 93 , 062318 (2016).
[7] Nitzbon, J., Schultz, P., Heitzig, J., Kurths, J. & Hellmann, F. Deciphering the imprint of topology on nonlinear dynamical network stability. New J. Phys. 19 , 033029 (2017).
[8] Ji, P., Lu, W. & Kurths, J. Stochastic basin stability in complex networks. Europhys. Lett. 122, 40003 (2018).
[9] Kim, H., Lee, S. H., Davidsen, J. & Son, S.-W. Multistability and variations in basin of attraction in power-grid systems. New J. Phys. 20 , 113006 (2018).
[10] Kim, H., Lee, M. J., Lee, S. H. & Son, S.-W. On structural and dynamical factors determining the integrated basin instability of power-grid nodes. Chaos 29 , 103132 (2019).
[11] Montanari, A. N., Moreira, E. I. & Aguirre, L. A. Effects of network heterogeneity and tripping time on the basin stability of power systems. Commun. Nonlinear Sci. 89, 105296 (2020).
[12] Kim, H. How modular structure determines operational resilience of power grids. New J. Phys. 23, 063029 (2021).

9/27 Tuesday
16:45 - 17:45

Bursty time series analysis for temporal networks

Hang-Hyun Jo (CUK)

Characterizing bursty temporal interaction patterns of temporal networks is crucial to investigate the evolution of temporal networks as well as various collective dynamics taking place in them. The temporal interaction patterns have been described by a series of interaction events or event sequences, often showing non-Poissonian or bursty nature. Such bursty event sequences can be understood not only by heterogeneous interevent times (IETs) but also by correlations between IETs. The heterogeneities of IETs have been extensively studied in recent years, while the correlations between IETs are far from being fully explored. We introduce various measures for bursty time series analysis, such as the IET distribution, the burstiness parameter, the memory coefficient, the bursty train sizes, and the autocorrelation function, to discuss the relation between those measures. We also present a burst-tree decomposition method for the time series analysis. Then we show that the correlations between IETs can affect the speed of spreading taking place in temporal networks. Finally, we discuss possible research topics regarding bursty time series analysis for temporal networks.

9/28 Wednesday
09:30 - 10:30

Physical networks

Márton Pósfai (CEU)

Physical networks -- networks with nodes and links that are physical objects embedded in space -- are shaped by constraints such as volume exclusion, the cost of building and maintaining nodes and links, and local assembly. Although particular physical networks such as neural networks, vascular networks, or electric circuits, have long been studied, the general theoretical framework of physical networks is still in its nascence. In my talk, I will review recent advances in understanding how volume exclusion affects physical networks. First, I will introduce two classes of mathematically tractable network models, each capturing an important aspect of physicality and allowing us to understand mechanisms through which the abstract structure of networks is affected by physical constraints. Then, I will review descriptors that aim to quantify how much individual links and nodes are affected by volume exclusion. These descriptors are used to show that the centrality of nodes in the abstract network is positively correlated with their physical confinement. I will end my talk with a list of open questions.

9/28 Wednesday
10:45 - 11:45

Probabilistic Reference Networks and Creativity: Perspectives for human creativity in the Post-AI era

Juyong Park (KAIST)

Recent advances in the quantitative, computational methodology for the modeling and analysis of heterogeneous large-scale data are leading to new opportunities for understanding human behaviors and faculties, including creativity that drives creative enterprises such as science. While innovation is crucial for novel and influential achievements, quantifying these qualities in creative works remains a challenge. Here we present an information-theoretic framework for computing the novelty and influence of creative works based on their generation probabilities reflecting the degree of uniqueness of their elements in comparison with other works. Applying the formalism to a high-quality, large-scale data set of classical piano compositions–works of significant scientific and intellectual value–spanning several centuries of musical history, represented as symbolic progressions of chords, we find that the enterprise's developmental history can be characterised as a dynamic process composed of the emergence of dominant, paradigmatic creative styles that define distinct historical periods. These findings can offer a new understanding of the evolution of creative enterprises based on principled measures of novelty and influence.

9/29 Thursday
09:30 - 10:30

Advances in the analytical modeling of complex networks using network compression

Laurent Hébert-Dufresne (Vermont)

Analytical descriptions of complex networks start with the representation of network data using random networks constrained to reproduce key structural features of the data. These constraints range in complexity from using the entire network structure (message passing approaches) to only using the degree distribution of the network (configuration model). However, none of the resulting analytical descriptions are exact and it is rarely clear when a more complicated model is justified by the data or by the quality of predictions. We will review new advances in network analyses and network descriptions to draw parallels between network modelling and network compression. In doing so, we outline a possible agenda for the future work of mathematical network models.

9/29 Thursday
10:45 - 11:45

Phase transition of growing complex networks and its application

Seung-Woo Son (Hanyang)

Complex networks are ubiquitous in diverse real-world systems, ranging from co-authorship social networks to protein interaction biological networks. Many of these empirical networks grow as time goes, by increasing the number of nodes and the number of links. The same thing happens even for the first scale-free network model. Percolation transition of the growing random networks model exhibits an infinite-order phase transition. The giant cluster in such growing networks emerges continuously with infinite-order critical behaviour. However, when the growth of large clusters is suppressed under some effects such as the Achlioptas process, the transition type changes to the second-order one. Furthermore, when the growth of large clusters is suppressed with global information, the continuous percolation transition changes to a discontinuous transition with an abrupt jump of the order parameter at a delayed transition point. Accordingly, the features of infinite-order, second-order, and first-order transitions all occur in a single framework when the infinite-order phase transition of growing networks is suppressed. We present a simple argument to explain the underlying mechanism of these abnormal transition behaviours, and derive an analytic form explicitly as a function of a control parameter, which represents the suppression strength, using the scaling ansatz. Finally, we discuss several applications and variations of the growing network.

9/29 Thursday
14:15 - 15:15

Scale-dependent landscape of semi-nested community structures of 3D chromosome contact networks

Sang Hoon Lee (GNU)

Mammalian DNA folds into 3D structures that facilitate and regulate genetic processes such as transcription, DNA repair, and epigenetics. Several insights derive from chromosome capture methods, such as Hi-C, which allow researchers to construct contact maps depicting 3D interactions among all DNA segment pairs. To better understand the organizing principles, several groups analyzed Hi-C data assuming a Russian-doll-like nested hierarchy where DNA regions of similar sizes merge into larger and larger structures. However, while successful, this model is incompatible with the two competing mechanisms that seem to shape a significant part of the chromosomes` 3D organization: loop extrusion and phase separation.

The first part of our work [1] aims to map out the chromosome`s actual folding hierarchy from empirical data, by treating the measured DNA-DNA interactions by Hi-C as a weighted network. From such a network, we extract 3D communities using the generalized Louvain algorithm with an adjustable resolution parameter, which allows us to scan seamlessly through the community size spectrum, from A/B compartments to topologically associated domains (TADs) [2]. By constructing a hierarchical tree connecting these communities, we find that chromosomes are more complex than a perfect hierarchy. Analyzing how communities nest relative to a simple folding model, we find that chromosomes exhibit a significant portion of nested and non-nested community pairs alongside considerable randomness. In addition, by examining nesting and chromatin types, we discover that nested parts are often associated with actively transcribed chromatin.

Another reoccurring issue that seems to reflect the fundamental limitation of community detection in the case of stochastic algorithms is the possibility of inconsistent detection results (the same community detection method may disagree with itself) [3,4]. If too strong, such inconsistencies may cause problems if the data interpretation relies too heavily on a specific community structure when there are others equally feasible. This is a fundamental problem pertaining to any data clustering scheme that cannot be solved using better community detection algorithms. In the second part of our work, we investigate the inconsistency of 3D communities in Hi-C data. We utilize an inconsistency metric [4], map out the community spectrum at different scales of the Hi-C contact network, and quantify where the community separation is most inconsistent. As a result, we find that the nodal inconsistency or functional flexibility [3] are also related to the local chromatin activity as in the nestedness analysis.

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9/29 Thursday
15:30 - 16:30

Dynamics of clusters in synchronization and percolation models

Young Sul Cho (Jeonbuk Nat'l Univ.)

In this presentation, we introduce our recent studies on the behaviors of clusters in synchronization and percolation models. Specifically, the first part of the presentation introduces a unified theoretical framework to understand diverse cluster synchronizations and its applications. The second part of the presentation introduces scaling behaviors of information entropy of cluster distributions observed in broad range of explosive percolation models.

9/29 Thursday
16:45 - 17:45

Interdependent Networks

Shlomo Havlin (Bar-Ilan)

A framework for studying the vulnerability of networks based on the theory of interdependent networks will be presented. In interdependent networks, such as infrastructures, when nodes in one network fail, they cause dependent nodes in other networks to also fail. This may happen recursively and can lead to a cascade of failures and to a sudden fragmentation of the system. I will present analytical solutions based on percolation theory, for the critical thresholds and the giant component of a network of n interdependent networks. I will show, that the general theory has many novel features that are not present in the classical network theory. I will also show that interdependent networks embedded in space are significantly more vulnerable compared to non-embedded networks. In particular, small localized attacks of zero fraction but above a critical size may lead to cascading failures that dynamically propagate and yield catastrophic consequences. I will also discuss the recent theory and experiment in interdependent superconducting networks where we identified a novel abrupt transition although each isolated system shows a continuous transition.

References:

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9/30 Friday
09:30 - 10:30

Long-tailed distributions of inter-event times as mixtures of exponentials

Naoki Masuda (Buffalo)

A main feature of empirical temporal network data is long-tailed distributions of inter-event times for individual nodes and edges. This feature affects various structural and dynamical properties of temporal networks such as epidemic spreading. In general, various power-law distributions can be represented as a mixture of infinitely many exponential distributions, and even a mixture of a small number of exponential distributions can approximate power-law distributions reasonably well over practically relevant scales. We exploit this correspondence, which facilitates theoretical analysis and fast algorithms, to provide intuitive explanations of empirically observed long-tailed distributions of inter-event times. Specifically, we (i) propose and analyze models in which nodes (such as human individuals) independently flip between high-activity and low-activity states, and (ii) analyze individuals performing random walks on a standard metapopulation network, finding that inter-event times obey mixtures of exponential distributions in both models. We also theoretically analyze epidemic spreading on such a temporal network model to characterize the importance of having a mass of short inter-event times rather than long ones.

9/30 Friday
10:45 - 11:45

Effect of heterogeneous adoptability and adaptation in complex contagions on networks

Byungjoon Min (CBNU)

How to predict and control complex contagion processes on complex networks is an important problem of much interest. In this talk, we study complex contagion dynamics with heterogeneous adoption thresholds and adaptation. When we consider heterogeneous adoption threshold, we find a double phase transition exhibiting a continuous transition and a subsequent discontinuous jump in the fraction of adopted nodes. Additionally, we observe hysteresis curves in the fraction of adopted nodes owing to adopted nodes in the densely connected nodes in a network. We also study cascade threshold models on adaptive networks to prevent global cascades. Our results on adaptive networks show the consequence of the interplay between dynamics and topology in complex contagions.

9/30 Friday
14:15 - 15:15

Revealing the role of flow network organization in the global efficiency of urban traffic flows

Young-Ho Eom (U. of Seoul)

Urban traffic flow is relevant with various problems such as congestion, pollution, and wellbeing in a city and can be represented as a network of local traffic flows between two intersections. Traffic percolation, removing low-quality links in order, is a major approach to characterize the global efficiency of urban traffic flow networks as a minimum requirement for their function is their global connectivity. Most traffic percolation analyses, however, do not tell us whether the observed efficiency comes from the network organization or the quality distribution of urban traffic flows. In this talk, by analyzing the traffic flow network data of Seoul with a null model for comparison, we disentangle the roles of flow network organization and flow quality distribution. We demonstrate that the flow network in rush hour is more globally inefficient than its corresponding null model with the same quality distribution yet the flow network in non-rush hour is more globally efficient than its null model. We reveal that, in rush hour, flows with high edge betweenness (EB), likely to connect the traffic network as one, tend to have low quality and the traffic network becomes more inefficient than its null model since high EB flows are removed first in the percolation process. On the other hand, in non-rush hours, flows with high EB have high quality and the network becomes more efficient than its null model. Finally we will discuss the observed differences between morning and evening rush hours. Our results emphasize that comparison with an appropriate null model is a key for understanding the global efficiency of urban traffic flow networks.

9/30 Friday
15:30 - 16:30

A critical revision of spreading dynamics on single, multilayer, and higher-order networks

Yamir Moreno (Zaragoza)

Modern network science has contributed significantly to our understanding of many processes in diverse fields of science. Arguably, spreading dynamics -including network epidemiology- is the area in which network concepts have had a bigger practical impact. Nowadays, we are able to model how diseases unfold and spread with unprecedented precision, which also makes it possible to analyze other spreading-like processes, such as rumor spreading and social contagion. In this talk, we revise this broad area of research by discussing how the modeling of spreading processes has evolved in the last two decades. We start by analyzing contagion-like dynamics in single populations that are described by different network topologies. Next, we discuss cases in which a multilayer approach is needed. Finally, we revisit recent works on contagion dynamics in higher-order networks, which have been claimed to show a much richer phase space for the dynamics of the system. We round off the talk by discussing the challenges that remain for future research.

9/26 Monday
16:45 - 18:00

[P1] Role of Geometric Correlations in Mutual Percolation: Multiscale Nature and Topological Explanation

Gangmin Son (KAIST)

Recently, it has been observed that geometric correlations (GCs) lead to continuous transitions in the mutual percolation of multiplex networks [1]. Here, we further study the role of GCs in the mutual percolation of multiplex networks in two ways. First, we extend the concept of GCs from the microscale to the mesoscale thereby defining a spectrum of GCs. We examine how the mesoscale correlations affect the types and scaling behaviors of the transitions. Second, we investigate whether the geometric effects can be explained as purely topological properties. In particular, we find that the GCs induce correlated edge overlaps in multiplex networks, leading to continuous transitions. Our results may help to understand the interplay between network geometry and dynamics.

[1] K.-K. Kleineberg, L. Buzna, F. Papadopoulos, M. Boguñá, and M. Á. Serrano, Phys. Rev. Lett. 118, 218301 (2017).

[P2] Universal mechanism underlying in hybrid percolation transitions

Hoyun Choi (SNU)

Hybrid percolation transitions (HPTs) exhibit both discontinuous jump, and critical behavior of order parameter at transition point. Here, we uncover the universal mechanism of HPTs on the network. We studied two models that exhibit HPTs in the cluster-merging process at a microscopic level and find that the two features occur in three steps: (i) suppression rule against the growth of large clusters causes accumulation of medium-sized clusters and creates bump at cluster size distribution, (ii) the stagnated clusters are merged and a giant cluster appears rapidly, and (iii) the suppression effect disappears and kinetics is governed by the ErdH{o}s-R`enyi type of dynamics. We characterize the criticality using two sets of critical exponents from the order parameter and cluster size distribution which are linked by a scaling relation. This also unifies the theoretical framework of the HPT in the cluster pruning process. We remark that the transition point of the HPT has intrinsic fluctuation, and a specific method is therefore introduced for finite-size scaling analysis.

[P3] Higher-order components in hypergraphs

Jung-Ho Kim (Korea U.)

The 'order' of components in hypergraphs could be defined in terms of the number of common nodes between hyperedges. We found that hitherto largely unnoticed higher-order components (HOCs) exist ubiquitously in real-world hypergraphs, but their randomized counterparts have a very different HOCs profile. To understand the impact of HOCs, we propose a novel random hypergraph model, which has the analytically calculable giant HOC by introducing the concept of subgroups of nodes that act together during hypergraph formation process. Using the model and real-world hypergraphs, we confirm that the existence of giant HOC can significantly impact the higher-order contagion dynamics.

[P4] Structure of international trade hypergraphs

Sudo Yi (KIAS)

We study the structure of the international trade hypergraph consisting of triangular hyperedges representing the exporter-importer-product relationship. Measuring the mean hyperdegree of the adjacent vertices, we first find its behaviors different from those in the pairwise networks and explain the origin by tracing the relation between the hyperdegree and the pairwise degree. To interpret the observed hyperdegree correlation properties in the context of trade strategies, we decompose the correlation into two components by identifying one with the background correlation remnant even in the exponential random hypergraphs preserving the given empirical hyperdegree sequence. The other component characterizes the net correlation and reveals the bias of the exporters of low hyperdegree towards the importers of high hyperdegree and the products of low hyperdegree, which information is not readily accessible in the pairwise networks. Our study demonstrates the power of the hypergraph approach in the study of real-world complex systems and offers a theoretical framework.

[P5] A simple and realistic growing hypergraph models

Dahae Roh (Korea U.)

There has been growing interest in group interaction and how to introduce them into complex system study. Hypergraph, one of the higher-order representations, consists of nodes and hyperedges, repre- senting individuals (or objects) and their groupwise interactions, respectively. Several growing graph and hypergraph models have been proposed in the literature. However, few models could account for in hyperedge size distribution and intersection distribution both heterogeneous which prevails in real complex systems. Heterogeneous intersection distribution indicates that new interaction is often based on previous relation, suggesting groups play a key role in growth process. Accordingly, we propose a family of simple and realistic growing hypergraph models, considering the roles of both the node- and hyperedge-dynamics in growth process. The resulting hypergraph has power-law hyperdegree distribution P(k) and exponential hyperedge size distribution P(s) and intersection distribution P(c). For hyperedge-random process, P(k) and P(s) are solved exactly. The model is studied first for limiting cases and then expanded into probabilistic-mixture models. Finally, a variation in the hyperedge- dynamics rule that can give rise to power-law hyperedge size distribution is discussed.

[P6] (k,q)-core pruning process of hypergraphs

Jongshin Lee (KENTECH)

We present a theory on the (k,q)-core pruning process in the uncorrelated random hypergraphs. We derive accurate governing equations describing the time evolution of hypergraph structures by the pruning process and solve them numerically. After the pruning process, we confirmed that the percolation property of the remaining components was divided according to the mean hypergraph degree and mean hyperedge size. In particular, it is theoretically confirmed using self-consistency equations that show continuous transition for $(2,2)$-core at the critical line showing critical slowing down, but hybrid percolation transition for $kge 3$ or $qge 3$. We support our theoretical framework by showing that the Monte Carlo simulation is consistent with the results derived from time evolution equations for the Erd"os--Ren`yi type and the Scale-free type hypergraphs. Finally, we show that our pruning process can also be helpful for refining data by applying it to actual coauthorship data.

[P7] Effective control of nonlocal cascading failures in complex networks using graph neural networks

Bukyoung Jhun (SNU)

A small, localized disturbance can propagate through the entire infrastructure network. Such phenomena are called cascading failures (CFs). Numerical simulation is necessary to study the avalanche dynamics and mitigation strategy of nonlocal CFs; however, computational complexity is high. Here, we first propose an avalanche centrality (AC) of each node, a measure related to avalanche size, based on the Motter and Lai model. Moreover, we train a graph neural network (GNN) with the AC in small networks. Then, the trained GNN predicts the AC ranking in much larger networks and real-world electrical grids. This result can be used effectively for avalanche mitigation. The framework we develop can be implemented in other complex processes that are computationally costly to simulate in large networks.

[P8] A generalized model for wealth exchange in heterogeneous networks

Hyun Gyu Lee (KIAS)

Unequal distribution of wealth is a consequence of enormous amounts of decision-making processes between individuals. Pinpointing the exact cause of the wealth inequality is almost impossible because not only of the sheer number of individuals, but also of the unpredictability of how a human makes economic decisions. However, rather recent and successful attempts to understand economic phenomena via principles of physics (so-called 'econophysics') frequently assumes dramatically simple microscopic processes comprising a macroscopic system. One of such attempts to understand the unequal wealth distribution, which can also be represented by the seemingly universal Pareto's law (i.e., the probability distribution of wealth has power-law form), has been made by Bouchaud and Mézard in 2000. In this work, they introduced a simple model of economy which incorporates multiplicative random noise and proportional exchange (transferred amount is proportional to the donor's wealth) and showed that, as a result of the competition of the two elements, a spectrum of inequality distribution is possible. At the extreme inequality end, power-law distribution could be obtained. Meanwhile, the so-called Yard-Sale model provided an agent-based approach to the wealth inequality. It was shown analytically that the long-time solutions to the Yard-sale model also produces power-law distribution. The exchange rule utilized in the model inherently places advantage to wealthy individuals, leading to a time-irreversible process in which the wealthier grows even wealthier. A generalized version of Yard-sale, on the other hand, would probably assume an additional exchange rule which counters this time-irreversible effect, distributing wealth to a greater population.

In our work, we introduce a parameter to realize this effect, and suggest a generalized Yard-Sale model in an effort to draw parallel with the work by Bouchaud and Mézard. Furthermore, we report several scaling behaviors which can be significant in statistical mechanics' perspective.

[P9] The heterogeneity of complex network affects on the phase diagram of the AT model with a repulsive interaction

Cook Hyun Kim (KENTECH)

Until now, the Ising model on the complex networks have been actively investigated. Because the Ising spin model on the complex network can describe opinion dynamics. The complex networks different from the regular lattices or random networks, have a unique structure called a hub which has strong influences on other nodes. Due to the existence of the hub, the complex networks display new properties on the phase diagram. In other words, the network topology affects the physical properties and the phase transition of the system. From a sociological point of view, it means that the social structure influences the formation of public opinion.

Inspired by this result, we systematically study how the network topology affects the formation of consensus. In order to do this, we considered the Ashkin-Teller model on the double-layer network with repulsive inter-layer interaction and studied how the network topology changes the phase diagram of the Ashkin-Teller model. As a result, we find various types of phase transitions that do not appear in lattice structures or random networks, and it is also confirmed that this was due to the hubs.

[P10] Optimal strategy for enhancing synchronization in growing coupled oscillators

Jong-Min Park (KIAS)

We study the optimal condition for enhancing the synchronization of coupled oscillators described by the Kuramoto model on a growing network. Synchronization is often required to carry out proper functions for coupled oscillators, such as biological systems, neural networks, and power-grid systems. Although population growth is a common feature of those systems, the synchronization of growing systems has been rarely studied. In this context, we propose effective strategies to enhance the synchronization of growing systems. By means of the strong coupling approximation, we find the approximate optimal natural frequencies of a newly added oscillator. We compare our approximations with other plausible strategies numerically on the random growing and the Barabasi-Albert networks. The numerical data show that the proposed strategies outperform others over a wide range of coupling strengths, confirming that our strategies are useful even far from the strong coupling limit.

[P11] Energy-threshold-based stability analysis of power-grid systems

Daekyung Lee (KENTECH)

Basin stability is a widely used approach for assessing the stability of dynamic systems. Observing the system's response to various perturbations, it effectively quantified a node's ability to maintain its synchrony from external stimulation. Even if the methodology provided much insight into understanding the dynamic system, it has a few issues with physical implications. Since most complex dynamic systems reveal diverse chaotic and non-chaotic regions sensitive to perturbation conditions, the scheme of basin stability has difficulty capturing each region's detailed characteristics. In the present work, we propose an energy-based methodology to estimate the system's boundary between chaotic and non-chaotic regions. Extending the result of stability analysis for a busbar system, we approximate each node's minimum energy threshold to break the synchronization of the entire system. Numerical results on several model networks show that our methodology suitably estimates the actual energy threshold, representing the local vulnerability of synchronization dynamics.

[P12] A Bifurcation and Numerical Continuation approach to selective extinction in Complex Mutualistic Networks

Andrus Giraldo (KIAS)

Our problem of interest is the species abundance and extinction of a plant-pollinator empirical ecological network. A generalized Mutualistic-Competitive Lotka-Volterra equation is used to model its dynamical behavior, where some plants and pollinators have a mutualistic relation, and uniform intra-group competition exists. We consider two parameters in the Lotka-Volterra equation representing the strength of mutualism and competition. Thus, some species can go extinct under particular combinations of these two parameters.
Using a dynamical system approach, we will show how we transform the species extinction problem into a bifurcation problem that can be readily solved using numerical continuation techniques. By doing so, we systematically build the species survival`s bifurcation (phase) diagram as a function of the mutualism and competition parameters. Furthermore, we unveiled the spontaneous existence of multistability, where different extinction scenarios emerge due to Hopf bifurcations.

[P13] Message-passing theory for metapopulation epidemic models

Jeehye Choi (CBNU)

In this study, we derive the message-passing theory for metapopulation modeling and propose a method to determine influential spreaders. Based on our analysis, we identify the most dangerous city as a potential seed of a pandemic when applied to real-world data. Moreover, we particularly assess the relative importance of various sources of heterogeneity at the subpopulation level, e.g., the number of connections and mobility patterns, to determine properties of spreading processes. We validate our theory with extensive numerical simulations on empirical and synthetic networks considering various mobility and transmission probabilities. We confirm that our theory can accurately predict influential subpopulations in metapopulation models.

[P14] Contagion dynamics on hypergraphs with nested hyperedges

Jihye Kim (Korea U.)

Hyperedges in a hypergraph can have diverse sizes and share any number of nodes with other ones. Empirically, hyperedges, which describe multi-body interactions, tend to share nodes with one another more than expected on a random basis. One prominent node-sharing pattern in hypergraphs that is absent in conventional pair-based networks is the nested structure, which means that some hyperedges exist as proper subsets of another, larger hyperedge. However, the effects of such nested organization of hyperedges on dynamics, such as spreading processes, remain to be understood. Here we propose a model for hypergraphs with nested hyperedges and formulate an analytical framework called the group approximation (GA) for investigating the effect of hyperedge-nestedness on a hypergraph contagion model. We derive self-consistent equations for a susceptible-infected-susceptible (SIS) model on hypergraphs with nested hyperedges and apply them to simple hypergraphs composed of two-body and three-body interactions. By using GA, we find that hyperedge-nestedness increases the dependence of threshold points on higher-order contagion processes. Our framework could contribute to the future work reflecting the general nested organization of hyperedges.

[P15] Lattice structure and spatial network models incorporated into simulating human-assisted invasion of a forest pest population

Tae-Soo Chon (Ecology and Future Research Institute, Pusan National University)

Due to climate change, invasion of alien species has been a global issue in recent years, causing disturbances in population stability and biodiversity sustainability in ecology. The damage by forest pest populations is especially critical because of vulnerability of disease occurrence in spatially continued conditions of vegetation and the difficulty of pest management in forest conditions. Notably, the dispersal of forest pest is additionally enhanced by human-assisted transportation (e.g., sapling distribution for landscape developments). Lattice structure model (LSM) and spatial network model (SNM) were incorporated into simulating both short- and long-distance movements of a forest insect pest, the Western conifer seedbug, Leptoglossus occidentalis. LSM was formed to present natural population growth along with active movement (e.g., movement distances) and a passive movement type due to traffic effects. Additionally SNM was developed according to the Gravity law to present another type of passive movements reflecting effect of forest-product transportation across local areas in Korea. The combined model outputs effectively illustrated the fast movement from the southern area (Jinju) to northern area (Seoul) in a short period along the course of national highway in the Korean Peninsula around 5 years. Possibility of developing population dispersal models by incorporating natural and human-assisted movements of insect pests was further discussed for prognosing advancement patterns and providing management strategies for forest pests.

[P16] Evolution of Social media activity-financial market network Relationship

Jinjoo Yoon (Chosun U.)

The evolution of the relationship between social media activity and financial market in terms of network coincides with an important factors in financial market risk such as instability of economic system. It is unclear how coupling between social media and stock market network disconnects during financial crisis to directly support to systemic risk induced by connectedness in financial market. In this paper, we analyze the dynamics of social media activity(SMA) - financial market (FM) relationship using the never finance data and stock market prices in a sample of 320 firms. We find that the market factors effects on coupling between SMA and FA specialized to certain industry. In particular, SMA-FA relationship was associated with market risk and COVID-19 pandemic as a financial crisis. To test the evolution of SMA-FA coupling in stock market, we estimated the degree of connectivity in the social media activity support the return fluctuations in an individual firm. Leveraging the return time series and social media activity from 480 firms with whole period sample, we applied Pearson correlation between the return data of firms during the period with COVID-19 pandemic. While the average connectivity estimated from both the equity market and social media activity reflects the risk behavior in financial market during COVID-19 period, SMA-FM coupling measured during a financial crisis period shows a lower value that is it is decoupled.