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Invited Speakers

Navigating network dynamics

Baruch Barzel

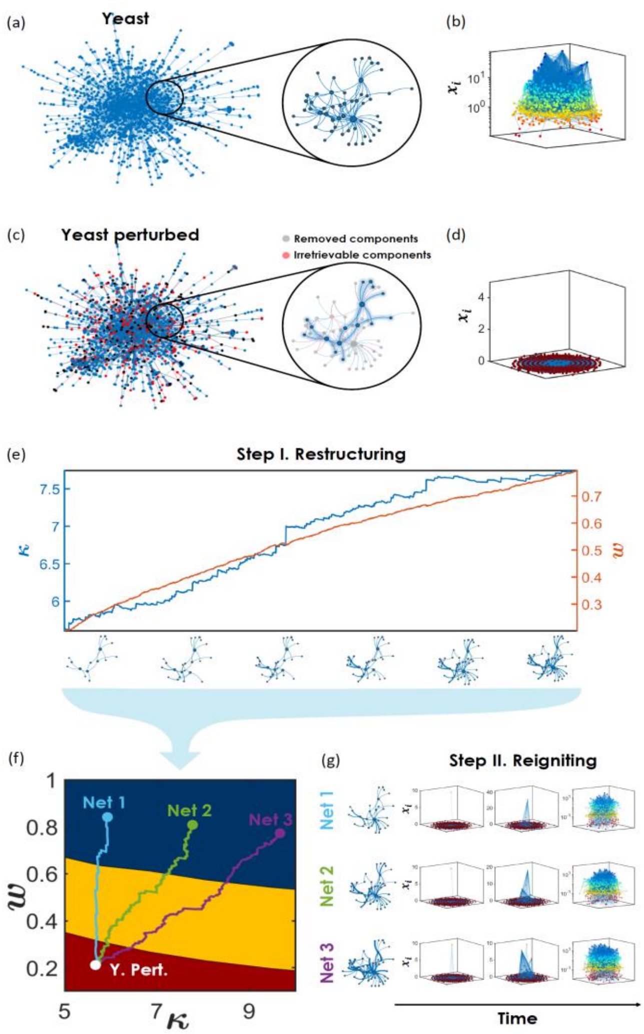
Department of Mathematics, Bar-Ilan University, Ramat-Gan, Israel, 52900
The Gonda Multidisciplinary Brain Research Center, Bar-Ilan University, Ramat-Gan, Israel, 52900

Universal network characteristics, such as the scale-free degree distribution and the small-world phenomenon, are the bread and butter of network science. Yet, translating these topological features into an understanding of a system's dynamic behavior remains elusive and intractable: how does the small-world structure shape the patterns of information flow? How does the presence of hubs influence the distribution of impact across the system? And finally, how does scale-freeness affect the system's dynamic timescales and transitions?

These questions probe the intricate interplay between network structure and nonlinear dynamics - a combination that rarely yields to analytical treatment. Consequently, network dynamics often appear diverse and unpredictable: a *zoo* of timescales, propagation patterns, spreading processes, and critical transitions. It may therefore seem that the concept of *universality*, which fueled the rise of network science at the turn of the century, breaks down when it comes to dynamics, as diversity wins over universal rules.

Our research over the past decade offers an optimistic perspective on these questions, revealing a deep and quantifiable universality underlying network dynamics. This universality enables a systematic translation from structure to dynamics, encompassing state transitions, propagation timescales, information flow, localization, and spectral behavior.

Ultimately, it allows us to identify the key parameters that govern a system's behavior, thereby enabling prediction and control of network dynamics, from predicting a network's response to invoking a desired response, and steering systems toward designated states (see Figure).



Illustrating dynamic interventions: reigniting a failed network. Perturbations to the Yeast cellular network lead to a dynamic collapse – from gene expression $x_i > 0$ in (b) to cell death $x_i = 0$ in (d). (e) **Step I**. To reverse the damage we restructure the lost links (κ) and strengthen their weights (ω). This, however, is insufficient, as the system does not spontaneously regain its functionality, remaining in the inactive $x_i = 0$ state. (f) We therefore steer the system into the *recoverable phase* (blue), a state in which we can reignite its lost functionality by artificially controlling just a few nodes. Here we show three alternative restructuring paths (blue, green, purple) all landing the network in the recoverable phase. (g) **Step II**. We can now drive the system back to functionality (all $x_i > 0$, right plots) by externally activating a small number of nodes.

Complete Synchronization and Pattern Selection Through Amplitude Dynamics and Diffusion in Heterogeneous Oscillatory Media

Nicolas Thomé[1],Yukiteru Murakami[1], **Katharina Krischer**[1],
[1] *School of Natural Sciences, Physics Department, Nonequilibrium Chemical Physics, Technische Universität München, Germany* - krischer@tum.de

Abstract: Synchronization is a universal phenomenon that is vital across disciplines, ranging from chemistry and biology to power grids and neuroscience. While theoretical treatments have traditionally relied on phase-reduced descriptions, the mechanisms that enable synchronization under strong coupling, where amplitude degrees of freedom become essential, remain poorly understood. We will discuss an intricate mechanism of pattern formation in heterogeneous oscillatory media under strong global coupling.

The study is based on experimental observations during the anodic electrochemical etching of silicon. It was observed that the electrode surface splits into two amplitude–phase regions, while all oscillators remain frequency-locked. Additionally, the relative ratio of the pattern could be tuned via a control parameter.

To describe these patterns, we introduce a heterogeneous, complex Ginzburg–Landau equation with global coupling. Neglecting diffusion shows that frequency entrainment arises from amplitude adaptation. Diffusion, on the other hand, enforces the selection of a unique cluster ratio. In quantitative agreement with simulations, a center-manifold reduction yields a Lyapunov functional that predicts the selected ratio. Both results establish a theoretical framework that connects experiment and theory. Moreover, they show how heterogeneity and diffusion convert degenerate cluster dynamics into robust pattern selection.

Reservoir Computing for the Prediction and Control of Complex Dynamics

Manish Shrimali[1]
[1] *Central University of Rajasthan, India* - e-mail:shrimali@curaj.ac.in

Abstract:

Reservoir Computing (RC), a paradigm of ML, provides a robust and efficient framework for approximating the dynamics of complex systems by leveraging nonlinear information processing with minimal training requirements. The framework utilizes a fixed nonlinear dynamical system (often referred to as reservoir) to map the low dimensional input signal into a high-dimensional space In recent times, RC has demonstrated its capability in capturing temporal dynamics, reconstructing underlying attractors, predicting collective behavior of oscillators in a network from limited data and learning the coupling between oscillators. In addition to its success in predicting complex dynamical behaviors, RC has recently been employed for controlling dynamical systems. A data-driven framework for the adaptive control of dynamical systems has been demonstrated, leveraging the RC scheme. RC has been extensively applied to the data-driven modeling, prediction of complex nonlinear dynamical systems across climate science, neuroscience, and engineering applications.

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Nonlinear dynamics of large-scale human brain networks – insights from epilepsy

Klaus Lehnertz[1]
[1] *University ob Bonn, Germany* - klaus.lehnertz@ukbonn.de

Abstract: Epilepsy is a chronic neurological disorder that affects approximately 50 million people worldwide. Despite decades of research covering virtually all levels of the open, adaptive, and nonlinear complex system that is the brain, we still do not understand why and how it transitions into and out of epileptic seizures – the main symptom of the disease. This inability may also explain why currently available therapies fail to control seizures in about 25 % of individuals. Over the last three decades, an improved characterization of the spatial-temporal dynamics of the human epileptic brain has been achieved with concepts and methods from nonlinear dynamics, statistical physics, synchronization and network theory. This talk focuses on recent advances in predicting critical transitions into extreme events – epileptic seizures – in large-scale human brain networks together with implications for seizure dynamics and control [1, 2, 3].

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Stability classifiers of complex systems

Chandrakala Meena [1], and Yuvraj Singh Patil[1]
[1] *Indian Institute of Science Education and Research (IISER) Pune, India-*
meenachandrakala@gmail.com,yuvrajsingh.patil@students.iiserpune.ac.in

Abstract: Complex systems, from the brain to social, ecological or cellular networks are often described by interaction structure, whose dynamical state is captured by the activities of all nodes, e.g., the excitation of neurons in brain networks or the expression levels of genes in subcellular interactions. To capture the stability of a system, we perturb dynamical states from their fixed point steady states and then seek system's response to the perturbation e.g., a local spike in neuronal activity or a sudden hike in the expression of one or several genes. The system will be stable if perturbation decays otherwise, it will lose its stability and may transient to an entirely new state. System's response to the perturbation is encoded within the system's stability matrix, namely the Jacobian, but is hard to retrieve, due to the scale and diversity of the relevant systems, their broad parameter space and their nonlinear interaction dynamics. To address this complexity, we use the dynamic Jacobian ensemble [Ref. 1], which provides a systematic framework for investigating the fixed-point dynamics of a wide range of graph-based nonlinear interaction models, including social, biological, chemical, and technological systems. These Jacobians reveal universal scaling patterns, where structure and dynamics are intricately connected. To predict system's stability using the Jacobian ensembles, we develop two stability classifier methods, based on two approach: (i) approximating complex network structure using star network and (ii) Gershgorin Disk Theorem. Our proposed classifiers captures the influence of both network topology and dynamics, enabling the classification of a large complex systems into stable, unstable, or sensitively stable categories (ref. Figure 1).

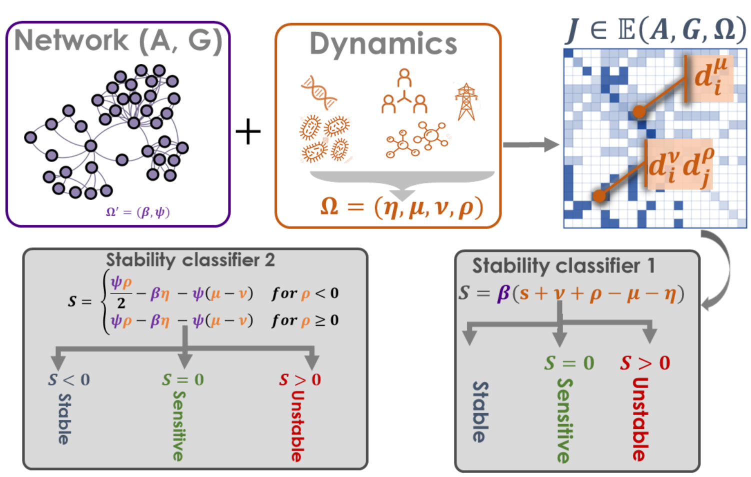

Figure 1: Stability classifiers of complex system using Jacobian Ensembles.

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Synchronization and Navigation of Active Droplets

Punit Parmananda[1]
[1] *IIT Bombay, India.*
E-mail:punit@phy.iitb.ac.in

Abstract: Active particles harvest energy from the environment and convert it into directed motion. Examples include biological systems like bacteria, insects, animals, or synthetic systems of self-propelled rod, discs, light-induced active particles, and chemically driven systems. An elegant manifestation of chemically driven systems are Marangoni Surfers at the air–water interface. The motility of these surfers is attributed to underlying Surface Tension gradients. In this talk the collective dynamics, observed experimentally, of such systems will be discussed. Furthermore, the ability of these active system to exhibit pathway selection in the presence of different asymmetries will be explored. Finally, the biologically inspired run and tumble dynamics is studied experimentally.

Recurrence-based local dimension estimates from time series: multi-scale variability and transient patterns in chaotic dynamical systems

Reik V. Donner[1,2]
[1] *Magdeburg–Stendal University of Applied Sciences, Magdeburg, Germany* - reik.donner@h2.de
[2] *Potsdam Institute for Climate Impact Research, Potsdam, Germany*

Abstract: Fractal dimensions are a widely used concept in dynamical system theory, with a heterogeneity of local estimates in phase space being indicative of a possibly multifractal nature of the system under study. Different types of global and local fractal dimensions can be estimated from recurrence plots, making use of the scaling of the density of local recurrences with the size of the considered neighborhood, higher-order single-scale properties like recurrence network transitivity and local clustering coefficients [1], or instantaneous fractal dimensions exploiting generalized extreme value theory for local distance distributions [2].

In my talk, I will first present an extension of recurrence-based global and local fractal dimensions to characterizing multi-scale properties of dynamical systems based on time series of characteristic observables. When considering the successive recombination of intrinsic mode functions obtained using empirical mode decomposition, chaotic systems exhibit considerable differences in their structural organization reflecting variability at different temporal scales, leading to the new concept of chameleon attractors that can be observed in both paradigmatic low-dimensional systems like deterministic and stochastic Lorenz-63 systems [3] and real-world data sets of experimental turbulence [4].

Given the rising number of apparently successful applications, the reliability of local dimension estimates from time series presents an outstanding challenge. To address this issue, two recurrence-based estimates are analyzed in greater detail, both of which do not make use of the actual time information associated with the individual observations. By considering two different subsampling strategies to very long time series (ensembles of state vectors drawn independently at random from the complete record versus contiguous time series segments), I demonstrate that local estimates obtained from finite time series may primarily reflect transient features of the dynamics, such as the temporary proximity to certain unstable periodic orbits in dissipative, or stickiness in Hamiltonian systems. This finding may have important repercussions for the interpretation of corresponding estimates from real-world time series reported in previous studies.

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Distribution of lowest eigenvalue in k-body bosonic random matrix ensembles

N. D. Chavda[1]
[1]*Department of Applied Physics, Faculty of Technology and Engineering, The Maharaja Sayajirao University of Baroda, Vadodara-390001, India* - ndchavda-apphy@msubaroda.ac.in

Abstract: We present numerical investigations demonstrating the result that the distribution of the lowest eigenvalue of finite many-boson systems (say we have m number of bosons) with k-body interactions, modeled by Bosonic Embedded Gaussian Orthogonal [BEGOE(k)] and Unitary [BEGUE(k)] random matrix Ensembles of k-body interactions, exhibits a smooth transition from Gaussian like (for $k = 1$) to a modified Gumbel like (for intermediate values of k) to the well-known Tracy-Widom distribution (for $k = m$) form. We also provide ansatz for centroids and variances of the lowest eigenvalue distributions. In addition, we show that the distribution of normalized spacing between the lowest and next lowest eigenvalues exhibits a transition from Wigner's surmise (for $k = 1$) to Poisson (for intermediate k values with $k \leq m/2$) to Wigner's surmise (starting from $k = m/2$ to $k = m$) form. We analyze these transitions as a function of q parameter defining q-normal distribution for eigenvalue densities.

Multiscale Connectivity and Dynamic Coupling: The Informational Grammar of Bio-Social Systems

Dipanjay Ray[1,2]

[1] *Department of Psychology, Ashoka University, Sonipat, India*
[2] *Koita Centre for Digital Health at Ashoka (KCDH-A)*
E-mail: dipanjan.ray@ashoka.edu.in

Abstract: A central challenge in the study of complex systems is the integration of disparate scales—ranging from the physical scaffolding of biological networks to the abstract dynamics of human behavior. This talk presents a series of case studies where the tools of Network Science, Information Theory, and Functional Data Analysis (FDA) are utilized to decode the "informational grammar" of these integrated systems.

1. Multiplex Connectivity in the Aging Brain

We first examine the brain as a multiplex system, consisting of interdependent structural (SC) and functional (FC) layers. Using the CAM-CAN dataset, we quantify the informational coupling between these layers across the human lifespan. We demonstrate that healthy aging is characterized by a systematic Information Divergence (measured via Jensen-Shannon Distance), where subcortical relay hubs progressively decouple from their structural constraints. This suggests that as the system ages, its operational dynamics become increasingly autonomous from its physical architecture, reflecting a fundamental shift in the system's topological constraints.

2. Dynamic Coupling and Affective Manifolds

Moving from static networks to temporal dynamics, we investigate the dynamic coupling between external acoustic perturbations (music) and internal affective states. Utilizing Functional Data Analysis (FDA), we treat emotional responses as continuous trajectories in a 2D phase space (Valence-Arousal). We show a dissociation in coupling strengths: while "Arousal" remains tightly coupled to the physical properties of the stimulus (bottom-up driving), "Valence" emerges as a top-down construction, where the coupling is modulated by the system's internal "priors" (personality traits and anxiety).

3. Topological Integration of Social Scaffolding

Finally, we expand the lens to the scale of Social Connectivity. Using Mixed Graphical Models (MGMs), we map the conditional dependencies within a 35-variable system of biological, psychological, and social factors influencing eating behavior. We demonstrate that this high-dimensional system exhibits a highly segregated, "small-world" architecture. Crucially, the system is integrated not by downstream behavioral nodes but by socio-economic "hubs"—such as education and employment—which function as the primary bridges linking social reality to psychological health.

Conclusion

By weaving together these scales, we argue that "connectivity" must be understood both as Topology (the architecture of bridges) and Dynamics (the strength of coupling). Understanding the human condition requires a methodology that can navigate these transitions between the structural seams of the brain and the social scaffolds of society.

Keywords: Complex Systems, Multiplex Networks, Dynamic Coupling, Information Theory, Mixed Graphical Models, Indian Classical Music.

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The synchronized dance of waves

P. Khan[a], S. Dutta*[b]

[a]*Department of Earth and Planetary Science, FAS, Harvard University Cambridge, MA 02138*

[b]*Department of Chemistry, Indian Institute of Technology Guwahati, Guwahati - 781039*

e-mail: sumana@iitg.ac.in

Excitation waves are responsible for a plethora of dynamics in the natural world. From the beating of the heart to the transduction of signals in the brain, it is the synchronization of the individual cells or their activities that give rise to the overall phenomena. Hence, the understanding of such harmony is of great interest to researchers.

In an effort to understand how synchronization in excitable systems can be controlled by coupling and geometry, we study a collection of rotating waves in a chemical reaction diffusion system. With table-top experiments we are able to observe and showcase the fascinating phenomena of synchronization. By modifying the existing mathematical models of the reaction kinetics of the BZ-reaction system and computer-based simulations of the new model, we have been able to explore various regimes of wave activity, from stable spirals to oscillation death. In between the two extremes, we show how instability sets in, with anisotropy leading to drifting spirals, core defects resulting in spiral breakup and turbulence, chaotic oscillations, and target patterns, before the system finally reaches a non-oscillating steady state.

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Tipping in complex networks with higher-order interaction

Richita Ghosh[1], and **Manish Shrimali**[1]
[1] *Central University of Rajasthan, India* - e-mail:shrimali@curaj.ac.in

Abstract:

The tipping point is a critical threshold where small changes trigger abrupt, large-scale, often irreversible shifts in a system. Many real-world systems exhibiting tipping behavior can be represented as networks of interacting multistable units, including vegetation patches and infrastructure networks, subject to pairwise and/or higher-order interactions [1]. In this talk, we examine how higher-order interactions influence the dynamics of tipping cascades in complex networks [2]. Numerical simulations on random, scale-free, and small-world networks demonstrate that higher-order interactions can trigger tipping cascades. We also investigate the route to cascades through bifurcation analysis. Our results emphasize the essential influence of higher-order interactions on cascade dynamics, offering important insights into the anticipation and mitigation of critical transitions in ecosystems, climate systems, and socio-technical infrastructures.

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Identifying dyssynchronous states in neuronal network excited by local Lévy noise using reservoir computing

Tomasz Kapitaniak[1]
[1] *Lodz University of Technology, Poland.*
E-mail: tomasz.kapitaniak@p.lodz.pl

Abstract: Chimera states, characterized by the coexistence of synchronized and desynchronized regions within oscillator networks, have been increasingly linked to the abnormal spatiotemporal dynamics observed in neurological disorders such as epilepsy and Parkinson's disease. However, conventional modeling approaches often rely on deterministic frameworks or Gaussian white noise with uniform distributions, which inadequately capture the localized and asymmetric features of pathological neural events, such as focal seizure onset and dopaminergic imbalance. In this study, we propose a biologically inspired modeling framework based on a non-locally coupled FitzHugh-Nagumo (FHN) neuronal network subjected to localized Lévy noise. This framework offers a more realistic representation of pathological brain activity. The heavy-tailed and skewed characteristics of Lévy noise effectively simulate the burst-like, intermittent discharges typical of epileptic foci, as well as the asymmetric firing patterns observed in Parkinsonian basal ganglia circuits. To address the limitations of traditional numerical solvers in capturing such complex, noise-driven dynamics, we introduce a deep learning-based solver that integrates short-term memory and global signal dependency modeling. This method significantly enhances computational accuracy, generalization, and robustness, especially under strong non-Gaussian perturbations. In particular, we demonstrate that reservoir computing algorithms are highly effective in identifying dynamic states within coupled neuronal networks. Our results reveal the emergence of diverse chimera patterns across varying Lévy noise parameters, highlighting transitions from globally synchronized states to localized seizure-like activity or widespread chaotic regimes. These findings establish a mechanistic and computational link between deep learning and neurodynamics, offering new insights into the early propagation of seizures and disruptions in Parkinsonian networks.

Infrasonic acoustic amplification in driven architectured granular chains

Presenting Surajit Sen[1], Luis P.S. Machado[2], Elbens Carlos Viana Reis[2]
[1] *Dept of Physics, State University of New York at Buffalo, Buffalo, NY, USA* - sen@buffalo.edu
[2] *Faculty of Physics, Federal University of Pará, Tucuruí, Brazil* - luismachado@ufpa.br

Abstract: When two macroscopic elastic spheres are compressed against one another, the repulsive force between them is described by the intrinsically nonlinear Hertz law. Hence, alignments of elastic spheres in gentle mutual contact and held between end walls exhibit rich and unexpected dynamics. Here we take monodispersed and tapered alignments of spheres and drive harmonically at one end to show that these systems can serve as transmitters of frequencies in the infrasonic range (below 20 Hz) and filter out all higher frequencies. Our studies show that these simple systems can serve to detect signals at a few Hertz regime, typically encountered in geophysical events such as from earthquakes, oceanic signals, etc. [**?**, **?**].

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Metastability, transient dynamics and the role of different timescales

Ulrike Feudel[1]
[1] *Carl von Ossietzky University Oldenburg, Germany* - ulrike.feudel@uni-oldenburg.de

Abstract: Metastability, characterized typically as a variability of dynamical regimes over time, is a ubiquitous behavior in many systems. We examine this behavior using dynamical systems theory to provide a consistent and accessible framework for explaining different forms of metastability [1]. We provide a general and clear definition of the behavior and discuss many possible dynamical mechanisms that can generate metastability. Special emphasis is given to transient dynamics which is one of the key features of metastability since it focusses on the transitions from one metastable state to another. We discuss two particular structures in state space (i) chaotic saddles [2] and (ii) critical manifolds in slow-fast systems [3] that play an important role in different cases of metastability and point out their role for critical transitions.

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Evolution beats random chance: Performance-dependent network evolution for enhanced computational capacity

Sudeshna Sinha
Indian Institute of Science Education and Reseach (IISER) Mohali, India
sudeshna@iisermohali.ac.in

Abstract:
The quest to understand structure-function relationships in networks across scientific disciplines has intensified. However, the optimal network architecture remains elusive, particularly for complex information processing. Therefore, we investigate how optimal and specific network structures form to efficiently solve distinct tasks using a framework of performance-dependent network evolution, leveraging reservoir computing principles. Our study demonstrates that task-specific minimal network structures obtained through this framework consistently outperform networks generated by alternative growth strategies and Erdős-Rényi random networks. Evolved networks exhibit unexpected sparsity and adhere to scaling laws in node-density space while showcasing a distinctive asymmetry in input and information readout node distribution. Consequently, we propose a heuristic for quantifying task complexity from performance-dependently evolved networks, offering valuable insights into the evolutionary dynamics of the network structure-function relationship. Our findings advance the fundamental understanding of process-specific network evolution and shed light on the design and optimization of complex information processing mechanisms, notably in machine learning.

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Reliability of energy landscape analysis of resting-state functional MRI data

Pitambar Khanra[1], Johan Nakuci[2], Sarah Muldoon[3], Takamitsu Watanabe[4], Naoki Masuda[5]

[1] *UPES, Dehradun, India* - pitambar.khanra89@gmail.com

[2] *Georgia Institute of Technology, Atlanta, Georgia, USA*

[3] *State University of New York at Buffalo, Buffalo, New York, USA*

[4] *The University of Tokyo, Tokyo, Japan*

[4] *University of Michigan, USA*

Abstract: Energy landscape analysis is a powerful method for modeling brain dynamics from fMRI data. However, its reliability at the individual level remains unestablished, hindering its use for personalized fingerprinting. We assessed the test-retest reliability of this method by comparing energy landscapes within and between participants using two datasets: Midnight Scan Club (MSC) and Human Connectome Project (HCP). We computed four discrepancy indices-measuring differences in interaction strengths, local minima, attractive basins, and energy barriers-and found significantly higher within-participant than between-participant reliability for all indices (permutation test, $p < 0.05$). A variational Bayesian method achieved comparable reliability without data concatenation. Our results [1, 2] confirm that energy landscape analysis provides a reliable fingerprint of individual brain dynamics, enabling robust person-level characterization in health and disease.

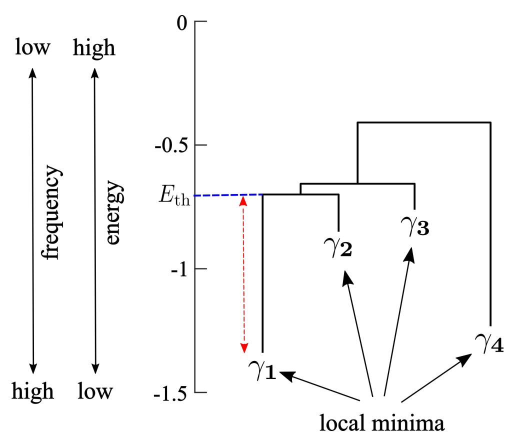

Figure 1: Schematic of a disconnectivity graph showing the relationships between the activity patterns that are energy local minima. The arrow indicates the height of the energy barrier between local minima γ_1 and γ_2 from the viewpoint of γ_1.

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Before the Collapse: Critical Slowing Down in Abrupt Desynchronization

Sarika Jalan[1]

[1] *Department of Physics, IIT Indore, India*
E-mail: sarika@iiti.ac.in

Abstract: The theory of phase transitions continues to attract wide interest within the physics community.

We examine a system of coupled phase oscillators described by the Kuramoto model, which appears to exhibit signatures of criticality at a first-order transition. While the second-order phase transition to synchronisation in the Kuramoto model has been intricately explored analytically and numerically, displaying a universal scaling, to our knowledge, no theoretical investigation exists on the correlation in length and time associated with abrupt transitions. We show that the abrupt desynchronization transition from synchronous to asynchronous state yields the signs of critical slowing down, which is marked by diverging correlation length and time scale. Few previous studies have reported divergent time scales at a first-order transition in spatially interacting systems and termed it a mixed-order transition. On the contrary, here we observe such divergences due to interactions in a number space which does not hold any concept of locality.

Further, although scaling relations at saddle node bifurcations have been analyzed within mathematical nonlinear dynamics, this work connects mathematical formulations with first-order phase transitions in physical systems (modelled by Kuramoto oscillators).

The results fill an essential gap in the study of the celebrated Kuramoto model and address an important aspect of physics: the first-order phase transition.

Elections as complex system : Turnouts drive key election statistics

M.S. Santhanam[1]
[1] *IISER Pune, India.*
E-mail: santh@iiserpune.ac.in

Abstract: Elections are regarded as complex system due to the varied human interactions and interests that shape their outcomes. Earlier works, including our previous work, shows that quantitative analysis of election data gives us insights into the existence of universality in elections. A robust universality was demonstrated using data from nearly 34 countries. In this talk, we show that voter turnout contains even more crucial information that can accurately predict several key electoral statistics. Using empirical election data from 12 countries spanning multiple decades and random voting model, we demonstrate that the distributions of votes secured by winners and runner-ups are strongly correlated with turnout distributions. The former can be predicted from the knowledge of turnout distribution.

Adaptive Diversification: speciation, fitness, predictability and the speed of evolution.

Vaibhav Madhok[1]
[1] *IIT Madras, India.*
E-mail: madhok@iitm.ac.in

Abstract: Most theories of evolutionary diversification are based on equilibrium assumptions: they are either based on optimality arguments involving static fitness landscapes, or they assume that populations first evolve to an equilibrium state before diversification occurs, as exemplified by the concept of evolutionary branching points in adaptive dynamics theory. Recent results indicate that adaptive dynamics may often not converge to equilibrium points and instead generate complicated trajectories if evolution takes place in high-dimensional phenotype spaces. I will describe the consequences of this on predictability of evolution as well as how speciation takes place in high dimensions. This leads to the question of the role of fitness in evolutionary theories. If time permits, I will also discuss the effect of competition on the speed of evolution.

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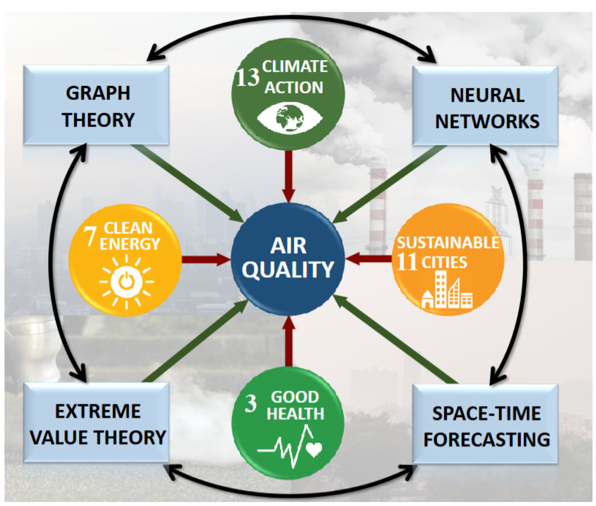
Everything is connected: Space, Time, and Geometric Deep Learning

Madhurima Panja[1], **Tanujit Chakraborty**[1], Anubhab Biswas[2], Soudeep Deb[3]
[1] *, Sorbonne University, Abu Dhabi, UAE* - tanujit.chakraborty@sorbonne.ae
[2] *University of Applied Sciences and Arts of Southern Switzerland, Switzerland*
[3] *Indian Institute of Management Bangalore, India*

Abstract: Air quality forecasting is critical for public health and pollution management, yet faces significant challenges due to complex spatiotemporal patterns in atmospheric data. Pollutant concentrations exhibit nonlinear dynamics, spatial correlations between monitoring stations, and extreme values—particularly in severely polluted cities like Delhi, India—that conventional models fail to capture adequately. This presentation introduces an enhanced deep learning framework combining geometric deep learning with extreme value theory. We extend the Spatiotemporal Graph Convolutional Network (STGCN) to explicitly model extreme pollution events by treating monitoring stations as interconnected nodes while capturing temporal patterns through specialized neural components. The innovation lies in incorporating statistical theory for extremes directly into the learning process, enabling effective handling of both typical and severe pollution episodes. Applied to 37 air quality monitoring stations across Delhi, our approach demonstrates robust performance across multiple forecasting horizons and seasons, with notable improvements in capturing extreme events. Combined with conformal prediction techniques, the framework generates reliable probabilistic forecasts that quantify prediction uncertainty—essential for decision-making. This work demonstrates how integrating geometric deep learning with extreme value theory provides a powerful approach for forecasting interconnected environmental phenomena, particularly valuable for highly polluted urban environments where accurate predictions are most crucial.



Heterogeneous Nucleation in Adaptive Dynamical Networks

D. V. Senthilkumar
School of Physics, Indian Institute of Science Education and Research Thiruvananthapuram, Thiruvananthapuram, 695551, Kerala, India.

Abstract: We investigate the influence of adaptation disparity and phase lag on the heterogeneous nucleation leading to multi-step and single-step phase transitions in a finite size adaptive network due to frequency disorders. We elucidate that the adaptation disparity predominates the effect of frequency disorder in seeding the heterogeneous nucleation. Further, a large phase lag facilitates almost a continuous spectrum of partially and fully synchronized frequency clusters, and multistability among them. We also find that the underlying mechanisms of heterogeneous nucleation due to the adaptation disparity and phase lag parameters are distinctly different from that observed only in the presence of disorders. Furthermore, we also analytically deduce the macroscopic evolution equations for the cluster dynamics using the collective coordinates framework and show that resulting reduced dynamics mimic the observed heterogeneous phase transitions of the adaptive network under adaptation disparity and phase lag. Further, we deduce the upper bound for the coupling strength for the existence of two intra-clusters explicitly in terms of the adaptation disparity and phase lag parameters for the onset of the abrupt single-step transition.

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Brevity is best: Reservoir Computing and the Minimum Description Length Principle

Antony Mizzi, David Walker, Michael Small[1]
[1] *The University of Western Australia, Australia.*

Abstract: The reservoir computing paradigm has excited consireable interest in the dynamical systems community, chiefly because of it's relative simplic- ity and ease with which it can be treated as a dynamical system. In a typical implementation, the reservoir consists of a recurrent network of neurons driven by some input signal and from which a target output is achieved through a linear combination of a regularised subset of the output neurons. In this talk we will introduce the minimum description length (MDL) principle and show how it can be implemented to provide an al- ternate approach to evaluating the parsimony of a model. Through a new subset selection scheme we deminstrate that the MDL approach achieves improved dynamical performance for models of typical dynamical systems - including Lorenz, R¨ossler and Thomas. Extensions of this idea suggest ways to evaluate the importance of structure within the reservoir and a new approach to optimisation in complex landscapes.

Multi-modal first-passage dynamics of a random searcher in a spatially disordered environment

Luca Giuggioli[1]
[1]*School of Engineering Mathematics and Technology, University of Bristol, Bristol, BS8 1TW, England, United Kingdom.*

Abstract: Understanding how spatial disorder affects the random search of a diffusing particle or agent is fundamental to a myriad of applications across disciplines. To unearth the effects that strong spatial heterogeneities may have on a diffusive searcher, we consider the dynamics of a random walker on a network and study the first-passage or first-hitting statistics to a target, which so far have relied on estimates provided by stochastic simulations, rather than rigorous mathematical tools. To close this knowledge gap we devise a general methodology to represent analytically the movement and search dynamics of a diffusing random walk on a graph, which is particularly convenient for sparse graphs. By considering small-world networks, we have uncovered the existence of a bi-modality regime in the time-dependence of the first-passage probability to hit a target node. By identifying the network features that give rise to the bi-modal regime, we challenge long-held beliefs on how the statistics of the so-called direct, intermediate, and indirect trajectories influence the shape of the resulting first-passage and first-absorption probabilities and the interpretation of their mean values.

Chaos, Ergodicity, and K-Mixing in High-Quality Pseudo-Random Generators

Vinod Patidar[1]
[1] *School of Computer Science, UPES, Dehradun, India.*
E-mail:vinod.patidar@ddn.upes.ac.in

Abstract: Pseudo-random number generators (PRNGs) are fundamental to Monte Carlo simulations, cryptographic protocols, and large-scale numerical experiments. The reliability of these applications depends critically on the statistical quality of the generated sequences. This talk explores the foundational role of ergodicity, conservative chaos, and invariant measures in the design of high-quality PRNGs. Starting from the Kolmogorov–Anosov theory of mixing, we discuss how ergodicity guarantees full coverage of the state space and how invariant measures ensure uniform sampling. The notion of K-mixing is introduced as a rigorous framework for achieving statistical independence of arbitrary order. Conservative chaotic dynamical systems, characterised by volume-preserving transformations and positive Kolmogorov entropy, are presented as deterministic yet unpredictable sources of pseudo-randomness. The talk will highlight some of our recent work on constructing conservative ergodic dynamical systems for pseudo-random number generation and present their statistical validation and performance analysis. We conclude by emphasizing the importance of decimation, long periods, and reproducibility, and outline future directions for chaos-based PRNGs in high-performance computing, secure communications, and data-intensive simulations.

Keywords: Ergodicity; Invariant Measure; Conservative Chaos; Pseudo-Random Number Generators; Kolmogorov–Anosov Mixing; PRNG

Projective Synchronization in Nonlinear Electrical Circuits

Thounaojam Umeshkanta Singh
Department of Physics, School of Engineering and Applied Science, Bennett University, Greater Noida, Uttar Pradesh 201310, India
Email: umeshkanta@gmail.com

Abstract: Projective synchronization is a dynamical behavior in which the response and drive of two coupled identical chaotic systems synchronize up to a constant scaling factor. Here, we use nonlinear electrical circuits to demonstrate the robustness of projective synchronization in physical systems. We present the first experimental realization of projective synchronization in coupled nonlinear electronic circuits based on Sprott oscillators [3]. The circuit implementation exhibits amplitude scaling between the drive and response systems while preserving the overall structure of the chaotic attractor. Intrinsic component heterogeneities induce transitions between in-phase and anti-phase projective synchronization, both of which are valid system solutions. These experiments confirm the robustness of projective synchronization in hardware and establish a flexible platform for investigating scalable synchronization in chaotic systems, with potential applications in secure communications and signal processing.

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Collective dynamics of higher dimensional Stuart Landau models

Ram Ramaswamy[1]
[1] *IISER Berhampur, India.*
E-mail: r.ramaswamy@gmail.com

Abstract: We study the collective dynamics of a system of Stuart-Landau oscillators in dimensions $D = 3$ and 4. Since the oscillators have SO(D) rotational symmetry, the coupling can be chosen to either preserve or break this symmetry: this leads to novel emergent dynamical phenomena that do not have analogues in the well-studied case of $D = 2$.

When rotational symmetry is preserved there can be various forms of synchronisation as well as multistability and *partial* amplitude death, namely, the quenching of oscillations within a subset of variables that asymptote to the same constant value. The oscillatory dynamics in these cases are characterised by phase-locking and phase-drift. When the coupling breaks rotational symmetry we observe *partial* synchronisation (when a subset of the variables coincide and oscillate), *partial* oscillation death (when a subset of variables asymptote to different stationary values), as well as the coexistence of these different partial quenching phenomena.

[work in collaboration with Pragjyotish B. Gogoi, Rahul Ghosh, Aryan Patel, Debashis Ghoshal and Awadhesh Prasad]

The Inverse Problem for Periodic Travelling Waves of the Linear 1D Shallow-Water Equations

Robert Hakl

Institute of Mathematics CAS, Brno, Czech Republic

hakl@ipm.cz

This is a joint work with Pedro J. Torres, University of Granada, Spain.

The motion of small amplitude waves of a water layer with variable depth along the x-axis is described by the equations of the shallow water theory

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\left[h(x)u\right] = 0, \qquad \frac{\partial u}{\partial t} + g\frac{\partial \eta}{\partial x} = 0, \tag{1}$$

where $\eta(x,t)$ is the vertical water surface elevation, $u(x,t)$ is the depth-averaged water flow velocity (also called wave velocity), $h(x)$ is the unperturbed water depth and g is the gravity acceleration. In what follows, we assume without loss of generality that $g = 1$.

The shallow water equations conform a system of coupled PDEs of first order that can be easily decoupled into a single wave equation for the surface displacement

$$\frac{\partial^2 \eta}{\partial t^2} - \frac{\partial}{\partial x}\left[h(x)\frac{\partial \eta}{\partial x}\right] = 0, \tag{2}$$

or for the wave velocity

$$\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2}{\partial x^2}\left[h(x)u\right] = 0. \tag{3}$$

There is a considerable number of papers devoted to finding sufficient conditions on the bottom profile $h(x)$ to ensure the existence of travelling waves or other explicit solutions. A travelling wave is a special solution of the form $q(x)\exp i\left[\omega t - \Psi(x)\right]$, where both q and Ψ are scalar real-valued functions. In the related literature, $q(x)$ is known as the amplitude of the travelling wave, ω is the frequency and $\Psi(x)$ is the phase, which is called non-trivial if it is non-constant. In this talk, we are going to study the following inverse problem: *given a prescribed amplitude $q(x)$, can we determine a suitable bottom profile $h(x)$ allowing the equation to admit a travelling wave with amplitude $q(x)$?*

The analysis of Tropical cyclones: Cyclone Okhi, A case study

Vinisha Kalwani, Rupali Sonone, **Neelima Gupte**[1]
[1]*Department of Physics, Indian Institute of Technology, Madras, Chennai 600036.*

Abstract: We apply the methods of climate networks studies for the analysis of tropical cyclones. Here, we apply thse methods to a specific cyclone, Cyclone Okhi (29th Nov to 6th Dec. 2017). This cyclone was classified as a severe cyclone with wind speeds ranging from 150 to 175 kms per hour and caused substantial destruction. The cyclone is studied using a geographic grid of finite size based on the Indian Ocean and networks on time scales of 15 days. We study various quantities such as heat maps, distributions of teleconnections, betweenness centralities and area weighted connections which constitute signatures of cyclonic behaviour. The geographic locations of peak values of these quantities shift substantially before, during and after the cyclones, demonstrating their potential for predictive behaviour. The climate network undergoes abrupt percolation transitions during this period. The location of tipping links which trigger the abrupt transition is identified relative to the region studied. We note that our methods and results can be generalised to other cyclones as well as other extreme events.

Extreme events in a multiplex FitzHugh-Nagumo neuronal networks

M. Senthilvelan[1]
[1] *Department of Nonlinear Dynamics Bharathidasan University Tiruchirappalli – 620024 India.*

Abstract: Extreme events in monolayer networks has been studied extensively [1]. To better understand the emergence, propagation and mitigation of extreme events in a complex network, it is essential to extend the earlier study to multilayer networks under various types of couplings and directional interactions. In this talk, we discuss the propagation of extreme events in a two-layer multiplex networks. In the two-layer network, we will consider one layer is globally coupled and exhibits extreme events, while the other layer remains uncoupled and exhibits disordered dynamics. The layers are comprised of FitzHugh-Nagumo neurons at each node. The interlayer interaction is either unidirectional or bidirectional. We show that unidirectional coupling between the layers induce extreme events in the uncoupled layer whereas bidirectional coupling tends to mitigate extreme events in the globally coupled layer. Using probability plots we characterize and identify distinct regions of extreme and nonextreme states in the parameter space. We also discuss the robustness of extreme events emergence under various network topologies in the uncoupled layer. Our findings suggest that extreme events in the uncoupled layer emerge through the gradual disappearance of disordered state, accompanied by occasional bursts of synchronized activity [2]. Finally, we discuss the impact of drive signal on extreme events in both monolayer and multilayer networks. The nature of the drive signal is represented by the typical relaxation oscillation of the FitzHugh-Nagumo neuron [3]

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Network Architecture and Dynamical Control of the Plant Circadian Clock

Shashank Kumar Singh[1], **Ashutosh Srivastava**[1*]

[1]*Department of Biological Sciences and Engineering, Indian Institute of Technology Gandhinagar, Gujarat, India.*

shashanksingh@iitgn.ac.in, **ashutosh.s@iitgn.ac.in*

Abstract: Circadian rhythms are self-sustained biological oscillations that coordinate plant growth, metabolism, and environmental responses through an interconnected transcription–translation feedback network. These rhythms emerge from nonlinear interactions among multiple regulatory loops that integrate external cues such as light, temperature and environmental conditions. Understanding how robustness and timing arise from this complex architecture remains a central challenge in circadian systems biology.

Here, we present M1, an extended mathematical model of the *Arabidopsis* circadian clock, developed by building upon the Pay (Pay ML et al, Insilico Plants, 2022) framework and incorporating additional light-dependent and post-translational regulatory modules. The updated architecture includes a GI/ZTL (GZ) module and revised inhibitory interactions that significantly improve the model's ability to reproduce experimentally observed phase, amplitude, and persistence of oscillations under varying light conditions.

To dissect the dynamical organisation of M1, we applied a multi-layered analysis combining virtual knockout analysis, period sensitivity analysis, phase portrait analysis, and Sobol-based network impact analysis. Together, these complementary approaches reveal a hierarchical network structure in which a compact transcription–degradation core centred on CCA1/LHY and PRR interactions generates self-sustained oscillations, while light-responsive pathways modulate phase and amplitude without destabilising the rhythm. Peripheral regulatory branches exhibit strong buffering, contributing to robustness against parameter perturbations.

Our results demonstrate that circadian timing in plants is governed by a small set of high-impact regulatory processes embedded within a larger, redundant network. By explicitly linking network structure to dynamical behaviour, the M1 framework provides a systems-level understanding of robustness, control, and adaptability in the plant circadian oscillator.

Mitigating cascades in complex networks

Karan Singh[1], V. K. Chandrasekar[2], Wei Zou[3], Jürgen Kurths[4,5], **D. V. Senthilkumar**[1]
[1] *School of Physics, Indian Institute of Science Education and Research Thiruvananthapuram, Thiruvananthapuram, 695551, Kerala, India.*
[2] *Department of Physics, Center for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur, 613401, Tamil Nadu, India.*
[3] *School of Mathematical Sciences, South China Normal University, Guangzhou 510631, China.*
[4] *Potsdam Institute for Climate Impact Research, Telegraphenberg Potsdam , D-14415, Germany.*
[5] *Institute of Physics, Humboldt University Berlin, Berlin, D-12489, Germany.*

Abstract: Cascading failures represent a fundamental threat to the functioning of complex systems. This study proposes a robust and pragmatic approach designed to attenuate the risk of such failures within complex networks effectively. The core of our strategy is to identify a subset of critical nodes within the network, a subset whose relative size is substantial. Further, we employ the graph coloring technique to precisely isolate the nodes (immune nodes) of paramount importance, thereby minimizing the size of the subset extensively, while maximizing its strategic value. Securing these nodes significantly bolsters the network's resilience against cascading failures. We substantiate the superiority of the proposed framework through comparative analyses with existing mitigation strategies and evaluate its performance across various network configurations and failure scenarios. Empirical validation is provided by applying the framework to various real-world networks, elucidating its potential as a strategic tool in enhancing network robustness.

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Transitions to Absorbing state: Non-DP transitions

Prashant Gade[1]
[1] *RTM Nagpur University, India.*
E-mail: prashant.m.gade@gmail.com

Abstract: Directed percolation universality class is very common in theoretical models of absorbing phase transitions. We show that directed percolation transition could occur in most unexpected situations. Quenched disorder is a relevant disorder and it can lead to complex Griffiths phase where we observe continuously varying complex exponents. For transitions to zigzag and checkerboard patterns in coupled maps, we observe critical behaviour over a range of parameters and not just the critical point. We investigate a couple of examples where the universality class is different. This happens in (i) unidirectionally coupled multiplex networks and (ii) transitions to period-3 synchronization.

Keywords: Ergodicity; Invariant Measure; Conservative Chaos; Pseudo-Random Number Generators; Kolmogorov–Anosov Mixing; PRNG

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Modeling the dynamics of leptospirosis in India

Antima[1], **Sandip Banerjee**[2]
[1] *Department of Mathematics, IIT Roorkee, Roorkee 247667, Uttarakhand, India -* e-mail:antima@ma.iitr.ac.in
[2] *Department of Mathematics, IIT Roorkee, Roorkee 247667, Uttarakhand, India -* e-mail:sandip.banerjee@ma.iitr.ac.in

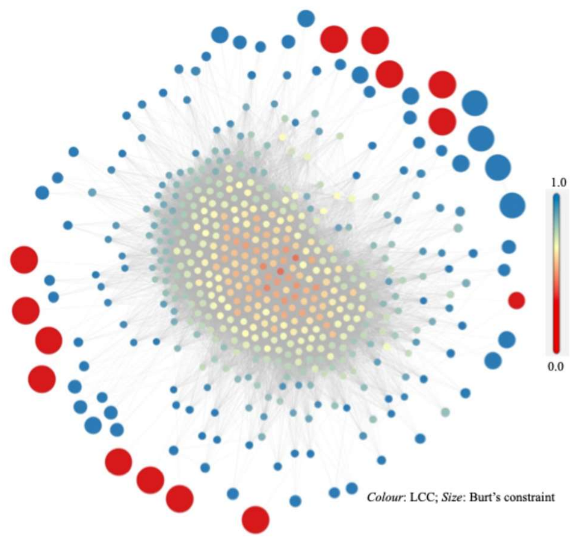
Abstract: Leptospirosis, a formidable zoonotic threat spawned by Leptospira, plagues tropical and subtropicalrealms. This study delves deep into tropical Indian states, namely, Kerala, Gujarat, Karnataka,Maharashtra, and Tamil Nadu, unraveling the dynamics of leptospirosis through a comprehensive mathematical model that embraces temperature-driven growth rates of Leptospira. Sensitivity analysis and parameter estimation techniques fortified the model's accuracy, unraveling the factors shaping leptospirosis transmission. Notably, the numerical results highlight the significant impact of rainfall, fishing, climate, mining, agriculture, and cattle farming on leptospirosis prevalence in the endemic states of India. Finally, our study urges resolute preventive action to control and combat leptospirosis in India. Strengthening surveillance, impactful awareness campaigns, targeted interventions, and improved hygiene practices among high-risk individuals are vital. Embracing these proactive strategies will alleviate the burden of leptospirosis and enhance public health in India and beyond.

The Evolution and Formation of Indian Political Debate Networks

Satyam Mukherjee

School of Management and Entrepreneurship, Shiv Nadar Institution of Eminence, Greater Noida, India

*Corresponding Author E-mail: satyam.mukherjee@snu.edu.in



Recent studies have used tools from network science to model voting behaviour in parliaments. In this work, we explore the structure and formation of a network of debating members in the Rajya Sabha, the upper house of the Indian Parliament, for all debates between 2010 and 2021. Two members are connected if they participate in a debate during a parliament session. We implement the valued-Exponential Random Graph Model (valued-ERGM) (Krivitsky, 2012), which accounts for the frequency of debates between two members of the Rajya Sabha between 2010 and 2021. The figure presents the networks of debaters.

The input variables are the network configurations, including the *k*-core index, Burt's constraint measure, local clustering coefficient (LCC), nodal attributes of gender and educational qualification (highest degree achieved), and the homophily effects. The valued-ERGM, defined as the probability distribution function of valued link formation between Rajya Sabha members, is given as:

$$\begin{aligned}\Pr(Y=y) = h(y)(1/\kappa)\exp\big(&\theta_1 NonZero(y,x) + \theta_2 Sum(y,x) + \theta_3 k_{core}(y,x) \\ &+ \theta_4 Constraint_{Burt}(y,x) + \theta_5 LCC(y,x) + \theta_6 Nodefactor_{Gender}(y,x) \\ &+ \theta_7 Nodematch_{Gender}(y,x) + \theta_8 Nodefactor_{HighestDegree}(y,x) \\ &+ \theta_9 Nodematch_{HighestDegree}(y,x)\big)\end{aligned}$$

In the above valued-ERGM, the *NonZero* variable accounts for the situation where the count of debates between two members would be relatively high, even if the network were sparse. The constant term of the *Sum* accounts for the likelihood of the strength of two debating members without any knowledge about their nodal attributes.

We observe that the effect for Professional Graduate and Intermediate degree holders is positive and significant ($p<0.001$), while a weakly significant effect exists for Post Graduates ($p<0.05$). On the contrary, strong negative effects are seen for Matriculation and Professional Post Graduates ($p<0.001$), while a weak negative effect exists for Doctorate and members with no formal degree ($p<0.05$). Interestingly, no significant impact was observed among the graduate members ($p>0.05$). We also observe a negative coefficient for the education homophily term ($p<0.01$), suggesting that debaters with similar educational qualifications are less likely to debate. No significance was observed for the gender attributes.

Our findings suggest that homophily of the highest educational degree has higher statistical power than gender homophily in the upper house of the bicameral parliament of India. Our research questions have policy implications for government bodies that emphasise gender diversity in decision-making.

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Conflict and cooperation among tandem-running ants: A game-dynamical perspective

Joy Das Bairagya[1], Manish K. Pathak[2], Udipta Chakraborti[2], Sumana Annagiri[2], **Sagar Chakraborty**[1]
[1]*Department of Physics, Indian Institute of Technology Kanpur, Uttar Pradesh, PIN: 208016, India* - sagarc@iitk.ac.in
[2]*Behaviour and Ecology Lab, Department of Biological Sciences, Indian Institute of Science Education and Research, Kolkata, Mohanpur 741246, India*

Abstract: In the lives of social animals, outcomes rarely depend solely on an individual's own decisions—they are deeply intertwined with the actions of others. Yet, beyond studies on humans and monkeys, game-theoretic perspectives are rarely applied to nonhuman animals in behavioural research, except within the context of evolutionary dynamics. We are of the view that if we aim to understand behaviour at the proximate (mechanistic or decision-making) level—not just at the ultimate (evolutionary) level—then game theory may equally be applicable across species with cognitive abilities.

In this talk, we will delve deep into the experimental results on nest relocation behaviour in the Indian queenless ant, *Diacamma indicum*, illustrating how their management of bidirectional traffic can be understood through the behavioural game theory framework—particularly coordination games and a variant of Braess' paradox. This framework moves beyond traditional von Neumann–Morgenstern (VNM) rationality, adopting instead procedural rationality—a model of bounded rationality. In the course of arguments, we will also allude to a theoretical study showing that procedural rationality can be evolutionarily stable against the invasion of classical VNM rationality.

Together, these findings showcase how game theory can serve as a unifying framework–spanning from evolutionary timescales to real-time behavioural interactions, and from the ant colonies to the complex human societies.

Multi-agent target search optimization by threshold resetting

Arnab Pal[1,2]
[1] *The Institute of Mathematical Sciences, Chennai* - arnabpal@imsc.res.in
[2] *Homi Bhabha National Institute, Mumbai* - arnabpal@imsc.res.in

Abstract: I will introduce a new class of first-passage time optimization driven by threshold resetting, inspired by many natural processes where crossing a critical limit triggers failure, degradation or transition [1]. In here, search agents are collectively reset when a threshold is reached, creating event-driven, system-coupled simultaneous resets that induce long-range interactions. I will show how to compute search times for such correlated stochastic processes, and then use ballistic and diffusive searchers as representative examples to highlight a wide range of optimization behaviors.

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Coherence Resonance in Excitable Systems and Networks

ECKEHARD SCHÖLL

Institut für Physik und Astronomie
Technische Universität Berlin, Hardenbergstr. 36, D-10623 Berlin, Germany
schoell@physik.tu-berlin.de • *www.tu.berlin/en/physik/agschoell*

Coherence resonance is a counterintuitive phenomenon in nonlinear stochastic systems. It is associated with the constructive role of noise, which leads to a nonmonotonic dependence of the coherence upon noise intensity, i.e., for intermediate values of noise intensity the oscillations in a nonlinear dynamical system are most regular. It was first discovered by Hermann Haken [1], and later studied in various systems ranging from lasers to the brain [2], using nonlinear Langevin equations. Specifically, I will consider laser dynamics [1], semiconductor superlattices [3], coherence-resonance chimeras in neural networks [4], and a socio-economic model for economic cycle dynamics [5]. Coherence resonance can be controlled by time-delayed feedback [6].

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Bunching of extreme events on complex network

Ravindra E. Amritkar[1,2]

[1]Department of Physics, Banaras Hindu University, Varanasi 221005, India.
[2]Physical Research Laboratory, Ahmedabad 380009, India

Abstract

Extreme events such as earthquakes, floods, power blackouts etc., frequently display a localized bunching or bursting phenomena where they occur multiple times within a short duration. In this study, we explore similar bunching events on complex networks using a transport model of random walks. An extreme event on a node is defined as an event where the number of walkers on a node exceed a certain threshold. Our study shows that a small cluster sparsely connected with the rest of the network, shows bunching of extreme event. The inter event time distribution shows a stretched exponential behavior, suggesting correlations in the extreme events in the smaller cluster. These correlations emerge naturally in our system. The remaining network or large cluster does not show bunching of extreme events and the inter event time distribution shows an exponential behavior. We further study other measures such as the burstiness parameter, memory coefficient, and autocorrelation, confirming the bunching phenomena. Our study shows that the network structure plays an important role in the bunching of extreme events.

Spatiotemporal dynamics of cell shape oscillations

Arkayan Laha, Suman Halder, and Rumi De[1]
[1] *SDepartment of Physical Sciences, Indian Institute of Science Education and Research Kolkata, Mohanpur, Nadia 741246, West Bengal, India.*
E-mail:rumi.de@iiserkol.ac.in

Abstract: Periodic oscillations in cell shape often mark the onset of coordinated collective behaviours, revealing how mechanical feedback and biochemical activity intertwine to drive morphogenetic pattern formation. To elucidate these processes, we develop a general coarse-grained theoretical framework: (i) a global mean-field description and (ii) an active continuum gel model that incorporates key cellular processes such as actomyosin contractility, mechanochemical feedback, and the viscoelasticity of the cell-substrate system. This approach captures diverse morphogenetic processes - from cell shape oscillations to large scale deformations and predicts a variety of spatiotemporal patterns, including propagating waves, oscillatory instabilities, and spatiotemporal chaos. Together, these formulations provide a unified theoretical framework for understanding the dynamics of actomyosin cortex to the emergence of coordinated collective cellular motion during tissue development.

Topological Phase Transitions in Antisymmetric Lotka-Volterra Dynamics

Sirshendu Bhattacharyya[1]
[1] *Raja Rammohun Roy Mahavidyalaya, West Bengal, India* - sirs.bh@gmail.com

Abstract: Topological phases, originally discovered in quantum condensed matter systems, have increasingly been explored in nonlinear and biological dynamics. In this talk, I will discuss how the antisymmetric Lotka–Volterra equation (ALVE), a paradigmatic nonlinear and mass-conserving dynamical system, gives rise to robust topological phases in rock–paper–scissors (RPS) type interactions. First, I will outline the emergence of topological polarization states and solitonic modes in one-dimensional RPS chains, where a transition between left- and right-boundary localization can be classified [1]. Building on this, I will present our recent results on an extended quasi one-dimensional RPS doublet chain, where exponential localization, robustness to perturbations, and bulk spectral gaps are observed [2]. We demonstrate that a topological phase transition occurs at a critical skewness parameter, confirmed by topological band theory through the computation of winding numbers. The study highlights how nonlinear dynamical systems can host topologically protected modes, suggesting possible realizations in biological and soft-matter contexts, and opening avenues for engineering robust dynamical behaviors beyond equilibrium.

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Recurrences in the climate dynamics of India

G. Ambika
Indian Institute of Science Education and Research (IISER TVM)
Thiruvananthapuram- 695 551, India
g.ambika@iisertvm.ac.in

Abstract: I present the recurrence-based analysis of temperature and relative humidity data from the various locations spread over India, including the mountainous region, coastal region, and central and north eastern parts of India. By reconstructing the dynamics from the data over the period 1948 to 2022, the recurrence pattern in the underlying dynamics is captured through recurrence plots and recurrence networks. Their measures are computed using a sliding window analysis on the data sets, which brings out both the temporal variability at each location and the heterogeneity across different spatial locations. Then based on the spatiotemporal pattern underlying the climate dynamics of India can be grouped into five clusters. The variations observed in dynamics can be correlated with reported shifts in the climate related to strong and moderate El Niño–Southern Oscillation events. Similar studies on the rainfall data in the location of Kannur, Kerala brings out the variations in the pattern of summer monsoon over the period 2000-2024 .

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Nonlinear fore-wake structures excited by a moving charged object in a plasma

Abhijit Sen
Institute for Plasma Research,
Bhat, Gandhinagar, India - senabhijit@gmail.com

Abstract: Fore-wake excitations in the form of solitons or shocks ahead of a moving object in a fluid is a spectacular phenomenon that has often been observed in front of fast moving ships and has been widely studied in hydrodynamics. Can a similar phenomenon occur in plasmas in front of a moving charged object? I will discuss this question, that has surprisingly not received much attention in plasma physics, and describe our recent work that establishes the existence of such excitations theoretically [1] as well as in laboratory experiments done using a dusty plasma flowing over electrostatic potential barriers [2]. The excitation of such precursor solitons can be modelled by a driven form of the Koreteweg de Vries (KdV) equation – the so called forced KdV equation – that has a rich variety of coherent solutions. The fKdV and its generalizations in higher dimensions, such as the forced Kadomtsev-Petviashvili (fKP) equation, provide novel paradigms to study a host of new theoretical and experimental areas of research in plasmas. Nonlinear fluid, molecular dynamic and Particle-in-Cell (PIC) simulations provide further confirmation and insights into the nature of such solutions [3]. A potential application of fore-wake precursor solitons is in the detection and tracking of small sized space debris objects that are difficult observe by optical means [1] - an idea that is now being tested as part of an Intelligence Advanced Research Projects Activity (IARPA) initiative under its Space debris Identification and Tracking (SINTRA) program [4].

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From Coexistence to Collapse: Dynamical Outcomes of Species Introduction

Nandadulal Bairagi[1]
[1] *Centre for Mathematical Biology and Ecology, Department of Mathematics, Jadavpur University, Kolkata-700032, India.*

Abstract: Introducing new species is a common strategy in conservation biology, either to protect endangered species or to regulate native populations, yet such programs often yield mixed outcomes. Introduced species may fail to establish and go extinct, or they may disrupt ecosystem balance and drive native species to extinction. Using mathematical modelling and dynamical systems theory, this study examines the success and failure of species introduction in an ecosystem where native prey and predators exhibit cyclic dynamics, and a generalist super-predator is introduced. Our results show that coexistence critically depends on two factors: the population densities of native species at the time of introduction and the initial density of the introduced species. Successful introduction requires a sufficiently high initial density of the new species and timing during the growth phase of the intermediate species. In contrast, introduction during the growth phase of the basal prey leads to extinction of the introduced species while native species persist. More critically, if introduction occurs when both basal species are declining, all species may go extinct, causing ecosystem collapse. These conditions are experimentally testable and offer a dynamic framework for guiding species introduction strategies in conservation practice.

Mitigating cascades in complex networks

Karan Singh[1], V. K. Chandrasekar[2], Wei Zou[3], Jürgen Kurths[4,5], **D. V. Senthilkumar**[1]
[1]*School of Physics, Indian Institute of Science Education and Research Thiruvananthapuram, Thiruvananthapuram, 695551, Kerala, India.*
[2]*Department of Physics, Center for Nonlinear Science and Engineering, School of Electrical and Electronics Engineering, SASTRA Deemed University, Thanjavur, 613401, Tamil Nadu, India.*
[3]*School of Mathematical Sciences, South China Normal University, Guangzhou 510631, China.*
[4]*Potsdam Institute for Climate Impact Research, Telegraphenberg Potsdam , D-14415, Germany.*
[5]*Institute of Physics, Humboldt University Berlin, Berlin, D-12489, Germany.*

Abstract: Cascading failures represent a fundamental threat to the functioning of complex systems. This study proposes a robust and pragmatic approach designed to attenuate the risk of such failures within complex networks effectively. The core of our strategy is to identify a subset of critical nodes within the network, a subset whose relative size is substantial. Further, we employ the graph coloring technique to precisely isolate the nodes (immune nodes) of paramount importance, thereby minimizing the size of the subset extensively, while maximizing its strategic value. Securing these nodes significantly bolsters the network's resilience against cascading failures. We substantiate the superiority of the proposed framework through comparative analyses with existing mitigation strategies and evaluate its performance across various network configurations and failure scenarios. Empirical validation is provided by applying the framework to various real-world networks, elucidating its potential as a strategic tool in enhancing network robustness.

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Entropic origins of order-disorder transitions in network percolation: the role of symmetry breaking

Md. Kamrul Hassan[1]
[1] *Department of Physics, University of Dhaka, Bangladesh*

Abstract: Here we contrast the properties of four basic models of percolation: bond percolation on a 2D square lattice (2DL), the Erdös-Rényi (ER) random graph, the Product Rule (PR) for explosive percolation, and the Inverse Product Rule (IPR). The 2DL and ER models are random processes where bonds/edges are occupied uniformly at random, whereas the PR and IPR models are correlated processes based on edge competition. By directly tracking the evolution of the order parameter, the entropy, the susceptibility, and the specific heat, we show that the 2DL and PR percolation phase transitions display second-order characteristics, with an order-disorder transition and finite-size scaling as a power of system size N. In contrast, the ER and IPR percolation phase transitions do not display order-disorder transitions, instead the disordered phase persists well into the supercritical regime and the system gradually becomes ordered. The associated slow growth of the order parameter and response functions result in ER and IPR displaying finite-size scaling that is best captured with $\log N$ scaling suggestive of an infinite order phase transition. Finally, we show that edge competition introduces a mechanism for symmetry breaking that can lead to an order-disorder transition in network percolation. We show explicitly that processes like PR and the associated Sum Rule (SR) are formulated in terms of favoring the edge that maximizes entropy given the constraints and how this leads to the buildup of a powder keg, elucidating the entropic origins of explosive percolation.

Cell signalling, bistability and drug targets

Samrat Chatterjee[1]
[1] *Complex analysis group*
Translational Health Science and Technology Institute,
NCR Biotech Science Cluster 3rd Milestone, Faridabad-Gurgaon Expressway,
Faridabad-121001

Abstract: Traditional computational approaches struggle to capture the complex interactions that occur across multiple molecular layers in disease systems, particularly as the volume of biological data continues to grow. We developed mathematical model–based computational tools to identify potential drug targets from large-scale datasets. Focusing on bistability in cell signalling networks, we investigated how protein–protein interaction (PPI) motif structures influence input–output (I/O) relationships. A model-based analysis is conducted to explore the critical conditions responsible for the emergence of different bistable protein–protein interaction (PPI) motifs and their potential applications in identifying drug targets. The influence of stochastic perturbations that could hinder the desired functionality of any signalling networks is also explored. To account for intrinsic cellular noise, we employed stochastic differential equation (SDE) models to study the relationship between motif architecture and signal–noise dynamics. We quantified node vulnerability to stochastic perturbations and identified noise-sensitive, highly druggable motifs as promising therapeutic targets. Finally, we proposed a theoretical framework for systematic drug-target identification and applied it to three cancer signalling networks, validating the predicted targets using established databases.

Approaching Quantum Chaos using OTOCs

Tibra Ali[1]
[1]*Department of Mathematics and Natural Sciences, BRAC University (BRACU), Dhaka, 1212, Bangladesh.*

Abstract: In recent years, out-of-time-order correlators (OTOC) have emerged as a new tool for studying quantum chaos. This tool has grown out of a holographic analysis of chaos of black hole physics. In this talk, I shall apply OTOCs to analyze the behaviour of some of the simplest systems known to be classically chaotic: one dimensional billiard systems such as the Sinai, the cardioid and the diamond billiard. We shall compare this approach to the traditional method of analyzing quantum chaos using level statistics. We shall then outline an approach in connecting the two different approaches.

Emergent Market States and Phase Transitions in Financial Systems

Suchetana Sadhukhan[1], Hirdesh K. Pharasi[2], Parisa Majari[3], Anirban Chakraborti[4], and Thomas H. Seligman[5]

[1] *School of Computer Science, UPES, Dehradun, Uttarakhand, India* s.suchetana@gmail.com

[2] *School of Engineering and Technology, BML Munjal University, Gurugram, Haryana-122413, India*

[3] *Tecnológico de Monterrey, Mexico*

[4] *School of Computational and Integrative Sciences, Jawaharlal Nehru University, New Delhi-110067, India*

[5] *Instituto de Ciencias Fısicas, Universidad Nacional Autonoma de Mexico, Cuernavaca-62210, Mexico*

Abstract: Complex systems display rich and often unpredictable behavior driven by interactions among their constituents. This is particularly evident in financial markets, where the interplay among stocks generates correlation patterns that shift rapidly during major events. By analyzing similarities among correlation matrices, we identify quasi-stationary market states that offer predictive insight into emerging transitions. Bubbles, crashes, and other critical events appear as well-separated phases in the market's state space, reflecting shifts between ordered and disordered collective dynamics. Using a combination of spectral indicators and network measures, we trace the formation and evolution of these phases. This approach deepens our understanding of systemic fluctuations and provides a pathway toward early detection of tipping points in financial systems.

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Contributory Talks

Dynamical analysis of a parameter-aware reservoir computer

Dishant Sisodia[1], Sarika Jalan[2]
[1] *Complex Systems Lab, Indian Institute of Technology Indore, India* - dishantsisodia.physics@gmail.com
[2] *Complex Systems Lab, Indian Institute of Technology Indore, India* - sarika@iiti.ac.in

Abstract: Reservoir computing is a useful framework for predicting critical transitions of a dynamical system if the bifurcation parameter is also provided as an input. Fundamentally, RC functions as a discrete map system. Our numerical analysis demonstrates how the trained reservoir map successfully generates the dynamics of a continuous system [1]. To learn the correct dynamical behavior around the Hopf bifurcation, the map undergoes the Neimark-Sacker bifurcation such that the critical point of the map is in immediate proximity to that of the original dynamical system. It also correctly captures the intricate behaviour in the phase space like torus formation by the successive crossing of two conjugate eigenvalue pairs. Our findings provide insight into the functioning of machine learning algorithms for predicting critical transitions. To the end, we will also discuss functioning mechanism of RC behind the prediction of discontinuous transitions [2].

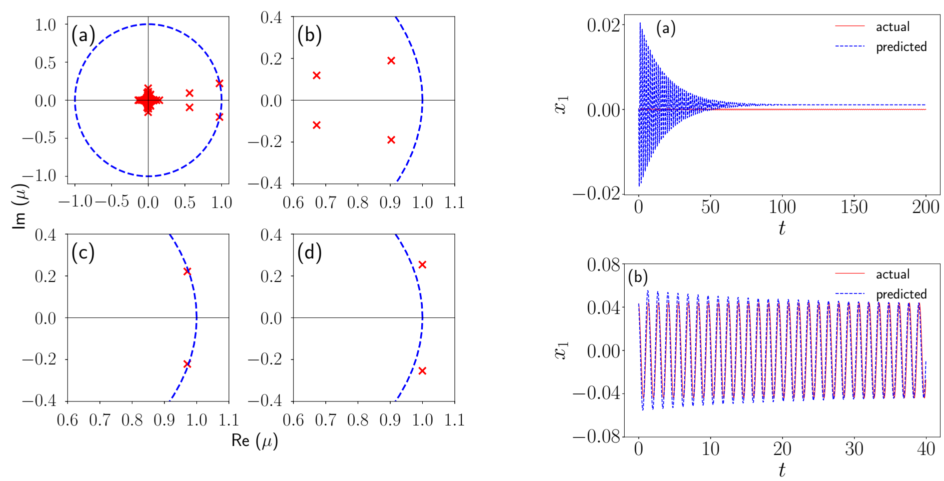

Figure 1: Eigenvalue analysis for a system of coupled Stuart-Landau oscillators. Left figure shows the Neimark-Sacker bifurcation. Figure on the right shows the comparison between the actual and the predicted time series after successful training.

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Blink it to sync it: Experimental evidence of synchronization of human brainwaves subjected to common photic forcing

Aarsh Chotalia[1], Sapna Yadav[2], Richa Phogat[3], P. Parmananda[4]
[1] *Indian Institute of Technology Bombay, Mumbai, India* - aarshchotalia@iitb.ac.in
[2] *Indian Institute of Technology Bombay, Mumbai, India* - 215120006@iitb.ac.in
[3] *University of Newcastle, Newcastle, Australia* - riphogat@gmail.com
[4] *Indian Institute of Technology Bombay, Mumbai, India* - punit@phy.iitb.ac.in

Abstract: In an effort to achieve synchronization in mesoscopic cortical activities, experiments were conducted on five individuals. An indirect coupling was established between the subjects via a common photic forcing. The results point to partial synchronization between intra- as well as inter-participant activities when subjected to common periodic photic stimulus. To investigate the possible mechanism, delayed correlations were computed. The constancy of phase shifts from these correlations, estimated by effective order parameter, suggests that partial phase resetting is the underlying mechanism.

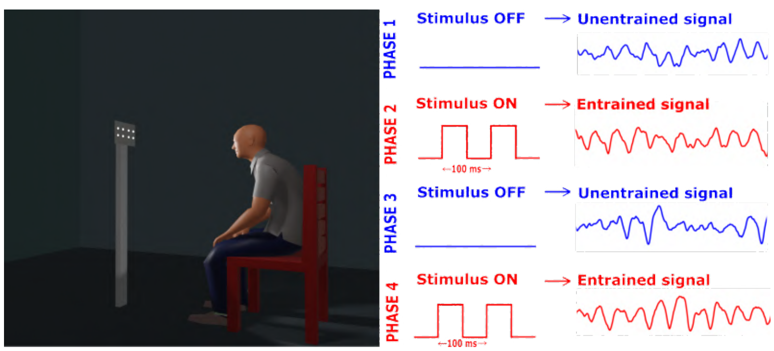

Figure 1: Experimental protocol: the subjects were seated on a chair in front of LED lights in an otherwise dark room. In phases 1 and 3, no stimulus was provided. During phases 2 and 4, a square wave pulse of 10 Hz was administered through the LEDs. Each phase lasted for 5 min. The EEG data of the occipital zone (electrodes positioned at O1, O2, and Oz) were recorded at the sampling rate of 1000 Hz.

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Disorder–Order Transitions and Explosive Synchronization in Heterogeneous Ginzburg–Landau Oscillators on Directed Networks

Kumar Sourav[1], Naveen Kumar Mendola[2], Thounaojam Umeshkanta Singh[3]
[1] *Bennett University, India-* e23soep0039@bennett.edu.in
[2] *Bennett University, India -* e21soep0032@bennett.edu.in
[3] *Bennett University, India -* Thounaojam.Singh@bennett.edu.in

Abstract: Diffusively coupled heterogeneous oscillators in large networks undergo complex transitions between ordered and disordered states [1], [2], [3]. Understanding the mechanisms that govern the onset and loss of synchronization in such systems remains a central problem in nonlinear dynamics and statistical physics. Here, we investigate the collective dynamics of three distinct ensembles of Ginzburg–Landau-type oscillators—anti-rotating, counter-rotating, and uniformly rotating—coupled diffusively on a directed ring network [1]. As the coupling strength increases, the system first exhibits enhanced disorder before undergoing an abrupt transition to a frequency-locked ordered state, characterized by explosive synchronization and hysteresis. Large-scale numerical simulations quantify the dynamics via frequency and amplitude deviations, while ensemble-averaging theory provides analytical estimates of the ensemble-averaged frequency and amplitude, in strong agreement with simulation results. These findings offer new insights into the self-organization of heterogeneous, non-isochronous limit-cycle oscillators under diffusive unidirectional coupling [3].

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Robust oscillatory dynamics in a mixed population of excitable and self-oscillatory Izhikevich neurons: Influence of second-order linear and nonlinear interactions

Soorya PP [1], **Biswambhar Rakshit** [2], Kazuyuki Aihara[3]
[1] *Amrita Vishwa Vidyapeetham, India* - sooryapp4@gmail.com
[2] *Amrita Vishwa Vidyapeetham, India* - b_rakshit@cb.amrita.edu
[3] *University of Tokyo, Japan* - kaihara@g.ecc.u-tokyo.ac.jp

Abstract: In this study, we investigate the robust collective oscillation in a globally coupled heterogeneous population of excitable and selfoscillatory Izhikevich neurons with second-order interactions. We consider both linear and nonlinear forms of second-order coupling and uncover a variety of complex behaviors. Depending on the fraction of excitable neurons and the coupling strengths, the system exhibits three distinct dynamical regimes: tonic spiking, bursting, and a death state. We also observe synchronized cluster formation, with excitable and oscillatory neurons forming separate groups. A two-parameter phase diagram shows that bursting tends to occur at lower values of the excitable neuron fraction. Increasing the strength of linear second-order coupling expands the region where bursting occurs, while stronger nonlinear coupling does not display any significant changes. Notably, period-adding bursting is observed in both interaction types. Finally, we investigate themechanismof aging transition through bifurcation analysis of a reduced model.

Edge-centric functional network organization reveals seizure pathways in mesial-temporal lobe epilepsy

Aditi Bose[1], Timo Bröhl[2,3], Klaus Lehnertz[2,3,4], Chittaranjan Hens[1,5]
[1] *Centre for Computational Natural Sciences and Bioinformatics, International Institute of Information Technology, Hyderabad 500032, India* - aditi.bose@research.iiit.ac.in
[2] *Department of Epileptology, University of Bonn Medical Center, Venusberg Campus 1, 53127 Bonn, Germany*
[3] *Helmholtz Institute for Radiation and Nuclear Physics, University of Bonn, Nussallee 14–16, 53115 Bonn, Germany*
[4] *Interdisciplinary Centre for Complex Systems, University of Bonn, Brühler Str. 7, 53175 Bonn, Germany*
[5] *Biomedical Research Center, International Institute of Information Technology, Hyderabad 500032, India*

Abstract: Spatiotemporal signal propagation is a defining property of complex networks [1, 2], yet the pathways that channel activity through the human brain during epileptic seizures remain poorly resolved. Using iEEG from seizures with medically refractory epilepsy, we introduce an edge-centric framework [3, 4] that tracks how influential functional connections form, persist, and transition as seizures unfold. Electrodes are grouped into three functional modules—clinician-defined seizure focus, nearby ipsilateral regions, and all other areas—and the top 2% of edges by centrality are followed over time. A probabilistic entropy approach reveals that path-based centralities exhibit a reproducible circular motif of seizure propagation across subjects, indicating a conserved pattern in functional interaction space. In contrast, strength-based centralities separate patients into two distinct classes: one in which cross-module edges serve as dynamic bottlenecks guiding ictal spread, and another in which these edges remain stable throughout the seizure. Together, these findings uncover a previously hidden universality in seizure dynamics and demonstrate that an edge-focused perspective can expose the fine-grained routes that govern ictal communication. This framework links theories of spatiotemporal propagation in complex networks with empirical human neuroscience, offering potential for improved prediction and intervention in epilepsy.

Keywords: Epileptic networks, seizure propagation, centrality measures, intracranial EEG, network neuroscience.

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A Delayed Tuberculosis Transmission Model with Vaccination and Subclinical Infection: Stability and Sensitivity Analysis

Aditya Bhattacharya[1], Anindita Bhattacharyya[2]
[1] *Department of Mathematics, Amity University, Major Arterial Road, Kolkata, 700135, West Bengal, India* - aditya.bhattacharya5745@gmail.com
[2] *Department of Mathematics, Amity University, Major Arterial Road, Kolkata, 700135, West Bengal, India* - aninmb@gmail.com

Abstract: Tuberculosis continues to pose a substantial global health challenge, with approximately 10.8 million new cases observed worldwide in 2024 as estimated by WHO. Existing deterministic models examining tuberculosis transmission dynamics have mainly focused on the latent and active phases of tuberculosis. However, recent studies have shown that additional categories of infection can be defined between the latent and active tuberculosis phases [1, 2]. Hence, this study formulates a delayed tuberculosis transmission model with vaccination incorporating the subclinical phase and analyses its dynamics mathematically. Local stability of the model equilibria is shown to depend on the reproduction number, and key transmission drivers are identified using comprehensive sensitivity analysis techniques including Latin Hypercube Sampling – Partial Rank Correlation Coefficient (LHS-PRCC) technique. It is shown that tuberculosis transmission intensity can be reduced by implementing appropriate vaccination policies, contact-based interventions and prompt diagnosis. Numerical simulations are presented to validate the analytical results obtained and it is shown that inclusion of the subclinical phase leads to a more biologically realistic model.

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Learning, Information, and the Emergence of Braess Paradox in a Microscopic Traffic Model

Ann Mary Mathew[1], Sasidevan V[1]
[1] *Cochin University of Science and Technology, Kerala, India* - annmaryettolil@gmail.com

Abstract: Braess paradox is a counterintuitive situation arising in transportation network models that shows how adding extra connecting links paradoxically increases the overall travel time. The paradox has been observed in cities such as Seoul, New York, and London and challenges our normal assumptions about optimisation in networks. Apart from the context of transportation, the model is applicable to a wide range of systems such as biological networks, power grids, mechanical systems, etc. [1].

Even when the model captures the large-scale behaviour of transportation networks with a specific structure, the model is limited by its inherent macroscopic and deterministic assumptions. The Wardrop equilibrium of the model is obtained under the assumption of perfectly rational agents acting under complete information, whereas real-world networks possess neither of these. A microscopic model with myopic agents can better reflect how individual decisions shape collective traffic flow, thereby capturing the emergence of the Braess paradox in real-world contexts [2].

We model the traffic network using a TASEP-based (Totally Asymmetric Simple Exclusion Process) framework and look at how bounded-rational agents who learn and act under incomplete information can influence the emergence of the Braess paradox. We analyse how the evolutionarily learning, interacting agents adapt their route choices when provided with different kinds of information from the network: public historical, personal historical and public-predictive. We characterise the effect of information and learning of agents on the system by analysing quantities such as the Price of Anarchy, which is the ratio of user optimum to the system optimum costs. We propose conditions under which the Price of Anarchy can be suitably controlled, which is of practical application in situations where connecting links are to be introduced in networks and Braess paradox is likely to occur.

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Spectral fluctuations and crossovers in multilayer network

Himanshu Shekhar[1],Ashutosh Dheer[2], Santosh Kumar[3],N. Sukumar[4]
[1] *Department of Physics, Shiv Nadar Institution of Eminence, Gautam Buddha Nagar, UP, India,201314.*himanshuphy02@gmail.com
[2] *Department of Physics, Shiv Nadar Institution of Eminence, Gautam Buddha Nagar, UP, India, 201314.* ad326@snu.edu.in
[3] *Department of Physics, Shiv Nadar Institution of Eminence, Gautam Buddha Nagar, UP, India, 201314.* Deceased
[4] *Amrita School of Artificial Intelligence, Amrita Vishwa Vidyapeetham, Coimbatore, Tamil Nadu, India, 641112.* n_sukumar@cb.amrita.edu

Abstract: In the past few decades, network theory has established itself as a powerful framework for analyzing a wide range of real-world systems, including social, biological, economic, transportation, and information networks [1, 2]. Many of these systems are inherently multilayered, as they encompass multiple types of interactions, relations, or dynamical processes occurring simultaneously [3]. Motivated by this, we employ the framework of random matrix theory (RMT) to investigate spectral fluctuations in multilayer networks, with the aim of distinguishing universal and non-universal spectral features[5, 4].

In this context, we consider general multilayer architectures—including purely intra-layer, purely inter-layer, combined, and multiplex structures—by constructing ensembles of random multilayer networks with Erdős-Rényi (ER) random graph connectivity and systematically varying intra- and inter-layer connection probabilities to examine the dependence of spectral statistics on connectivity patterns [4]. The adjacency matrix of a multilayer network naturally exhibits a block structure, with diagonal blocks representing intra-layer connectivity and off-diagonal blocks capturing inter-layer couplings. In this work, fluctuations are characterized using higher-order spacing ratios distibution(SRD), which are sensitive to spectral correlations [6]. To ensure comparability of spectral fluctuations across layers, we introduce scaling factors for diagonal and off-diagonal blocks that normalize variances irrespective of block size or connection probability.

In this work further, we are introducing a crossover model for bilayer networks, and capture the smooth transition of spectral properties from block-diagonal (two independent GOEs) to single-layer (one GOE) statistics as the relative strength of inter-layer to intra-layer connection varies. Furthermore, we apply the framework to empirical multilayer networks derived from protein crystal structures (1EWT, 1EWK, and 1UW6), modeling residues as nodes and spatial proximity as edges. By varying distance thresholds, we probe how changes in intra- and inter-layer connectivity drive transitions between universality classes, using both SRD and cumulative SRD (CSRD) to quantify the behavior.

Our findings show that, under appropriate scaling, multilayer networks exhibit the universal spectral fluctuations predicted by RMT, despite heterogeneity in layer structure and topology. This demonstrates that spectral universality is a robust feature of layered architectures and that the interplay between intra- and inter-layer couplings can be rigorously quantified within the RMT framework. Beyond protein systems, these results establish a general methodology for probing universality and coupling effects in complex multilayered systems, with broad relevance to communication, transportation, and biological networks.

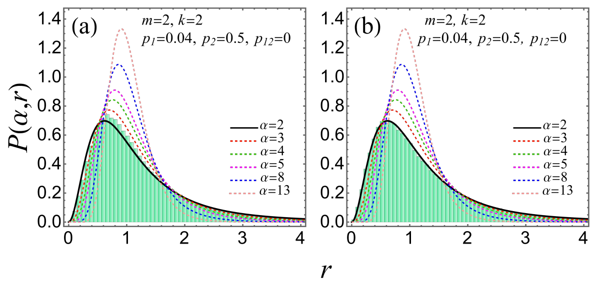

Figure 1: **Effect of scaling.** Higher-order SRD histograms for a bilayer network ($m = 2$) without inter-layer connections. The diagonal blocks of the adjacency matrix have dimensions 350×350 and 450×450, respectively. The histograms are obtained from numerical simulations over an ensemble of 250 adjacency matrices. The order of the spacing distribution and the edge probabilities used for the simulations are $(k, p_1, p_2) = (2, 0.04, 0.5)$ in both cases. (a) Without scaling the two blocks, the resulting distributions deviate from RMT predictions. (b) With appropriate scaling of the blocks, the histograms closely follow the analytical RMT expression corresponding to $\alpha = 2$.

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A Survival-Theoretic Interpretation of Change Point Detection under Autocorrelation and Transient Deviations

Agniva Das, Muralidharan K.
Department of Statistics, Faculty of Science, The Maharaja Sayajirao University of Baroda, Vadodara, PIN-390002, Gujarat, India - agniva.d-statphd@msubaroda.ac.in

Abstract: Change point detection (CPD) in time series with strong autocorrelation and transient deviations remains challenging, not only algorithmically but also conceptually. While numerous methods exist for detecting structural changes, comparatively less attention has been paid to the interpretation of detection delay and false alarms within a unified theoretical framework, particularly for highly volatile dynamical systems [1, 2]. In this work, we present a survival-theoretic perspective on change point detection that reinterprets regime changes as event times and detection rules as stopping mechanisms, thereby establishing a principled connection between CPD, reliability theory, and competing risks models.

From an online viewpoint, the occurrence of a true structural change and the triggering of a false alarm may be viewed as mutually exclusive terminating events [3]. This naturally leads to a competing risks formulation in which detection delay corresponds to residual life and false alarms contribute an additional hazard. Within this framework, the commonly used notion of detection delay admits an interpretation analogous to the mean residual life (MRL) function in survival analysis [4]. Under simple geometric change priors, the MRL admits a closed-form expression, providing a useful reference for detection latency [5]. More generally, we show how empirical estimates of residual life can be interpreted as offline approximations to expected detection delay under data-adaptive hazard processes.

Motivated by this perspective, we discuss a composite performance index that penalizes the reciprocal of empirical mean residual life by the number of false positive detections. Rather than viewing this index as ad hoc, we interpret it as an empirical proxy for a competing-hazards risk functional that balances timeliness of detection against over-sensitivity. The practical utility of this metric is illustrated through retrospective comparison across a range of existing change point detection methods, where it provides more stable and interpretable performance rankings in highly volatile and autocorrelated settings. This interpretation clarifies why excessive false alarms can artificially reduce detection delay metrics and highlights the need for joint consideration of delay and false alarm rates in volatile systems.

This work introduces a survival-theoretic lens that provides a unifying conceptual framework for understanding and evaluating change point detection methods in autocorrelated and noise-contaminated environments. By reinterpreting standard evaluation outputs through a competing-risks perspective, the proposed framework enables more meaningful post hoc assessment of existing detectors without altering their internal mechanisms. We further outline how this perspective naturally extends toward Bayesian formulations with covariate-dependent hazards driven by likelihood evidence, volatility measures, and persistence scores. The proposed viewpoint is broadly applicable to complex dynamical systems arising in finance, climate, geophysics, and engineering, and offers a foundation for future work at the interface of change point analysis, stochastic dynamics, and survival modelling.

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Emergent Market States and Phase Transitions in Financial Systems

Suchetana Sadhukhan[1], Hirdesh K. Pharasi[2], Parisa Majari[3], Anirban Chakraborti[4], and Thomas H. Seligman[5]

[1] *School of Computer Science, UPES, Dehradun, Uttarakhand, India* s.suchetana@gmail.com
[2] *School of Engineering and Technology, BML Munjal University, Gurugram, Haryana-122413, India*
[3] *Tecnológico de Monterrey, Mexico*
[4] *School of Computational and Integrative Sciences, Jawaharlal Nehru University, New Delhi-110067, India*
[5] *Instituto de Ciencias Fısicas, Universidad Nacional Autonoma de Mexico, Cuernavaca-62210, Mexico*

Abstract: Complex systems display rich and often unpredictable behavior driven by interactions among their constituents. This is particularly evident in financial markets, where the interplay among stocks generates correlation patterns that shift rapidly during major events. By analyzing similarities among correlation matrices, we identify quasi-stationary market states that offer predictive insight into emerging transitions. Bubbles, crashes, and other critical events appear as well-separated phases in the market's state space, reflecting shifts between ordered and disordered collective dynamics. Using a combination of spectral indicators and network measures, we trace the formation and evolution of these phases. This approach deepens our understanding of systemic fluctuations and provides a pathway toward early detection of tipping points in financial systems.

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Experimental Observation of Aging Transition in Locally, Globally Coupled Networks

P. Parmananda, Taniya Khatun, Sapna Yadav, **Presenting Author Aryan Nagpal**
Department of Physics, Indian Institute of Technology Bombay, India
Department of Physics, Indian Institute of Technology Bombay, India
Department of Physics, Indian Institute of Technology Bombay, India
Department of Physics, Indian Institute of Technology Bombay, India – 23b1802@iitb.ac.in

Abstract:
We experimentally observe aging transition, the collapse from oscillatory to non-oscillatory states, in minimal networks of ten Wien-bridge oscillators under local coupling and global coupling via LTspice hybrid simulation. For local coupling, experiments reveal: (i) Critical inactive fraction pc decreases with coupling strength; (ii) Networks sustain oscillations up to 50% inactive nodes at low resistance. Crucially, global coupling simulations demonstrate identical aging dynamics: pc remains stable across resistance ranges (4.7 Ω–13.6 kΩ), with abrupt network collapse beyond 60% inactivity. Phase diagrams confirm universal transition behavior across coupling topologies, while time-series data validate that active oscillators maintain frequency despite amplitude decay. This work provides the **first experimental evidence of aging transition** in locally coupled physical networks and extends it to global coupling via simulation, bridging theory with real-world applicability in biological/engineered systems.

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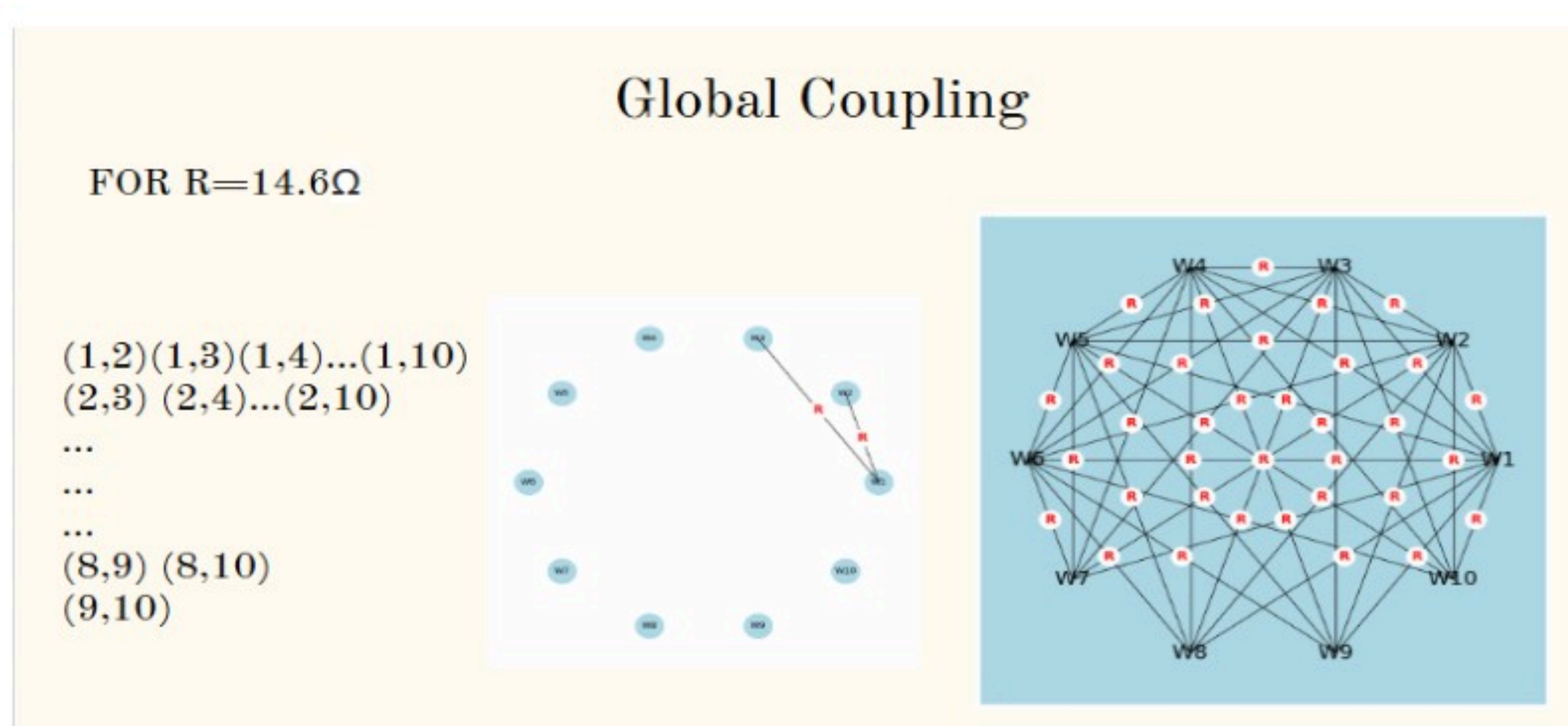

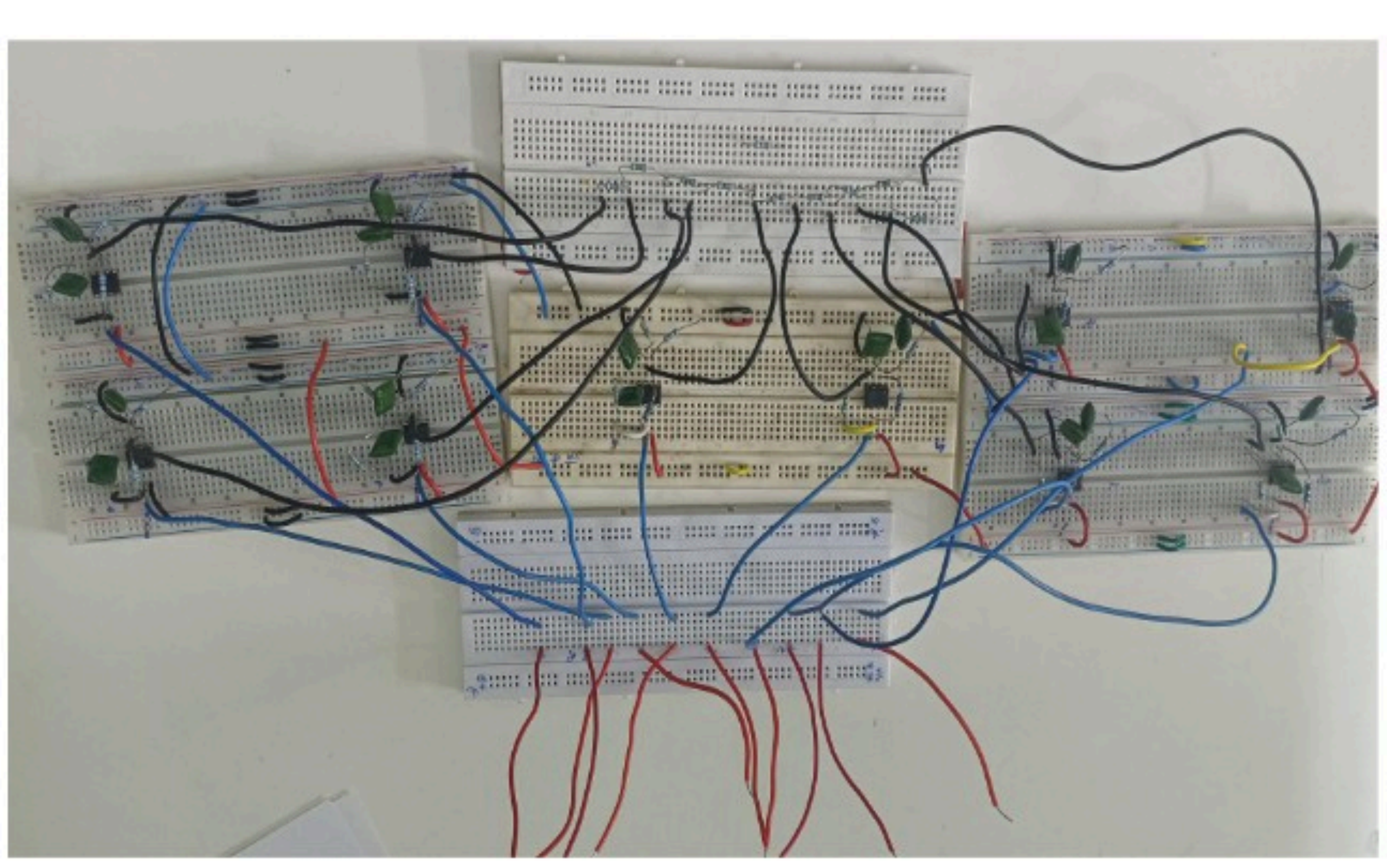

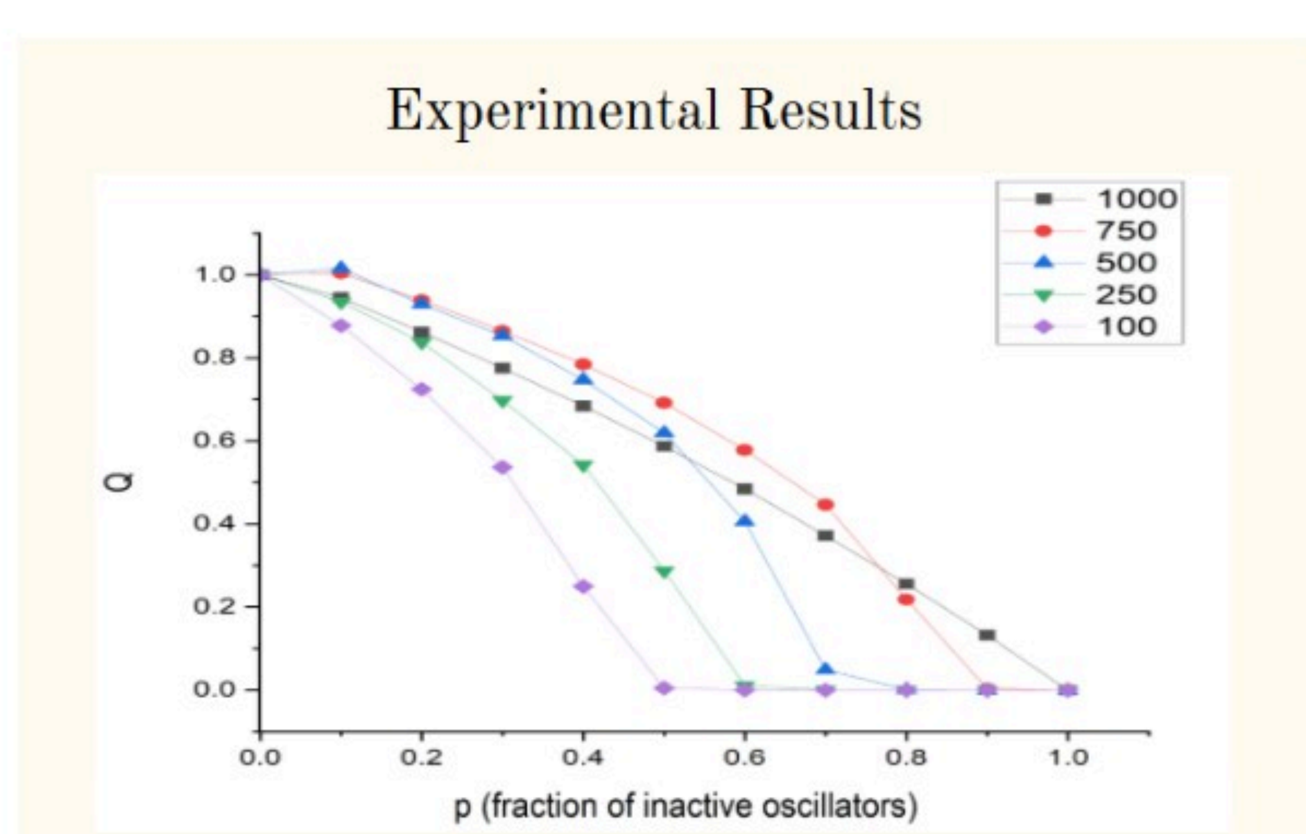

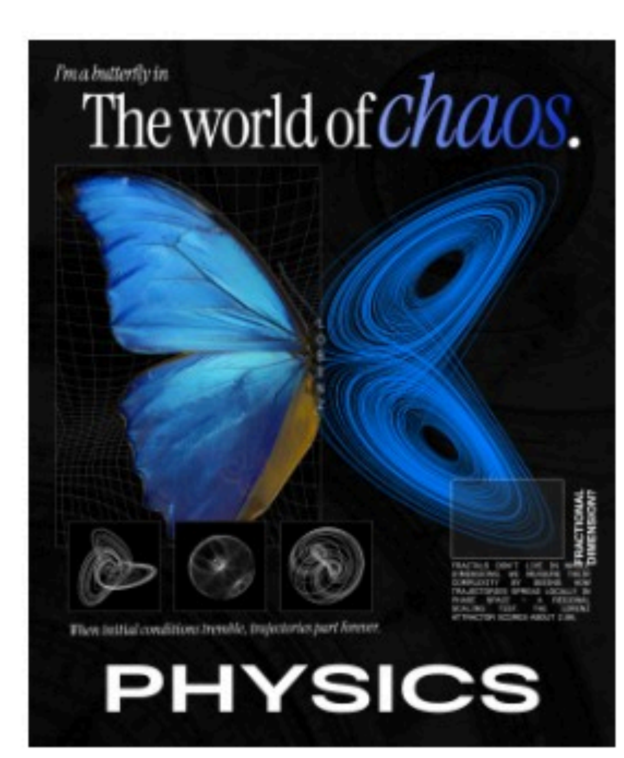

On investigation of complexity in extracellular matrix-induced cancer dynamics under deterministic and stochastic framework.

Amit Kumar Barman[1], **Ranjit Kumar Upadhyay** [1]
[1]***Indian Institute of Technology (Indian School of Mines) , India***
:amit.nonlinear@gmail.com;ranjit@iitism.ac.in

Abstract: Cancer attracts significant attention nowadays due to its rising global incidence, the complexity of its biological mechanisms, and the challenges it presents in treatment and prevention. In this talk, we present a comprehensive mathematical model describing the coupled dynamics of cancer cells, immune cells, cytokines, and the extracellular matrix with the aim of understanding the key dynamical mechanisms governing tumor progression. The emergence of critical dynamical transitions is demonstrated through the identification of saddle-node bifurcations and Hopf bifurcation phenomena. Higher-order dynamics, including codimension-two Bogdanov–Takens bifurcations, are examined via normal form analysis and center manifold theory. To assess the robustness of the model predictions, we perform an uncertainty analysis based on Latin hypercube sampling, followed by a sensitivity analysis to identify influential parameters driving tumor growth. Stochastic effects arising from environmental and biological fluctuations are incorporated through multiplicative white noise, allowing us to derive sufficient conditions for mean persistence and extinction of the system components.

Bayesian tit-for-tat fosters cooperation

Arunava Patra[1], Supratim Sengupta [2], Sagar Chakraborty[3]
[1] *Indian Institute of Technology Kanpur, India* - arunava20@iitk.ac.in
[2] *Indian Institute of Science Education and Research Kolkata, India* - supratim.sen@iiserkol.ac.in
[3] *Indian Institute of Technology Kanpur, India* - sagarc@iitk.ac.in

Abstract: Organisms are known to incessantly infer the environment (including other organisms) around them in order to make strategic decisions. In the course of such decision-making, the ability to make probabilistic estimations using Bayes updating in the presence of uncertainties is well documented, e.g., in humans [1], three-spined sticklebacks [2], and bumblebees [3]. When an organism gradually infers the opponent's strategy using Bayesian updating and acts accordingly, the strategy is termed a Bayesian inferential strategy [8].

Such strategies may critically influence the emergence and persistence of complex collective phenomena, such as cooperation [5] and the tragedy of the commons (ToC) [7]. We therefore use the paradigm of stochastic games [5] to mathematically establish the Bayesian tit-for-tat (BTFT)—a special kind of Bayesian strategy in which the player considers the opponent's action as evidence to progressively learn the opponent's strategy using Bayesian updating and adopts the argument of the global maximum of the posterior belief as her strategy to play with opponent in the next round.

Within the framework of natural selection, we investigate whether BTFT is evolutionarily stable (ESS) [6] when competing against strategies that do not learn—for instance, simple reactive strategies that merely react to the opponent's immediately preceding action. Furthermore, we investigate within the realm of mesoevolution whether the BTFT strategy can survive and promote cooperation in the long term, even when a population initially consists entirely of defectors. We find that the BTFT is ESS against a large class of reactive strategies, especially the always-defector strategy. Our analysis also reveals that the presence of BTFT increases the overall rate of cooperation and averts ToC in the long term.

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Asynchronous evolution induces Regularity in Coupled Neuronal Systems

Anupama Roy[1], Sudeshna Sinha[2]
[1] *Indian Institute of Science Education and Research Mohali, India* -anupamaroy@iisermohali.ac.in
[2] *Indian Institute of Science Education and Research Mohali, India* - sudeshna@iisermohali.ac.in

Abstract: Asynchronicity is a fundamental feature of dynamical evolution of complex interactive systems. In this work we inspect the impact of asynchronicity on the spatiotemporal dynamics in a ring of diffusively coupled maps modelling chaotic neurons [1, 2, 3]. Specifically, asynchronicity in the evolution is introduced here by updating of f_{sync} fraction of randomly chosen sites at each time step. Therefore, smaller value of f_{sync} indicates the stronger asynchronicity, while f_{sync} close to 1 reflects near synchronous evolution. Our crucial finding is that asynchronicity can suppress neuronal oscillations under sufficiently strong coupling in contrast to the synchronous evolution where all sites update in unison. For strong asynchronicity, one obtains complete cessation of neuronal activity in a very wide window of coupling strengths, while for weaker asynchronicity, neuronal activity is quenched over a smaller range of coupling (see Fig. 1). We also rigorously analyze a system of two coupled neurons, for the distinct cases of synchronous updates, sequential updates and random asynchronous updates. We find that our stability analysis is in complete agreement with results from numerical simulations, offering an underlying rationale for the surprising counter-intuitive effects of asynchronicity [4]. We also analyze the dynamics of large systems, in a time-averaged framework, and this analysis yields values of critical coupling very close to that obtained from simulations [4].

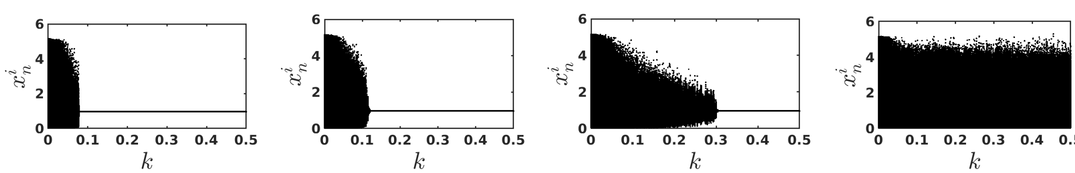

Figure 1: Bifurcation diagrams with respect to coupling strength (k) of the action potential of a representative neuron in a coupled neuronal system of size 100 for $f_{sync} = 0.2$, 0.5, 0.6 and 0.8 (from left to right).

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Turbulent dynamics in Gross-Pitaevskii model of Neutron Star interiors

Anirudh Sivakumar[1], Pankaj Kumar Mishra[2], Ahmad A. Hujeirat[3], and Paulsamy Muruganandam[1]

[1] *Bharathidasan University, Tiruchirappalli 620 024, Tamil Nadu, India*
[2] *Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India*
[3] *Interdisciplinary Center for Scientific Computing, University of Heidelberg, 69120 Heidelberg, Germany*

Abstract: We model the superfluid core of a neutron star as a Bose-Einstein condensate using the Gross-Pitaevskii equation, which exhibits glitch behavior by expelling vortices to the outer crust during spin-down [1]. By incorporating a phenomenological damping term and a pinning potential to mimic dissipative mechanisms and the outer crust, respectively, we investigate the dynamics [2]. Our simulations reveal turbulent flow after spin-down, characterized by Kolmogorov scaling in the incompressible kinetic energy spectrum, sustained by quantum pressure injection into the incompressible kinetic energy component [3].

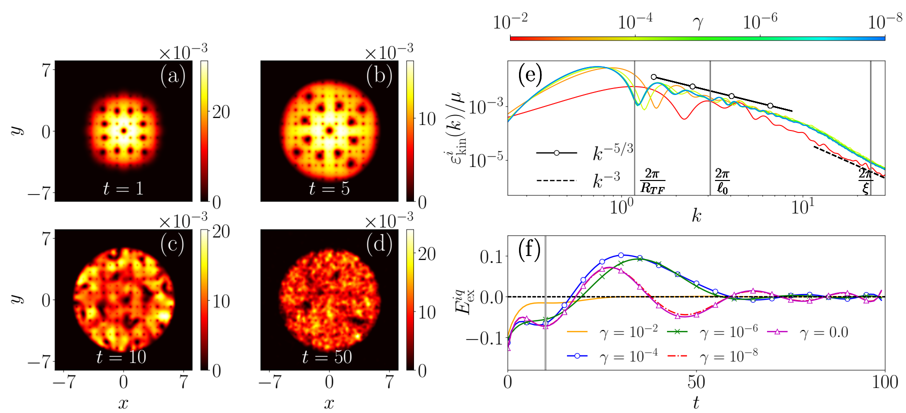

Figure 1: (a)-(d) Condensate density during spin-down. (e) The incompressible kinetic energy spectra with the Kolmogorov $k^{-5/3}$ scaling. (f) Injection of incompressible kinetic energy from the quantum pressure component

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Robust oscillatory dynamics in a mixed population of excitable and self-oscillatory Izhikevich neurons: Influence of second-order linear and nonlinear interactions

Soorya PP [1], **Biswambhar Rakshit** [2], Kazuyuki Aihara[3]
[1] *Amrita Vishwa Vidyapeetham, India* - sooryapp4@gmail.com
[2] *Amrita Vishwa Vidyapeetham, India* - b_rakshit@cb.amrita.edu
[3] *University of Tokyo, Japan* - kaihara@g.ecc.u-tokyo.ac.jp

Abstract: In this study, we investigate the robust collective oscillation in a globally coupled heterogeneous population of excitable and selfoscillatory Izhikevich neurons with second-order interactions. We consider both linear and nonlinear forms of second-order coupling and uncover a variety of complex behaviors. Depending on the fraction of excitable neurons and the coupling strengths, the system exhibits three distinct dynamical regimes: tonic spiking, bursting, and a death state. We also observe synchronized cluster formation, with excitable and oscillatory neurons forming separate groups. A two-parameter phase diagram shows that bursting tends to occur at lower values of the excitable neuron fraction. Increasing the strength of linear second-order coupling expands the region where bursting occurs, while stronger nonlinear coupling does not display any significant changes. Notably, period-adding bursting is observed in both interaction types. Finally, we investigate themechanismof aging transition through bifurcation analysis of a reduced model.

Dynamical complexity induced by prevalence-dependent mobility in a disease transmission model.

Amar Sha[1], **Pijush Panday,**[2], Abhishek Senapati[3]
[1]*Department of Mathematics, Goenka College of Commerce and Business Administration, Kolkata, India* - amar.sha95@gmail.com
[2]*Department of Mathematics, Faculty of Science and Technology, ICFAI Tech, ICFAI Foundation for Higher Education, Hyderabad, India* - pijush.math.ju@gmail.com
[3]*Saw Swee Hock School of Public Health, National University of Singapore, Singapore* - abhishekiz4u04@gmail.com

Abstract: The transmission of infectious diseases is influenced by human behavior, particularly mobility patterns, which often respond to prevailing disease prevalence. In this study, we analyze a two-patch SIR-type model in which human mobility explicitly depends on disease prevalence, governed by a parameter representing human awareness. Our analysis reveals that incorporating such prevalence-dependent mobility can generate complex dynamics, including oscillations and bistability, which are typically not observed under constant mobility. The resulting dynamics vary systematically with both transmission intensity, characterized by basic reproduction number ($\mathcal{R}_0$) and human awareness. At relatively low $\mathcal{R}_0(>1)$, increasing awareness drives transitions from a stable endemic equilibrium to bistability and eventually to stable endemic oscillations. For intermediate values of $\mathcal{R}_0$, awareness destabilizes the stable endemic equilibrium and leads to stable endemic oscillations. At moderately higher $\mathcal{R}_0$, the system undergoes two successive switches: first from stable endemic equilibrium to stable endemic oscillations and then back again to stable endemic equilibrium as awareness increase. When $\mathcal{R}_0$ is very high, awareness has little effect and the system remains in stable endemic equilibrium. Furthermore, we find that transmission heterogeneity between patches is required for oscillatory dynamics to emerge, and greater inter-patch connectivity suppresses such instabilities. Our findings identify awareness-driven mobility as a novel mechanism for generating complex epidemic dynamics.

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Deciphering Breast Cancer Organotropism using Complex Metabolic Network Dynamics

Garhima Arora[1], Samrat Chattterjee[1,*]
[1] *Translational Health Science and Technology Institute, India* - garhima@thsti.res.in

Abstract: Breast cancer organotropism represents a non-random, multiscale dynamical phenomenon in which metastatic dissemination follows preferential trajectories. To quantify the metabolic mechanisms shaping these trajectories, we integrated single-cell RNA-seq data from patient-derived xenografts with genome-scale metabolic models (GSMMs), generating 14 tissue-specific metabolic reconstructions corresponding to primary breast tumors and matched metastatic tumors in liver, bone, and brain using the mixed-integer linear programming–based tINIT method. Using constraint-based flux optimization to characterize steady-state flux distributions, we observed distinct metabolic adaptations across metastatic tissues, marked by coherent shifts in lipid metabolism, cofactor/vitamin processing, and amino acid biosynthetic fluxes. Applying the robust Metabolic Transformation Algorithm (rMTA) with linear and mixed-integer linear programming, we simulated gene overexpression and knockout perturbations to identify metabolic genes capable of driving transitions from non-metastatic to metastatic phenotypes during different breast organotropisms. We furthermore identified metabolites secreted by primary tumors with differential metastatic potentials, thereby delineating organ-specific metastatic axes. This mathematical systems-level framework characterizes distinct axes of breast cancer metastasis and identifies key perturbations capable of shifting the system dynamics of a primary tumor toward a metastatic state, offering potential metabolic targets for therapeutic intervention aimed at halting metastatic progression.

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Spectral and Network-Based Classification of Complex Financial Markets

Yuvraj Malik[1], and **Hirdesh K. Pharasi**[2,3]

[1] *Kahlert School of Computing, University of Utah, Salt Lake City, Utah, USA* - u1547055@utah.edu

[2] *School of Engineering and Technology, BML Munjal University, Gurugram, Haryana, India* - hirdesh.pharasi@bmu.edu.in

[3] *Center for Advanced Data and Computational Science, BML Munjal University, Gurugram, Haryana, India* - hirdesh.pharasi@bmu.edu.in

Abstract: Complex systems are often studied through their spectral [1, 2] and network properties [2, 3, 4] to understand structure and dynamics across physical, biological, social, and financial settings. In financial markets, complexity arises from interactions among individual stocks, which generate correlation patterns that shift sharply during major events. In this work, we study the S&P-500 from 2008–2024 (N = 427) using spectral measures [1, 2]–eigen-entropy and eigenvalue centrality – together with network measures [2, 3] such as average degree, computed from rolling correlation matrices with non-overlapping epochs of 20 days. These measures allow us to track the evolution of market states and identify shifts between ordered and disordered phases [1].

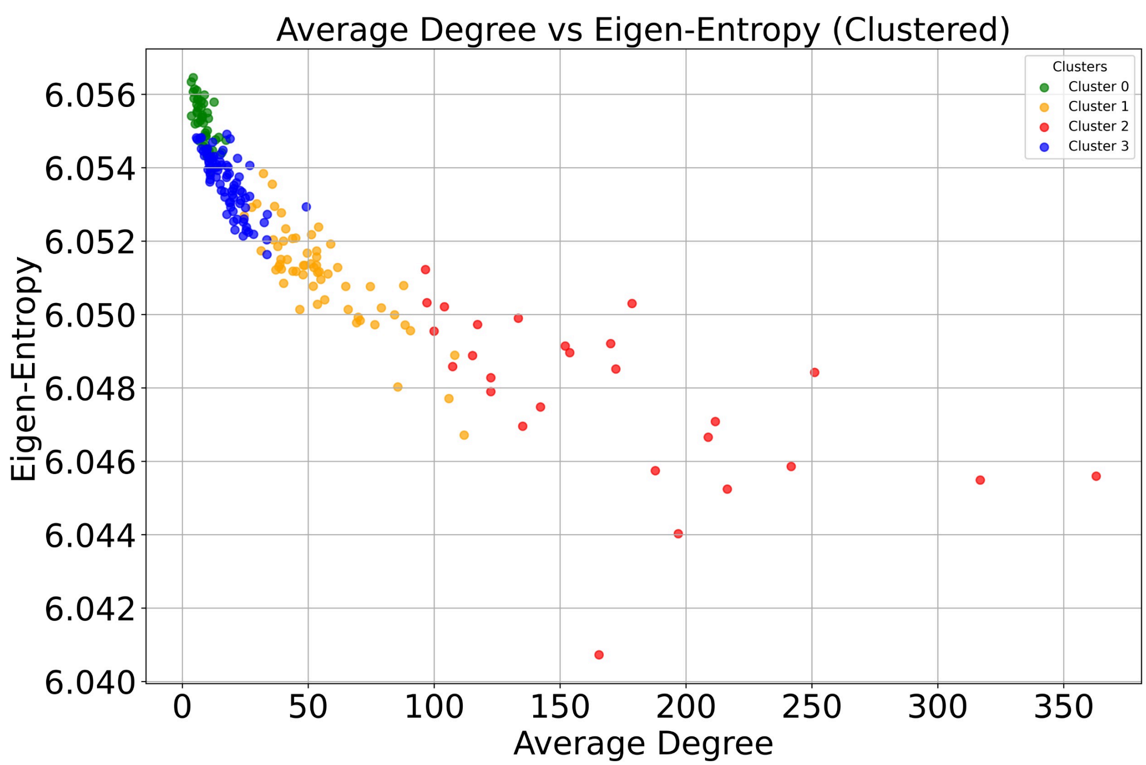

Figure 1: The scatter plot shows the phase separation of the S&P 500 market in four different phases based on the spectral and network analysis: Normal (Green), Bubble (Blue), Anomaly (Yellow), and Crash (Red). Different events are segregated into different parts of the scatter plot, based on eigenentropy and the average degree of the correlation networks.

Figure 1 shows that bubbles, crashes, and relatively calm periods occupy distinct regions in a phase space defined by these spectral and network features. The joint signature from eigen-entropy and network structure helps to detect and categorize critical events and the transitions from one state to the other. This provides a way to detect market changes and potential tipping points, which is useful for risk management and timely intervention during critical scenarios. The analysis also highlights the subtle distinctions among different categories of critical events, i.e., crashes. Although the study focuses on financial markets, the same framework can be applied to other complex systems where shifts in correlation patterns change the underlying dynamics.

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Collaboration-driven phase transitions in the Prisoner's Dilemma

Joy Das Bairagya[1], Jonathan Newton[2], Sagar Chakraborty[3]
[1]*IIT Kanpur, India* - joydas@iitk.ac.in
[2]*Kyoto University, Japan* - newton@kier.kyoto-u.ac.jp
[3]*IIT Kanpur, India* - sagarc@iitk.ac.in

Abstract:

Abstract

The evolution of cooperation has traditionally been explored through the Prisoner's Dilemma (PD) game, a framework illustrating how two von Neumann–Morgenstern rational agents [1] fail to achieve the mutually beneficial cooperative outcome [2, 3]. Yet, human societies exhibit cooperation at scales that the PD alone cannot explain. Classical mechanisms—kin selection, direct reciprocity, indirect reciprocity, network reciprocity, and group selection—provide important insights [4], but they overlook a uniquely human feature: *shared intentionality*, the capacity to collaborate toward a common goal such that all participants benefit [5, 6]. Recent studies indicate that such collaboration can fundamentally reshape strategic interactions, enabling cooperation even in PD-like settings [7].

In this work, we develop a theoretical framework to examine how simple microscopic rules of collaboration can drive a population from defection to cooperation. For analytical tractability, we consider a ring network in which individuals may form coalitions with their nearest neighbour. Using tools from non-equilibrium statistical physics and nonlinear dynamics, we show that the system exhibits three distinct phase transitions, with the average fraction of cooperators serving as the order parameter. The dynamics are governed by two key quantities: the benefit of cooperation b and the probability of collaboration p.

Our analysis reveals a non-equilibrium discontinuous phase transition from defection to cooperation at the critical point $b = \frac{2}{3}c$, where c denotes the cost of cooperation. Additionally, we identify two continuous phase transitions—from an active to an absorbing phase [8]—at $p = 0$ and $p = 1$, marking qualitative changes in collective behaviour.

Overall, this study highlights how minimal collaborative rules can fundamentally alter the strategic landscape, underscoring the relevance of non-equilibrium statistical mechanics and nonlinear dynamical methods for understanding collective phenomena in human societies.

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Nonequilibrium steady states in bead-spring models: Entropy production and probability distributions

Jetin E Thomas[1], Ramandeep S. Johal[1]
[1]*Indian Institute of Science Education and Research, Mohali, India -*
jetinthomas@iisermohali.ac.in

Abstract: We study non-equilibrium models comprising of beads connected by springs. The system is coupled to two thermal baths kept at different temperatures. We derive the steady state probability distributions of positions of the bead for the one-bead system in the underdamped case. We employ the recently proposed technique of an effective temperature, along with numerical simulations to solve the Langevin equations and obtain their corresponding probability distributions. It is observed that the marginal probability distributions in the position are independent of mass. We also obtain theoretically and numerically the rate of entropy production for the one-bead system. The probability distribution of the positions in the two-beads system are obtained theoretically and numerically, both in the underdamped and overdamped case. Lastly, we discuss the notion of ergodicity and have tested the convergence of the time-averaging and the ensemble-averaging protocols. [1].

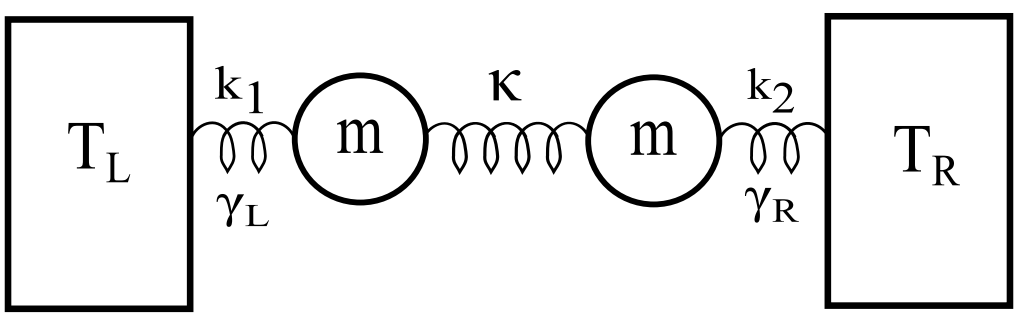

Figure 1: Two beads, each of mass m, simultaneously coupled to each other with a spring having spring constant κ as well as with a bath at temperature $T_L(T_R)$ with spring constant $k_1(k_2)$. The frictional drag coefficient is $\gamma_L(\gamma_R)$ for the left (right) particle.

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Dendritic Learning as a measure of intervention in Atrial Fibrillation

Jyoti Prasad Deka[1]
[1]*Department of Physics, Assam Engineering College, Guwahati-781013* jyotiprdeka@gmail.com

Abstract: In this work, we present our findings on how dendritic learning could be a way to design interventive measure in *Atrial Fibrillation* (AtFib). AtFib is one of the most common form of arrhythmias that arises in the heart's upper chambers known as the atria. Here, in this work, we investigated the implications of the dendritic Learning rule known as the *Input-Correlation* learning as a measure of intervention in this cardiac condition using the database of PhysioNet [1-2]. In our investigation, it could be seen that when the reference signal is Sinus Rhythm and the stimulus signal is of Atrial Fibrillation, the output is observed to be of intermittent spiking (Figure 1a). But when both signals are Sinus Rhythms, then no such spiking output is observed (Figure 1b). In the former case, spiking outout is observed when the reference and the stimulus perfectly coincide with each other and as such, the *Input-Correlation* learning rule could be seen as a coincidence detector from our analysis. The spiking output could be utilized in an *Implantable Cardioverter Defibrillator* to deliver electrical pulses to the cardiac muscles so that rhythmic heartbeats could be restored.

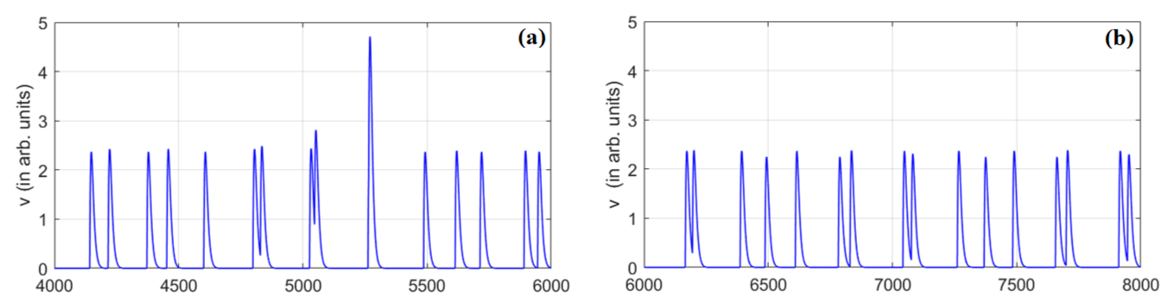

Figure 1: Output of the ICO learning rule for (a) Reference - Sinus and Stimulus - AtFib and (b) Reference and Stimulus - Sinus

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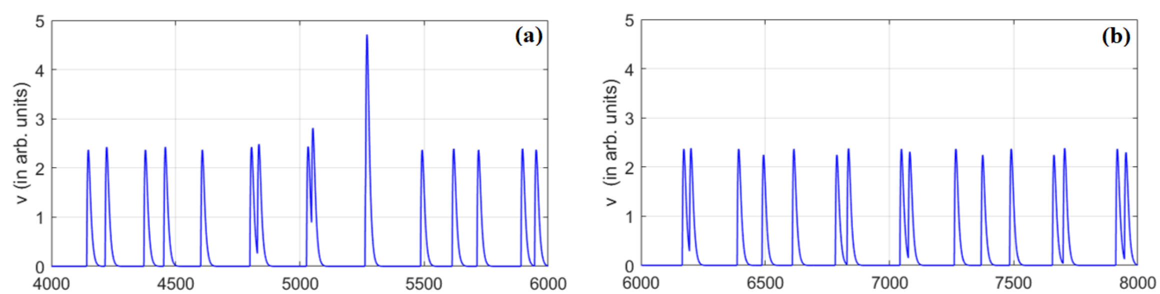
Dendritic Learning as a measure of intervention in Atrial Fibrillation

Jyoti Prasad Deka[1]
[1] *Department of Physics, Assam Engineering College, Guwahati-781013* jyotiprdeka@gmail.com

Abstract: In this work, we present our findings on how dendritic learning could be a way to design interventive measure in *Atrial Fibrillation* (AtFib). AtFib is one of the most common form of arrhythmias that arises in the heart's upper chambers known as the atria. Here, in this work, we investigated the implications of the dendritic Learning rule known as the *Input-Correlation* learning as a measure of intervention in this cardiac condition using the database of PhysioNet [1-2]. In our investigation, it could be seen that when the reference signal is Sinus Rhythm and the stimulus signal is of Atrial Fibrillation, the output is observed to be of intermittent spiking (Figure 1a). But when both signals are Sinus Rhythms, then no such spiking output is observed (Figure 1b). In the former case, spiking outout is observed when the reference and the stimulus perfectly coincide with each other and as such, the *Input-Correlation* learning rule could be seen as a coincidence detector from our analysis. The spiking output could be utilized in an *Implantable Cardioverter Defibrillator* to deliver electrical pulses to the cardiac muscles so that rhythmic heartbeats could be restored.



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Disorder–Order Transitions and Explosive Synchronization in Heterogeneous Ginzburg–Landau Oscillators on Directed Networks

Kumar Sourav[1], Naveen Kumar Mendola[2], Thounaojam Umeshkanta Singh[3]
[1] *Bennett University, India*- e23soep0039@bennett.edu.in
[2] *Bennett University, India* - e21soep0032@bennett.edu.in
[3] *Bennett University, India* - Thounaojam.Singh@bennett.edu.in

Abstract: Diffusively coupled heterogeneous oscillators in large networks undergo complex transitions between ordered and disordered states [1], [2], [3]. Understanding the mechanisms that govern the onset and loss of synchronization in such systems remains a central problem in nonlinear dynamics and statistical physics. Here, we investigate the collective dynamics of three distinct ensembles of Ginzburg–Landau-type oscillators—anti-rotating, counter-rotating, and uniformly rotating—coupled diffusively on a directed ring network [1]. As the coupling strength increases, the system first exhibits enhanced disorder before undergoing an abrupt transition to a frequency-locked ordered state, characterized by explosive synchronization and hysteresis. Large-scale numerical simulations quantify the dynamics via frequency and amplitude deviations, while ensemble-averaging theory provides analytical estimates of the ensemble-averaged frequency and amplitude, in strong agreement with simulation results. These findings offer new insights into the self-organization of heterogeneous, non-isochronous limit-cycle oscillators under diffusive unidirectional coupling [3].

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8th International Conference on Complex Dynamical Systems and Applications (CDSA)
23th - 26th Jan, 2026, Dhirubhai Ambani University, Gandhinagar, India

Universal Patterns in the Blockchain: Analysis of EOAs and Smart Contracts in ERC20 Token Networks

Kundan Mukhia[1], **Kundan Mukhia**[1], SR Luwang[1], Md. Nurujjaman[1‡], Tanujit Chakraborty[2,3], Suman Saha[4], Chittaranjan Hens[5]

[1] *Department of Physics, National Institute of Technology, Sikkim 737139, India*
[2] *SAFIR, Sorbonne University, Abu Dhabi, UAE*
[3] *Sorbonne Center for Artificial Intelligence, Sorbonne University, Paris, France*
[4] *School of Electronics Engineering, Vellore Institute of Technology, Chennai 600127, India*
[5] *Centre for Computational Natural Sciences and Bioinformatics, IIIT Hyderabad 500032, India*

Abstract: Blockchain technology enables decentralized transactions through distributed ledgers. In Ethereum, ERC20 tokens are managed by two types of accounts: Externally Owned Accounts (EOAs), which are controlled by human users through their private keys, and Smart Contracts (SCs), which are autonomous programs that execute predefined code on the blockchain. [1, 2]. This creates two distinct transactional modes—human-driven and algorithm-driven—within the ERC20 ecosystem.

Scaling laws provide a powerful lens for analyzing heterogeneous behaviors in decentralized systems. In this study, we examine more than 44 million ERC20 token transfers over a nine-month period. To investigate the stability of scaling behavior, we divide the dataset into three consecutive three-month windows and classify interactions into four categories: EOA–EOA, EOA–SC, SC–EOA, and SC–SC. We then apply two canonical scaling laws—power-law distributions and temporal Taylor's law—to assess whether universal patterns persist across periods.

Our results show that EOA-driven (human-driven) transactions exhibit highly consistent statistical regularities: a near-linear scaling between trade volume and unique counterparties, stable power-law exponents ($\gamma \approx 2.3$), and strong adherence to Taylor's law ($\beta \approx 2.3$). By contrast, automated code-driven interactions involving smart contracts—particularly SC–SC transactions—display sublinear scaling, unstable and heavier-tailed power-law exponents ($\gamma < 2$), and substantially fluctuating Taylor coefficients ($\Delta\beta = 0.51$). These patterns indicate bursty, algorithmic, and volatile transaction dynamics.

Overall, the results reveal clear statistical contrasts between human-controlled and automated behaviors on Ethereum. By integrating scaling-law analysis with blockchain transaction data, this study provides a principled framework for understanding ERC20 token dynamics in decentralized financial ecosystems.

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When Growth Meets Division: Conditions for Self-Reproduction in Growing-Dividing Autocatalytic Dynamical Systems

Parth Pratim Pandey[1,2], Sanjay Jain[3,4,5]

[1]*Department of Physics, School of Advanced Engineering, UPES, Dehradun 248 007, India*
[2]*Centre for Stochastic Modelling and Simulation, UPES, Dehradun 248 007, India*
[3]*Department of Physics and Astrophysics, University of Delhi, Delhi 110 007, India*
[4]*Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, USA*
[5]*Department of Physics, Ashoka University, Sonipat, Haryana 131 029, India*

parth.pratimji@gmail.com
jain@physics.du.ac.in

Abstract: Self-reproduction in living systems, such as bacteria, exemplifies remarkable regulation wherein thousands of intracellular chemical components synchronize their highly nonlinear and decentralized dynamics so that all double in unison. How such balanced growth emerged in primordial chemical systems and persists in modern cells remains unclear. While autocatalysis is known to drive growth, the role of the division mechanism in maintaining homeostasis has been overlooked. In the present work we construct a general class of dynamical systems that we call growth-division dynamics (GDD). While the growth part of cellular dynamics has many existing examples in the literature and also a formalization in terms of autocatalytic chemical reaction systems, the division part has few examples and no systematization. Building on our previous work [1], here we systematize the treatment of division in these models by explicitly distinguishing (a) *division control* from (b) the *birth of the daughter cell*, which are two distinct parts of the division process. We show that the models can be analyzed via geometric constructs in phase space which provide insight into the dynamics. In particular we show that cellular trajectories in an N dimensional phase space (where N is the number of chemicals) shuttle between two N-1 dimensional surfaces – a 'division surface' and a 'birth surface'. We find that the relationship between these surfaces and the growth trajectories determines something as fundamental as cellular homeostasis and self-reproduction. Visualizing bacterial growth and division geometrically reveals, for the first time, that the same autocatalytic chemical system can display a broad spectrum of steady-state behaviors, ranging from exponential balanced growth to non-exponential balanced growth to even system collapse (loss of homeostasis) - depending solely upon the choice of the division mechanism. We thus show that division mechanisms are active determinants of a system's long-term fate; the system's 'growth dynamics' and the 'division strategy' needs to be mutually compatible for self-reproduction to robustly emerge. Our framework opens new avenues for thinking about cells and the construction of synthetic cells.

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Agent-based Model of Walkers in a Lethal Landscape

Paramvir Kasana[1] Poulomi Sadhukhan[1]
[1] *Bennett University, India* - e23bspu0003@bennett.edu.in
[1] *Bennett University, India* - poulomi.sadhukhan@bennett.edu.in

Abstract: We present an agent-based model built in NetLogo in which walkers move through a landscape composed of light (safe) and dark (dangerous) regions while collecting food to sustain their energy. Time spent in darkness reduces an agent's energy, encouraging them to seek safety while periodically leaving safe areas to regain energy. This creates a trade-off between survival and exploration that shapes collective behavior. By varying the spatial arrangement of safe regions and the distribution of food, we observe distinct system-level outcomes, including stable survival, gradual population decline, sudden collapse and oscillatory behavior. Small changes in environmental structure can lead to large differences in long-term behavior. This work demonstrates how simple behavioral rules can generate complex, collective outcomes, and highlights the utility of ABMs for exploring ecological systems with state-dependent feedback. Analytical work in similar direction has been done for the survival probability of walkers in Ref. [1].

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Abstract

Migration from rural to urban areas is a complex phenomenon driven by multiple interacting factors, among which economic opportunities play a dominant role. It can cause issues such as stress on the environment, compromised sustainability, and other social challenges; therefore, it is important to study the factors on which migration depends.

In this work, we present an economic framework to understand urbanization dynamics using GDP per capita as a measure of regional economic attractiveness. A mathematical model is proposed to describe migration between rural and urban regions, where the migration rate depends on the difference in GDP per capita, indicating a tendency of people to move toward economically favorable regions. Through our model, we reproduce the urbanization trajectories of various countries. While the urbanization trajectories for different countries vary depending on their particular socio-economic landscape, the model provides an effective approach to capture large-scale migration and urbanization trends, offering insights into the development of sustainable urban growth policies.

Collective dynamics of Stuart Landau oscillators due to the competition between asymmetric and symmetric couplings

Naveen Mendola[1], Thounaojam Umeshkanta Singh[2]
[1] *Bennett University, India* - naveen.maindola95@gmail.com
[2] *Bennett University, India* - umeshkanta@gmail.com

Abstract: In this work, we studied a system of identical nonisochronous Stuart-Landau oscillators with both asymmetric and symmetric couplings. Earlier work in this area [1] reported that such a system does not support the trivial synchronized state, and that heterogeneity is necessary to maintain synchronization. Later, it was revealed [2] that synchronization is, in fact, a trivial solution for such systems. Intrigued by these conflicting reports, we thoroughly investigated the dynamics of these systems and found that they exhibit a rich variety of dynamical states, depending on the weights of the couplings, rather than just the trivial synchronized or desynchronized states. Due to the interplay between the two types of coupling, the oscillators can exhibit different modes of phase relationships, such as phase-locking and phase-drifting. Each of these modes contains distinct locked or drifting solutions (including the synchronized state), which were not previously discussed in earlier studies. We derive the common frequency and amplitude solutions for oscillators in phase-locking states. By defining an appropriate order parameter for the system, we construct a phase diagram and identify several distinct collective dynamical regimes: (i) complete phase-locking, resulting in full synchronization, (ii) phase-drifting, leading to quasiperiodic traveling waves, (iii) uniform phase distributions among oscillators, giving rise to various splay states, and (iv) oscillation death with different steady states. More importantly, we show that both continuous and discontinuous phase transitions occur across different collective dynamical regimes. The phase transition between complete synchronization and traveling wave states is continuous, while the phase transition between traveling wave and splay states is discontinuous and exhibits hysteresis.

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Positional Embeddedness and User Innovation in Online Innovation Networks

Monica Dhyani[1] (Presenter),Dr. Satyam Mukherjee[2],Dr. Samit Bhattacharyya[3]

[1]Shiv Nadar Institution of Eminence , *India*- satyam.mukherjee@snu.edu.in
[2]Shiv Nadar Institution of Eminence , *India*- md434@snu.edu.in
[3] Shiv Nadar Institution of Eminence , *India*- samit.b@snu.edu.in

Abstract: In the digital era, online innovation networks have become vital for large-scale, collaborative knowledge creation. Platforms like Stack Overflow connect users across geographies, enabling collective problem-solving and knowledge exchange.This talk explores how innovation emerges within such communities using a network science approach. We focus on two key aspects influencing users' innovation productivity: their structural position in the network and their behavioral engagement over time. Network metrics such as degree, local clustering coefficient, and k-core highlight how well-connected or influential a user is, while consistent activity reflects sustained participation and community engagement. Our analysis reveals that innovation arises not from isolated efforts but from the interaction between connectivity and consistent contribution, enhancing both the quality and impact of user output.

These insights deepen our understanding of knowledge production in Stack Overflow and can guide strategies to promote collaboration, retain active contributors, and sustain innovation in online knowledge networks.

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A Coarse-Grained Model for Unfolding-Driven Fibrin Mechanics

Vivek Sharma[1], **Poulomi Sadhukhan**[2]
[1] *Bennett University, India* - vvkgautam143@gmail.com
[2] *Bennett University, India* - poulomi.sadhukhan@bennett.edu.in

Abstract:

Fibrinogen, the precursor of fibrin and a key structural component of blood clots, exhibits a highly complex architecture that gives rise to remarkable mechanical behavior. Its assembly into fibrin fibers through half-staggered packing, knob-hole interactions, and αC-region crosslinking produces a material with exceptional extensibility and nonlinear stress-strain characteristics that remain only partially understood[1, 2]. To elucidate the molecular origins of this behavior, we develop an Unfolding-Incorporated Coarse-Grained Polymer model that explicitly captures domain unfolding within fibrinogen[3]. The model accurately reproduces stretching responses observed in experiments and all-atom simulations[4]. We extend this framework to fibrin fibers and networks, enabling systematic investigation of how molecular unfolding events propagate to mesoscopic and macroscopic mechanical properties. Our approach provides a predictive model for understanding the nonlinear elasticity of crosslinked fibrin gels and represents controlled, mechanistic descriptions of domain unfolding in crosslinked biopolymer networks. Beyond fibrin, the our model offers a versatile tool for studying biological and synthetic systems governed by sacrificial-bond mechanics[5].

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Analysis of spiral wave in a Hopfield neural network under electromagnetic induction and control with external magnetic induction

Sajal Debnath[1], **Santimoy Kundu**[1]
[1]*Indian Institute of Technology (Indian School of Mines), Dhanbad, India*
22dr0325@iitism.ac.in,santimoykundu@iitism.ac.in

Abstract: In Hopfield neural networks (HNNs), fluctuations in membrane potential drive coupled neurons to generate electromagnetic induction fluxes through their mutual interactions. The computational efficacy of such networks is critically dependent on the structural and dynamical properties of coupling between neuronal oscillators. In this study, we formulate an integrated memristive HNN model in which neuronal units are interconnected via nonlinear coupling mechanisms described by hyperbolic-type memristors, enabling a more precise representation of induction-mediated flux dynamics. Characterizing the emergent spatiotemporal neuronal patterns provides an essential framework for deciphering the system's intrinsic complexity. Within this modeling paradigm, we systematically investigate how variations in the amplitude and frequency of an external forcing modulate the genesis and evolution of spiral-wave dynamics across the network. The resulting wave-propagation behaviors facilitate the simulation of neuronal synchronization and pathological signal transmission at microscopic scales, thereby offering valuable insights into the mechanisms associated with neurological disorders.

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Spatio-temporal eco-evolutionary dynamics of prey-predator systems with defended and undefended prey

Sourav Roy[1], Helen M. Byrne[2], Jeet Banerjee[3], Sourav Kumar Sasmal[4], **Sagarika Dutta**[5] and Dibakar Ghosh[5]

1 Department of Mathematics, Jadavpur University, Kolkata, India
2 Wolfson Centre for Mathematical Biology, Mathematical Institute, University of Oxford, Oxford, United Kingdom
3 Capgemini Technology Services India Limited, No: 158-162P & 165-170P, EPIP Phase II, Whitefield, Bengaluru, India
4 Department of Applied Mathematics and Scientific Computing, IIT Roorkee, Roorkee, Uttarakhand, India
5 Physics and Applied Mathematics Unit, Indian Statistical Institute, Kolkata, India

The dynamic interplay between evolutionary adaptations and ecological processes has emerged as a key focus for understanding biodiversity and species interactions. In predator-prey dynamics, spatial heterogeneity and eco-evolutionary feedback regulate species co-existence, shaping population stability and persistence. This study emphasizes the importance of integrating ecological and evolutionary perspectives to understand biodiversity maintenance, predator-prey coexistence, and long-term stability of structured ecosystems. We propose a spatial eco-evolutionary mathematical model for the interactions between undefended prey, toxicity-induced aposematic prey, and predators to explore their collective impact on species persistence and spatial organization. In particular, we focus on the roles of free space and the toxicity of defended prey (foraging efficiency). Most previous work neglects these factors and the spatial structure of the interacting species. We begin by conducting a linear stability analysis of the diffusion-free model and then perform a Turing analysis to determine the conditions for diffusion-driven pattern formation. Numerical simulations reveal the emergence of a range of spatio-temporal patterns and demonstrate how these patterns change as ecological and evolutionary factors vary, while also confirming the stability conditions derived analytically. Through this work, we highlight the roles of ecological and evolutionary factors in understanding the spatio-temporal dynamics of eco-evolutionary processes.

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Adaptive ML Estimator for Transient Chaos and Predictability Horizons in Non-Stationary Time Series

S.V. Manivelan, I. Manimehan
[1] *Department of Physics, M. R. Government Arts College (Affiliated to Bharathidasan University, Tiruchirappalli), Mannargudi, 614 001, Tamilnadu, India.* - manivelan.saminathan@gmail.com

Abstract: We present a novel, adaptive machine learning framework for estimating the Largest Lyapunov Exponent (LLE) in non-stationary time series, addressing the limitations of traditional Finite-Time Lyapunov Exponent (FTLE) methods in analyzing transient dynamics. Our approach employs a sliding-window k-nearest neighbor (KNN) predictor to infer trajectory divergence directly from the exponential growth of forecast errors [1]. A key innovation is the implementation of a per-window auto-tuning mechanism that dynamically adjusts embedding dimensions and compresses the forecast horizon based on local signal self-similarity, robustly preventing false positives in stable regimes. Validated on complex transient chaos and intermittency datasets, this data-driven estimator not only matches the accuracy of phase-space FTLE methods but also yields a real-time predictability profile[2, 3].

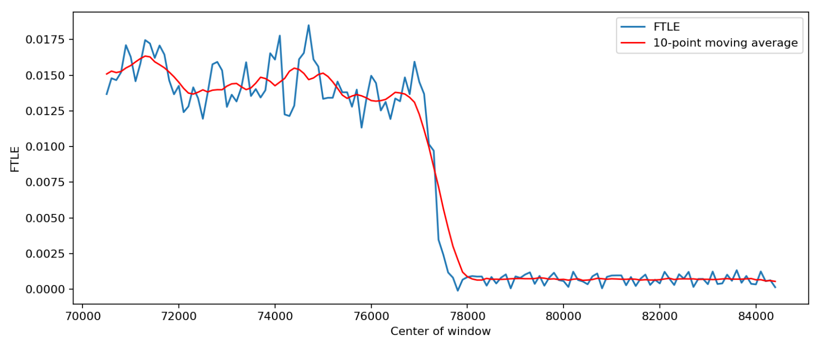

Figure 1: Finite-Time Lyapunov Exponent (FTLE) estimated via the traditional numerical method (blue) versus the proposed adaptive machine learning framework (red).

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A Comparative Analysis of Generalized and Multi-Order Fractional Frameworks for Modeling Dengue Transmission Dynamics: A Bayesian MCMC Approach

Ashwini Rai[1], Anindita Bhattacharyya[2]
[1] *Department of Mathematics, Amity University, Kolkata, India* - ashwini.rai52.ar@gmail.com
[2] *Department of Mathematics, Amity University, Kolkata, India* - aninmb@gmail.com

Abstract: Mathematical modeling is a critical tool for understanding the complex dynamics of dengue transmission. Conventional integer-order models, however, often fail to capture the memory effects and non-local behaviors inherent in biological systems. While fractional-order (FO) models provide a superior alternative, most existing applications assume a single, uniform fractional order for the entire system.

This study introduces and comparatively analyzes a hierarchy of three advanced fractional-order models [1] to explore the non-local dynamics of dengue. The investigation begins with a standard fractional-order (Caputo sense) dengue model as a baseline [2]. We then propose a generalized fractional model that incorporates operators on both the left and right-hand sides of the system, allowing for a more flexible representation of system memory.

The framework is then extended to our primary proposal: a multi-order, generalized fractional model. This novel, heterogeneous structure assigns distinct fractional orders to the human and mosquito sub-populations, designed to realistically capture the different time-scales and memory properties inherent to the human host versus the Aedes vector. The required theoretical work for these models, including the positivity, boundedness, and stability of equilibriums, has been established to ensure their epidemiological validity. Furthermore, a sensitivity analysis has been performed to identify the model parameters that are most influential on disease dynamics, which helps guide the subsequent estimation process.

A critical component of this research is moving beyond theoretical simulation to data-driven calibration. We will develop and implement a robust computational framework, utilizing the Adams-Bashforth-Moulton predictor-corrector method for the numerical solution of the fractional systems. This solver is integrated within a Markov Chain Monte Carlo (MCMC) algorithm to perform Bayesian inference. This methodology will be used to estimate key epidemiological parameters and, significantly, the values of the different fractional orders for all three models. This comparative approach aims to identify the optimal fractional framework for capturing dengue dynamics and improving public health forecasting.

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Brownian yet Non-Gaussian Heat Engine

I. Iyyappan[1], Jetin E. Thomas[2], and Sibasish Ghosh[3]
[1] *Krea University, India* - iyyap.si@gmail.com
[2] *Indian Institute of Science Education and Research Mohali, India* - jetinthomas@gmail.com
[3] *The Institute of Mathematical Sciences, India* - sibasish@imsc.res.in

Abstract: In this talk, I will discuss about the Brownian heat engine working in a heterogeneous thermal reservoir where the mobility becomes a fluctuating quantity [1]. We trap the Brownian particle by the time-dependent harmonic potential. By changing the stiffness coefficient value and the thermal reservoir temperature, we perform a Stirling heat cycle which consist of two isothermal and two isochoric processes. Using the framework of stochastic thermodynamics. We numerically calculate the average work, power and efficiency. We compare our results with the Brownian heat engine working in a homogeneous reservoir. Our results show that for the normal diffusive system i.e., the mean-squared displacement is directly proportional to time, the performance of a Brownian heat engine is bounded by the performance of Gaussian heat engine and hence the presence of non-Gaussianity decreases the stochastic heat engine performance. However, in the case of superdiffusive system, the non-Gaussian heat engine performs better than the Gaussian heat engine [2].

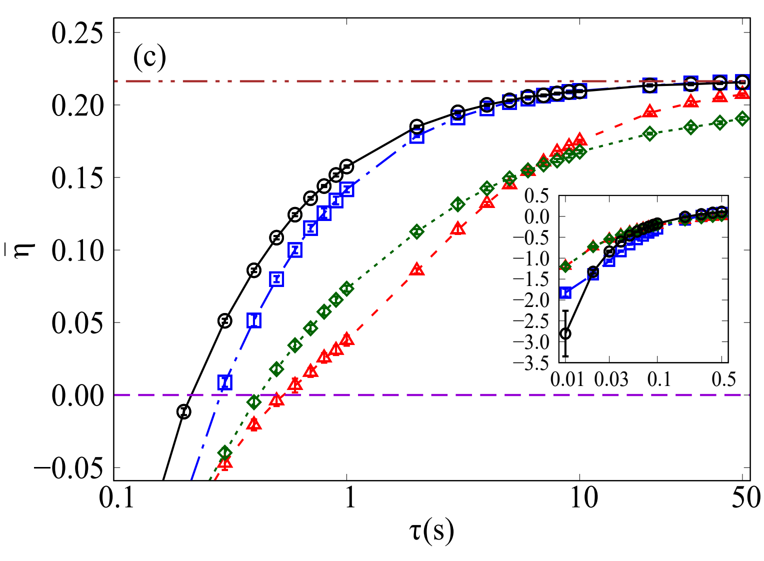

Figure 1: The average efficiency is plotted as a function of cycle time.

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Extreme value statistics of localised quantum states

Dharmesh Yadav, **J. Bharathi Kannan**, M.S Santhanam
Department of Physics, Indian Institute of Science Education and Research, Pune 411008, India

Abstract: Understanding the extremes in the behaviour of natural events is crucial for grasping the rare but significant variations that characterise complex physical systems. While extreme value techniques have been extensively studied in classical systems and random matrix situations, their application to quantum systems, particularly in the context of localisation, remains largely unexamined. In this study, we explore the extreme value statistics of quantum states displaying various types of localisation, ranging from strong exponential localisation to weak power-law localisation. We analyse three representative models: the quantum kicked rotor, which exhibits dynamical localisation; the one-dimensional Anderson model, known for disorder-induced exponential localisation; and a random matrix ensemble designed to demonstrate power-law-decaying eigenvector intensities. Our findings indicate that fluctuations in localisation lengths and the component intensities significantly affect the statistics of their maxima. In the case of the kicked rotor, the strong dynamical localisation results in considerable fluctuations in the eigenvector profiles, causing the maximum distribution to approach a universal generalised extreme value (GEV) form, often resembling the Gumbel class. In contrast, Anderson-localised states exhibit less stochastic behaviour, leading to maxima distributions that differ markedly from GEV behaviour. Furthermore, by modifying the synthetic eigenstates, we demonstrate that increased stochasticity is correlated with distributions of maxima that align more closely with the GEV class. Our results emphasise a notable statistical difference between various localisation mechanisms and suggest that extreme value statistics could serve as a sensitive diagnostic tool for quantum localisation. This can also be measured in experimental setups, such as optical lattices and cold atoms, where wavefunction intensities can be directly observed.

Effect of the Similarity Measure in Event Synchrony Based Multi-Scale Complex Network Analysis of Strong Rainfall

Guruprem Bishnoi[1,2], Reik V. Donner[1,2]
[1] *Magdeburg–Stendal University of Applied Sciences, Magdeburg, Germany -* guruprem.bishnoi@h2.de, reik.donner@h2.de
[2] *Potsdam Institute for Climate Impact Research (PIK) – Member of the Leibniz Association, Potsdam, Germany*

Abstract: Understanding the temporal organization and spatial coherence of strong rainfall episodes during the summer monsoon season is essential for improving climate risk assessment and predictive modeling across the Indian subcontinent. Building on complex network approaches to studying climate dynamics [1, 2] and recent advances in multi-scale analyses of rainfall [3], we introduce a wavelet-based multi-scale network analysis framework to examine the evolving structure of rainfall connectivity over India using daily IMD rainfall data (1990-2019). Specifically, we decompose rainfall time series into discrete temporal scales via the Discrete Wavelet Transform (DWT) and construct scale-specific network representations using two similarity measures based on Event Synchronization (ES) and Event Coincidence Analysis (ECA). Comparative analysis of network metrics such as degree, average link distance, and Jaccard similarity reveals a systematic, scale-dependent divergence between the networks based on the two measures. While ES captures transient, localized synchrony associated with short-lived rainfall events, ECA identifies spatially coherent and persistent long-range connections, particularly across the Western Ghats and central India. The results demonstrate that ECA maintains higher structural stability across temporal scales, with its pairwise similarity matrix $\mathbf{Q}$ showing higher information entropy than the ES-based $\mathbf{Q}$-matrix at every scale. By comparison, ES-based networks become progressively more fragmented at coarser time resolutions. These findings highlight the importance of multi-scale and method-aware functional network analyses for interpreting monsoon rainfall variability and outline a generalized approach for studying scale interactions and spatiotemporal connections in complex natural systems, extending beyond rainfall to other climate variables.

Keywords: Monsoon rainfall, wavelet transform, complex networks, event synchronization, event coincidence analysis, multi-scale variability

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Spatiotemporal Dynamics of Neuron-Astrocyte Interactions in Alzheimer's Disease: Insights from a Mathematical Model

Debasish Pradhan[1], Ranjit Kumar Upadhyay[1]
[1]*Department of Mathematics & Computing, Indian Institute of Technology (Indian School of Mines) Dhanbad- 826004, Jharkhand, India* - debasishp43@gmail.com,ranjit@iitism.ac.in

Abstract: Evidence suggests that neurons are excitable cells, while glial cells, particularly astrocytes, are non-excitable. Despite non-excitability, excessive amyloid-beta (Aβ) protein significantly impacts astrocytes, making them a key focus in Alzheimer's disease (AD) research. This study explores the interactions between neurons and astrocytes under AD conditions using a mathematical model incorporating bidirectional coupling within the tripartite synapse framework. We extend the model to a spatiotemporal setting in three distinct scenarios: (i) in the absence of diffusion, where bifurcation analysis reveals different temporal dynamics; (ii) with neuronal membrane voltage diffusion but without astrocytic diffusion, where complex Ginzburg–Landau equation (CGLE) analysis examines the stability of emergent spiral and antispiral patterns; and (iii) with both neuronal and astrocytic diffusion, where Turing pattern formation is analyzed via weakly nonlinear analysis. Further, we explore the model in a spatial network to investigate collective dynamics and synchronization behaviors, where stronger coupling leads to partially synchronized neuronal activity. Our findings suggest that bifurcation analysis provides insights into the underlying dynamical mechanisms of the system, while spatial patterns such as spirals and Turing structures reveal wave-like mechanisms in neural information processing. This work offers a crucial step toward understanding AD progression and its impact on brain network dynamics.

Coexistence of tonic spiking and bursting with Synchronization in Coupled Leech-heart inter neuron through Chemical and Electrical coupling

Debadri Bera[1], Ranjit Kumar Upadhyay[1],
[1] *Indian Institute of Technology (Indian School of Mines), Dhanbad, India-*
debadri.math@gmail.com, ranjit.chaos@gmail.com

Studying neuronal networks using biologically realistic neuron models is essential for gaining deeper insights into brain function and neurological disorders. In this work, we investigate the emergence of collective dynamical behaviors and response mechanisms in a coupled Leech heart inter neuron model incorporating both chemical and electrical synaptic interactions. First analyze the dynamics of the deterministic system and identify a rich repertoire of neuronal activities, including spiking, bursting, canard dynamics, and mixed-mode oscillations (MMOs). We then demonstrate the coexistence of distinct spiking states and explore the occurrence of Blue Sky Catastrophe phenomena through detailed bifurcation analysis by varying different control system parameters. Further, the long-term behavior of the coupled neurons is examined via synchronization analysis to characterize their collective dynamics. Finally, extensive numerical simulations are performed to validate the theoretical findings and to highlight the capability of the proposed model to capture biologically realistic neuronal phenomena.

Dynamics of Marangoni-Driven Elliptical Janus Particles

Ratan Sarka, **r**[1,a] , Pabitra Masanta[1,b], Raghunath Chelakkot[1,c], P. Parmananda[1,d]

[1] *Department of Physics, Indian Institute of Technology Bombay, Mumbai, Maharashtra 400 076, India.*

[a] *23d1060@iitb.ac.in*

[b] *pabitramasanta13@gmail.com*

[c] *raghu@phy.iitb.ac.in*

[d] *punit@uaem.mx*

Abstract: We investigate the spontaneous motion of an elliptical Janus particle, driven by Marangoni forces, on a water surface to understand how particle shape and size influence its dynamics. Janus Particle is a particle having two or more than two faces having different physical or chemical properties, this name is inspired from roman god Janus, who has two faces. The Janus particle is one-half infused with a substance such as camphor, which lowers the surface tension upon release onto the water surface. The resulting surface tension gradient generates Marangoni forces that propel the particle. For fully camphor-infused (non-Janus) particles, previous studies have shown that motion occurs along the short axis of the ellipse. However, for Janus particles, our experiments reveal a much richer steady-state dynamics, depending on both the particle's eccentricity and size. To understand these dynamics, we develop a numerical model that captures the connection between the spatio-temporal evolution of the camphor concentration field and the Marangoni force driving the particle. Using this model, we simulate the motion of particles with varying eccentricities— from nearly circular to highly elongated shapes. The simulations qualitatively reproduce all the trajectories observed in experiments and provide insights into how particle geometry influences the dynamics of chemically driven anisotropic particles.

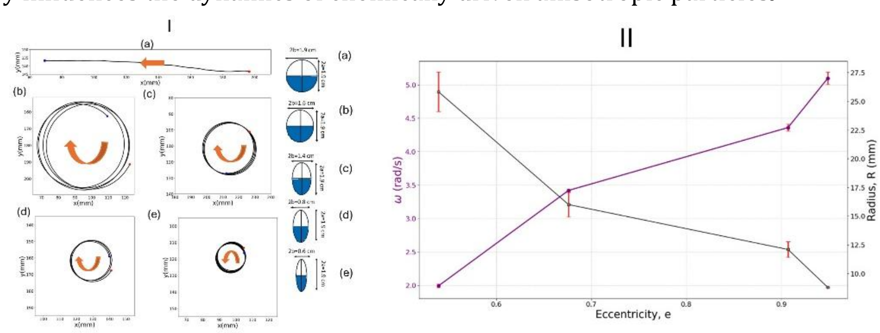

Figure 1: (I) Trajectory of centre of mass of Janus particle for different sizes. (a) shows straight path, while (b)–(e) show almost circular trajectories with radius R. (a) 2a = 2b = 1.9 cm; (b) 2a= 1.9 cm, 2b = 1.6 cm, R = (25±1.72) mm; (c) 2a = 1.9 cm, 2b = 1.4 cm, R = (16.00±1.06) mm; (d) 2a = 1.9 cm, 2b = 0.8 cm, R = (12.08 ± 0.67) mm; (e) 2a = 1.9 cm, 2b = 0.6 cm, R =(8.78± 0.03) mm. (II) shows the variation of angular speed ω and radius R with eccentricity e.

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Chaotic Dynamics and Bifurcation Analysis of the Hindmarsh–Rose Neuron Model with blue sky catastrophe Under Magnetic Field Influence

Ram Pravesh Yadav[1], Hirdesh K. Pharasi[2], R.K. Brojen Singh[1], and Anirban Chakraborti[1]

[1] *School of Computational and Integrative Sciences, Jawaharlal Nehru University, New Delhi, India*
Email-ram1008pravesh@gmail.com

[2] *School of Engineering and Technology, BML Munjal University, Gurugram, Haryana, India*

Abstract: This study examines the dynamics of the Hindmarsh–Rose single neuron model [1] with blue sky catastrophe [2] under the influence of an external magnetic field, revealing how electromagnetic perturbations reshape intrinsic neuronal behavior. The introduction of magnetic flux adds nonlinear effects that alter firing patterns and drive transitions between periodic, bursting, and chaotic regimes, as characterized through bifurcation analysis, phase-space trajectories, and permutation entropy. By analyzing how bifurcation structure and chaotic behavior evolve under magnetic influence Fig.1, the study uncovers mechanisms of neuronal modulation with potential implications for neuromorphic engineering, neural control strategies, and brain–machine interfaces. The study contributes to a deeper understanding of neuron–environment coupling and highlights the broader relevance of bioelectromagnetic interactions in shaping neural dynamics.

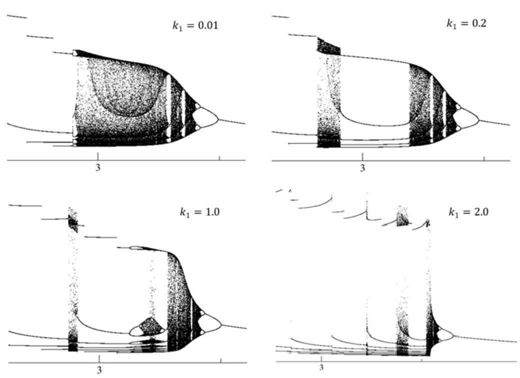

Figure 1: Bifurcation diagram: inter-spike interval vs. I_{ext}, for varying magnetic field.

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Co-mutation based genetic networks to infer temporal mutation dynamics in ancient human mitochondrial genomes

Rahul K Verma[1,2], Jesualdo A Fuentes-González[1],Jason Pienaar[1],Janna Fierst[1]
[1]*Department of Biological Sciences, Florida International University, USA*
[2]Amity University, India

Abstract: The evolutionary history of Homo sapiens is marked by complex interactions between environmental, cultural, and genetic factors. To investigate the molecular signatures of these processes, we analyzed ancient mitochondrial DNA (mtDNA) across temporal and geographic contexts using spatiotemporal co-mutation networks. Haplogroup-based assessments of variable sites revealed a major transition from foraging to agrarian lifestyles during the Copper–Bronze Age. Gene-level network analyses demonstrated that COX and CYB loci exhibited distinct temporal dynamics, with their interactions modulated by NADH dehydrogenase genes in a geological age-dependent manner. To complement the network approach, we constructed phylogeny-based gene interaction networks and assessed the polymorphism-to-divergence ratios of chimpanzees. tree-based networks showed topologies consistent with co-mutation analyses but showed reduced gene–gene connectivity. Polymorphism/divergence analysis further indicated that the CYB gene has undergone long-term purification selection, while the ATP6, COX and NADH dehydrogenase genes experienced episodic purification selection aligned with distinct historical phases. Collectively, our findings demonstrate that network-based analysis of ancient mtDNA provides information on early human lifestyle transitions and haplogroup diversification, contributing to the evolutionary foundations of modern human populations.

Controlling extreme events in excitable networks: A single driving signal approach

R Shashangan[1], S Sudharsan[2], Dibakar Ghosh[3] and M Senthilvelan[1]

[1]*Department of Nonlinear Dynamics, Bharathidasan University, Tiruchirappalli 620024, Tamil Nadu, India.*

[2]*Center for Nonlinear and Complex Networks, SRM TRP Engineering College, Tiruchirapalli 621105, Tamil Nadu, India.*

[3]*Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B. T. Road, Kolkata 700108, India.*

Abstract: Extreme events are serious threats to natural and human-engineered systems. It is inevitable to formulate strategies for devising the control tools to mitigate these events. In this talk, we discuss the use of a single driving signal to mitigate extreme events. The drive signal is a periodic signal which is the typical relaxation dynamics of the FitzHugh-Nagumo (FHN) neuron [1]. This method is demonstrated in three different FHN response networks: (i) a pair of coupled neurons, (ii) a monolayer network of N coupled neurons, and (iii) two-layer multiplex network [2]. In all three cases the response networks inherently exhibit extreme events. We show that extreme events in all three configurations can be controlled by applying the drive signal to just one neuron in the response network. In the two coupled case, the mitigation of extreme events occurs due to the breaking of phase-locking between the driving neuron and the targeted response neuron. In both the monolayer and multiplex networks, mitigation happens due to the disruption of protoevent frequency dynamics. Further, we observe that increasing the size of the target neurons in the monolayer and multilayer response networks, the onset of control occurs earlier in the response networks [3].

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Overcoming unfairness via repeated interactions: Evolutionary dynamics of mini-ultimatum game

Prosanta Mandal[1], Arunava Patra[2], Sagar Chakraborty[3]
[1]*Indian Institute of Technology Kanpur, India,* - prosantam21@iitk.ac.in
[2]*Indian Institute of Technology Kanpur, India,* - arunava20@iitk.ac.in
[3]*Indian Institute of Technology Kanpur, India,* - sagarc@iitk.ac.in

Abstract: While not predicted as an optimal equilibrium outcome for rational [1] players, fair play is witnessed in the Ultimatum Game(UG) [2], which has gathered limelight in the studies on the evolution of fairness as a social behaviour. The ultimatum game analyzes strategic decision-making in social interactions where individuals must agree on how to divide (more appropriately, offer and accept) a resource (often metaphorically referred to as a ”pie”). In the real world, interactions are often not one-off events. Instead, individuals often engage in repeated encounters before reaching a final agreement, making repeated game [3] models particularly suitable for capturing such dynamics. Our investigation focuses on finding the conditions under which fairness-enhancing strategies tend to dominate in micro- [4] and meso-evolutionary dynamics [5]. Specifically, using a simplified version of the ultimatum game, viz., mini-ultimatum game, we investigate how varying the probability of repeated interactions influences the evolution of fairness, especially when individuals employ reactive strategies—a class of strategies where decisions are based solely on the opponent's latest action [6]. This setup offers a simplified yet insightful lens into behavioural adaptation involving fairness under direct reciprocity.

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Dynamical Stability of Complex Systems using Gershgorin Disc Theorem

Yuvrajsingh Patil[1], Baruch Barzel[2], Chandrakala Meena[1]
[1] *Department of Physics, Indian Institute of Science Education and Research, Pune, India*
yuvrajsingh.patil@students.iiserpune.ac.in
[2] *Department of Mathematics, Bar-Ilan University, Ramat-Gan, Israel.*

Abstract: Prediction of the stability of large complex networks spanning ecological, biological, chemical, mechanical, electrical, and financial systems remains a major challenge. To address this, we develop a unified framework that integrates the Dynamical Jacobian Ensemble [1] with the Gershgorin Disc Theorem [2]. Using the Dynamical Jacobian Ensemble, we generate Jacobian matrices for complex networks and construct their corresponding Gershgorin discs. The Jacobian Ensemble fundamentally varies across networks, depending on the dynamical exponents η, μ, ν, and ρ, and on structural properties such as node degree and average nearest-neighbor degree. These dependencies appear in the diagonal and off-diagonal Jacobian entries, given by $J_{ii} = -C\, d_i^{\nu} d_{nn,i}^{\eta}$ and $J_{ij} = d_i^{\mu} A_{ij} G_{ij} d_j^{\rho}$, and these variations are reflected in the resulting Gershgorin discs (Fig. 1). Applying the Gershgorin Disc Theorem, we derive a stability criterion, S that classifies the system into three regimes: *stable*, *sensitively stable*, and *unstable*. Overall, combining the Dynamical Jacobian Ensemble with the Gershgorin Disc Theorem provides an effective theoretical approach for predicting the stability of complex dynamical systems, with potential applications across diverse scientific and engineering domains.

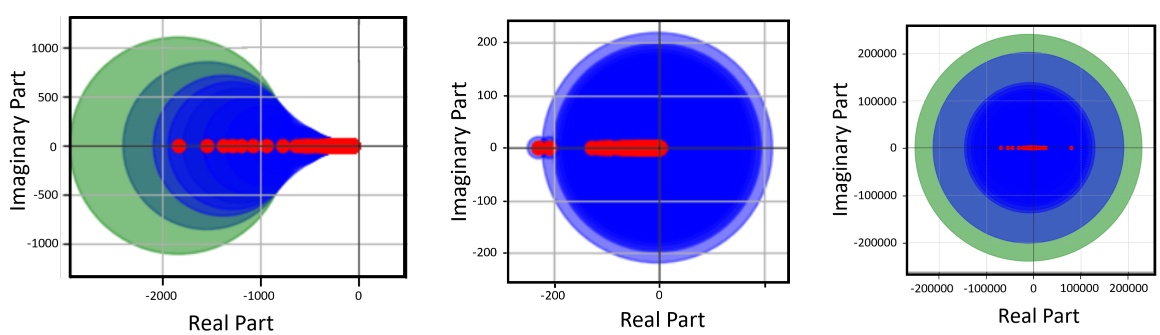

Figure 1: Three regimes of dynamical stability based on the stability classifier S

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Designing logic gate using active particles

In recent years, unconventional computing architectures that transcend traditional semiconductor - based systems have witnessed far - ranging research interest. Here we propose a new approach to the construction of logic gates, using active particles, specifically 1-pentanol-infused discs, exploiting the principle of Marangoni effect. In our experimental set-up, we design a channel with arms designated for inputs and an arm to observe the output. The inputs are provided by discs, where active discs infused with pentanol are considered to have a truth value of 1, while passive discs are considered to have a truth value of 0. The movement of a controller disc placed in a decision-making region, determines the output. We demonstrate that the complex interplay of surface tension, drag, repulsive and attractive forces, yields the fundamental AND and OR logic responses. Interestingly, the logic function can be switched by solely changing the activity of the controller by decreasing the pentanol concentration, thus giving the same channels the capacity to morph the logic functionality. Additionally, the complementary NAND and NOR logic can be obtained with a simple change in the output encoding. Such active matter-based logic gates have the potential to perform in fluid conditions, making them ideal for biomedical applications, bio sensing, molecular computing, and targeted drug delivery by responding to biological signals without external power sources.

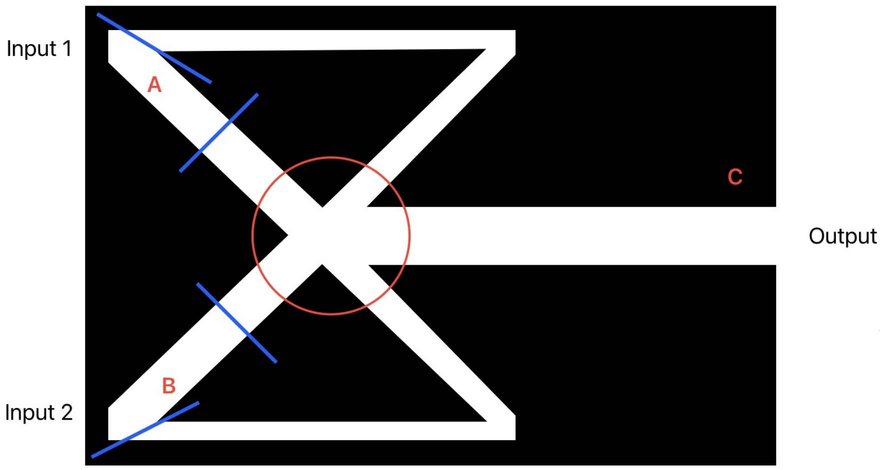

Figure I: Channel used for logic gate

HOPF BIFURCATION IN DELAY INDUCED ALZHEIMER'S DISEASE MODEL

Sevak Ram Sahu[1], Parimita Roy[2], Ranjit Kumar Upadhyay[3]

[1,3] Indian Institute of Technology Dhanbad, Jharkhand, India
[2] Thapar Institute of Engineering and Technology, Patiala, Punjab, India

*Corresponding Author: Sevak Ram Sahu (srsahu.maths@gmail.com)

Abstract:

Alzheimer's disease (AD) is characterized by the progressive aggregation of β-amyloid (Aβ) plaques in the brain, where Aβ oligomers are considered toxic and contribute to disease progression. In this study, we propose a mathematical model to describe the cytotoxic effects of Aβ oligomers. The model describes a feedback loop between Aβ and Ca^{2+}. We analyze the existence and stability of different equilibria and examine saddle-node and backward bifurcations. We compute the reproduction number R_0 to characterize AD progression. Additionally, we introduce a time delay in the accumulation of Aβ oligomers and observe a Hopf bifurcation concerning the delay parameter. These results may provide valuable insights for studying AD-related medical strategies.

Keywords: Bistable dynamics; Saddle-node; Time delay; Hopf bifurcation; Alzheimer's disease.

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Impact of noise on the dynamics of surface acoustic wave delay line feedback oscillator

Shashank Shekhar Jha[1], Pratibha Yadav[1]
[1] *Department of Physics, Nalanda College, Biharsharif, Nalanda-803101, Bihar, India -* ssank.5bhu@gmail.com

Abstract: In this study, we investigate the influence of additive white noise on a surface acoustic wave (SAW) delayed-feedback oscillator system [1]. In the absence of noise, the oscillator stabilizes at well-defined frequencies located near the intrinsic central frequency of the SAW delay line. However, when additive white noise is introduced, the system exhibits noise-induced transitions among these coexisting oscillatory states. We analyse the resulting frequency distribution and evaluate how the average residence time scales with parameters such as the delay duration, coupling strength of the SAW delay line, and the orbit frequency [2]. The findings demonstrate that oscillatory orbits closer to the central frequency possess significantly longer residence times, indicating enhanced robustness against noise-driven perturbations. These results provide deeper insight into noise-mediated multistability in delayed-feedback oscillators and may contribute to the design of SAW-based systems with improved stability under stochastic conditions.

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Parameter-Driven Species Preference and Stability Transitions in a Hierarchical Multi-Species May–Leonard Model

Shraosi Dawn[1] , Sirshendu Bhattacharyya[3], Rakesh Samanta[3], Sayantan Nag Chowdhury[2], Sk Jahiruddin[4], Chittaranjan Hens[1]

[1] *Center for Computational Natural Science and Bioinformatics, International Institute of Informational Technology, Gachibowli, Hyderabad 500032, India*

[2] *School of Science, Constructor University, P.O. Box 750561, 28725 Bremen, Germany*

[3] *Department of Physics, R.R.R Mahavidyalaya, Radhanagar, Hooghly 712406, India*

[2] Department of Physics, Sister Nibedita Government General Degree College for Girls, Hastings House, Alipore, Kolkata 700027, India

Abstract: Gaining insight into the role each species plays in maintaining ecosystem stability is essential for sustaining biodiversity in nature. Natural birth and death rates[1], system size [2] along with prey–predator interactions, play a vital role in maintaining this balance. We extend previous work by introducing hierarchical organization into an ecological model. In this study, we develop a generalized N-species hierarchical ecosystem model describing interacting populations. Each species occupies a distinct trophic level and preys upon the species immediately below it. Analytical expressions for equilibrium points corresponding to extinction, single-species survival, and multi-species coexistence states are derived. Using Jacobian-based linear stability analysis, we determine the conditions under which these equilibria remain stable or undergo transitions.

A detailed investigation of the five-species case reveals that the interior (full coexistence) equilibrium is inherently unstable for any positive parameter set, while extinction is globally stable when the intrinsic growth rates are lower than the death rates. Single-species equilibria arise when a species' per-capita growth rate surpasses its mortality rate, while for the remaining $(N-1)$ species, the mortality rate must exceed the growth rate. Feasible coexistence states occur only for particular two- or three-species combinations that satisfy hierarchical balance conditions. Eigenvalue spectra highlight neutral directions along coexistence manifolds and damped modes associated with invasion dynamics.

This hierarchical formulation provides a scalable mathematical framework to analyze complex interspecies dependencies and stability in ecological systems. It also lays the groundwork for data-driven modeling and simulation of multi-level biological or artificial ecosystems, contributing to broader applications in computational ecology and networked dynamical systems.

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8th International Conference on Complex Dynamical Systems and Applications (CDSA)
23th - 26th Jan, 2026, Dhirubhai Ambani University, Gandhinagar, India

Vaccination dilemmas in mitigating monkeypox outbreaks: An imitation dynamics game model approach

Susanta Kumar Das[1], Adrita Ghosh[1], Parthasakha Das[2], K.M. Ariful Kabir[3], Pritha Das[1], Dibakar Ghosh[4]

[1] *Indian Institute of Engineering science and Technology, Shibpur, Howrah 711103, India* - susantadas.maths@gmail.com,adyghosh5@gmail.com,prithadas01@yahoo.com

[2] *Rajiv Gandhi National Institute of Youth Development, Sriperumbudur, Tamil Nadu-602105, India* - parthasakha87das@gmail.com

[3] *Bangladesh University of Engineering and Technology, Dhaka, 1000, Bangladesh* - e-mail

[4] *Indian Statistical Institute, 203 B. T. Road, Kolkata 700108, India* - diba.ghosh@gmail.com

Abstract: The monkeypox epidemic poses a serious global health threat, making effective control strategies essential. Using a mechanistic SEIR (Susceptible-Exposed-Infectious-Recovered) model, this study incorporates both pro- and anti-vaccination attitudes among susceptibles to examine their impact on transmission. Sensitivity analysis via partial rank correlation coefficients (PRCC) identifies key parameters affecting the basic reproduction number (R_0). The model reveals both forward and backward bifurcations, indicating potential for stable infection states and persistent epidemics. To address vaccination behavior, a coupled vaccination game based on imitation dynamics is introduced. Results show that higher imitation rates increase pro-vaccine adoption and reduce infections. The study highlights the role of social dilemmas, where low pro-vaccine uptake and frequent strategy switching worsen outbreaks. High vaccination costs further reduce social payoff, but strong social learning still promotes uptake, even with low susceptibility or high costs. Overall, social learning strategies can enhance vaccination rates and curb monkeypox spread.

Tuning Competitive First-Passage Outcomes in Anomalous Diffusion via Resetting

Suvam Pal[1], Rahul Das[2], Arnab Pal[3]

[1] *Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road Kolkata, India* - suvamjoy256@gmail.com

[2] *The Institute of Mathematical Sciences, CIT Campus, Taramani, Chennai 600113, India & Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094, India* - rahuldas@imsc.res.in

[3] *The Institute of Mathematical Sciences, CIT Campus, Taramani, Chennai 600113, India & Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400094, India* - arnabpal@imsc.res.in

Abstract: Reaction and transport processes in complex environments are often governed by stochastic dynamics whose temporal evolution departs from the classical Debye relaxation. In such systems, broadly distributed waiting times generate memory and intermittency, leading to non-Markovian or anomalous transport. These long trapping epochs naturally give rise to extreme events, where the overall completion statistics are dominated by rare but significant pauses—a phenomenon encapsulated by the big-jump principle. Controlling these extreme fluctuations is thus crucial for optimizing first-passage kinetics in disordered or heterogeneous media. In this work, we develop a theoretical framework to study stochastic resetting in continuous-time random walks (CTRWs) confined between two absorbing boundaries. By intermittently restarting the dynamics, stochastic resetting [1] acts as an external control mechanism that truncates heavy-tailed waiting times, thereby suppressing large deviations and enhancing the efficiency of first-passage processes. We derive exact expressions for the conditional and mean first-passage times [2, 3] (FPTs) under general waiting-time statistics and demonstrate the emergence of a universal optimal resetting rate that minimizes the mean completion time. Interestingly, the universality condition known for Markovian systems is shown to persist even in the non-Debye regime, where memory plays a dominant role. Our findings establish resetting as a robust mechanism for regulating fluctuations and optimizing transport in non-Markovian stochastic systems.

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Exploring the Impact of Parameter Mismatch on Dynamics in Coupled Lorenz Oscillators

Swaati Saandhya[1]

[1]Department of Physics, Patliputra University, Patna

Email: [1]swatipu410@gmail.com

This study investigates the effects of parameter mismatch on the synchronization dynamics of coupled Lorenz oscillators. The Lorenz oscillator is a nonlinear system that exhibits chaotic behavior, making it an ideal model for studying complex systems. When two Lorenz oscillators are coupled, parameter mismatch can significantly impact the synchronization dynamics, leading to complex behavior, including phase slips, amplitude death, and chaos. This research examines how variations in oscillator parameters influence the stability and robustness of synchronized states, revealing complex patterns and bifurcations. Our findings provide insights into the intricate relationships between oscillator heterogeneity and collective behavior, with implications for understanding and controlling nonlinear systems. The results show that even small parameter mismatches can lead to significant changes in the collective behavior of the coupled system. The coupling strength and network topology play a crucial role in mitigating the effects of parameter mismatch. This research has potential applications in various fields, including secure communication systems, power grid synchronization, and biological systems, such as neural networks and circadian rhythms.

Keywords: Coupled Oscillators, Lorenz Oscillator, Parameter Mismatch, Synchronization Dynamics, Nonlinear Systems, Chaos Theory, Bifurcation, Phase Slips, Amplitude Death, Complex System.

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Enhanced Multifunctionality in Reservoir Computing

Swarnendu Mandal[1,a], Kazuyuki Aihara[1]
[1] *International Research Centerfor Neurointelligence (WPI-IRCN), The University of Tokyo, Japan*
[a] swarnendu@g.ecc.u-tokyo.ac.jp

Abstract: Multifunctionality is a well-observed phenomenon in neuroscience since the 1980s. It refers to the ability of a neural circuit to switch between different dynamical behaviors or tasks without altering its synaptic properties. The behavior of multifunctionality facilitates resource optimization in biological neural networks (BNNs). However, this concept is not limited to biological systems only. Multiple studies proved its implications in artificial neural networks as well. In this study, we discuss the multifunctionality in reservoir computing (RC), a recurrent neural network-based deep learning framework. The first proposed architecture of Multifunctional reservoir computing exploited a multistable dynamics of the hidden layer, making it capable of learning multiple attractors [1]. However, the application was significantly limited due to its 'seeing double' problem in learning attractors with a shared phase space region. Subsequent works devised different schemes to overcome that problem. In this study, we propose a bio-inspired architecture for reservoir computing that showcases enhanced performance beyond earlier limitations. Not only can it reconstruct multiple attractors on a single training, but it is also capable of learning parameter-dependent global dynamics of multiple systems. Moreover, our scheme can simultaneously learn to perform two different kinds of tasks, making it truly multifunctional.

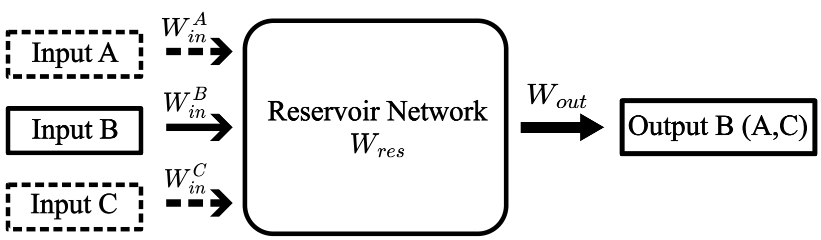

Figure 1: The proposed bio-inspired multifunctional RC architecture [2].

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Inferring network Dynamics using parallel reservoir computing

Swati Chauhan[1], Manish Dev Shrimali[1]
[1] *Central University of Rajasthan, India* - 2020phdph013@curaj.ac.in

Abstract: Inferring the collective dynamics of complex networks from limited data is a central challenge in nonlinear science, particularly when the governing equations are unknown. In this work, we present a unified, data-driven framework to infer and predict the emergent dynamics of complex networks using *parallel parameter-aware reservoir computing*.

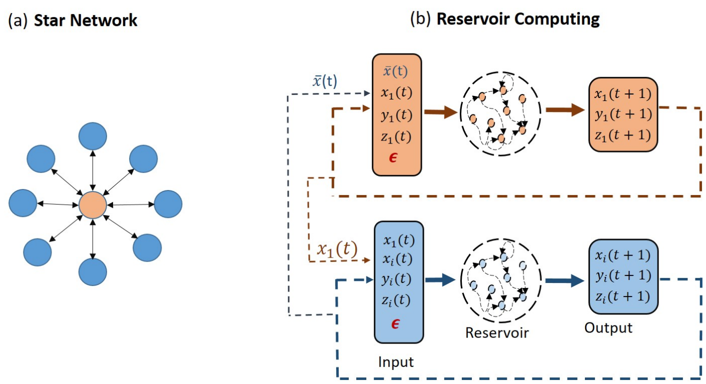

Figure 1: The schematic represents the (a) star network and (b) the proposed 'parameter-aware' reservoir computing scheme.

We demonstrate the framework on two representative classes of networks. First, we consider a star network of coupled nonlinear oscillators, where a central hub interacts bidirectionally with a large number of identical peripheral nodes. Using only two echo-state network (ESN)(see fig. 1) units—one trained on the central node and one on a single peripheral node. Despite being trained on limited data, the model accurately predicts multiple emergent collective states, including coherent, incoherent, chimera, and cluster synchronization regimes [1].

Second, we extend the approach to a two-layer multiplex network with distinct intralayer coupling mechanisms. By employing parallel reservoir units assigned to each layer and incorporating interlayer coupling as a control parameter, the framework reliably captures the transfer of collective phenomena between layers [2]. Crucially, it predicts critical transitions such as synchronization switching and the onset of oscillation death without prior exposure to these states during training.

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Structural sensitivity of a tri-trophic food chain model in a parameter plane

Ruma Kumbhakar[1], Saheb Pal[2], Nikhil Pal[3]
[1] *Visva-Bharati, Santiniketan-731235, India* - kumbhakarruma@gmail.com
[2] *SRM Institute of Science and Technology, Kattankulathur, Chengalpattu-603203, Tamil Nadu, India* - sahebp@srmist.edu.in
[3] *Visva-Bharati, Santiniketan-731235, India* - nikhil.pal@visva-bharati.ac.in

Abstract: Biological models are important in describing species interaction, disease spread, and environmental processes. One key aspect in improving the predictive capability of these models is deciding which parametrization is used to formulate the mathematical model. Considering two distinct functions with similar shapes and the same qualitative properties in a model can lead to markedly different model predictions. Such a phenomenon is recognized as the structural sensitivity of models. In this article, we investigate the structural sensitivity of a tri-trophic food chain model in a parameter plane by considering three nearly indistinguishable forms of the trophic function, namely, Holling type-II, Ivlev, and trigonometric. We use various tools, including bifurcation diagrams, isospike diagrams, and Lyapunov exponent diagrams, to explore the structural sensitivity of the model. The findings show that the functional form has a significant impact on the organization of periodic structures in the parameter plane. The emergence of the bistability phenomenon, as well as the mean population density of the species, also depends sensitively on the specific form of the response function. Another interesting observation of the present study is the changes in the nature of basin boundaries (fractal or smooth) of the coexisting attractors depending on the specific forms of the functional responses. Overall, the findings demonstrate that even subtle differences in the mathematical formulation of similar functional responses can lead to notable qualitative and quantitative changes in the system's behavior within the parameter plane.

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State-dependence in diffusion-controlled transport and stochastic resonance

Samudro Ghosh[1] and Moupriya Das*

d22065@students.iitmandi.ac.in

School of Chemical Sciences -scsoffice@iitmandi.ac.in

Indian Institute of Technology Mandi, Kamand, Himachal Pradesh 175075, India

Abstract: Most natural phenomena evolve through non-equilibrium pathways following non-linear dynamics involving the crossing of a potential energy barrier. During these processes, the systems transit from one state to another. We intend to understand in detail the significance of these states, their positions, and associated intrinsic fluctuations. As these systems are inevitably subjected to environmental noise, there appears to be complexity in studying their behaviour. We focus on analyzing the rate of diffusion-controlled transport in these complex systems under pertinent conditions. We implemented distinctions in the characteristics of the concerned states by altering their positions and the level of noise or diffusion coefficients linked to them. It has been observed that the variation of the reference point position and the diffusion coefficients has a significant impact on the rate. Our investigations unveil very important and critical aspects of the characteristic roles of the initial and final states in diffusion-controlled kinetics. We continued to develop an understanding of these fundamental transport phenomena where a periodic force is involved. This is a particular scenario where the constructive interplay of noise and the non-linearity of the system comes into effect in the presence of appropriate conditions. The phenomenon is termed stochastic resonance. We explored the significance of the state dependence in stochastic resonance, which manifests in many natural and designed processes, starting from climate systems to chemical reactions1-3. We developed a completely analytical theory in the adiabatic limit and a semi-analytical approach for the general case of stochastic resonance, considering state-dependent diffusion. The theoretical findings are substantiated with numerical simulation results. The results of our studies not only enrich the fundamental understanding of diffusion-controlled kinetics but also indicate the paths to developing advantageous technologies based on optimizing the conditions of transport.

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Mitigating polarisation and consensus in opinions through diversity

Sidharth Pradhan[1], **Sangeeta Rani Ujjwal**[2]
[1] *Department of Physics, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India* - siddhu0353@gmail.com
[2] *Department of Physics, Institute of Science, Banaras Hindu University, Varanasi, Uttar Pradesh 221005, India* - sangeeta.ujjwal@gmail.com

Abstract: We study opinion dynamics in a population using a variant of the Kuramoto model that incorporates ideas of Social Judgement Theory (SJT). In the model, the phase represents the opinion of individuals and the interactions between different individuals can be attractive, repulsive or neutral based on the differences between their opinions. We observe that such a system undergoes transition from scattered to clustered state and then an explosive transition to a consensus. The system exhibits hysteresis and multistability between different states. We study the effects of diversity among individuals of the population on the collective dynamics and nature of transitions and note that a more diverse population has less tendency to get polarised and form strong consensus. The neutral individuals that do not interact or change their opinions can make the transition irreversible and hence affect the nature of multistability. Ott-Antonsen analysis is employed to analyse the long term macroscopic behaviour of the system and verify the numerical results. Furthermore, the model is applied to language data to understand the assimilation of diverse languages in India and compare the results with those obtained from model equations.

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Dynamics of pulsating swarmalators on a ring

Samali Ghosh[1], Kevin O'Keeffe[2], Gourab Kumar Sar[3], Dibakar Ghosh[4]
[1] *Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata, India* - samalighosh816@gmail.com
[2] *Starling Research Institute, Seattle, Washington, USA* - kevin.p.okeeffe@gmail.com
[3] *University of Calgary, Canada* - mr.gksar@gmail.com
[4] *Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata, India* - diba.ghosh@gmail.com

Abstract: The physics of complex systems aims to understand how collective, self-organizing behaviours arise from interactions in numerous individual components. Within this broad landscape, Swarmalators constitute a distinct class of systems that couple spatial dynamics with internal rhythmic behaviour. O'Keeffe et al. first introduced a minimal swarmalator model that unifies the self-organization between the agents' spatial as well as the internal dynamics. To date, the Kuramoto model remains the predominant framework for describing each oscillator's intrinsic phase dynamics, but there are several well-studied biological phenomena, such as flashing fireflies, neuronal spike trains, rhythmic clapping in crowds, and technical systems like communications in wireless sensor networks or drone swarms, that involve pulsatile rather than continuous interactions. In this work, we develop a new class of 1D swarmalator systems in which the agents move along the ring and interact through both long- and short-range pulse-like signals governed by Winfree-type phase coupling. Our analysis reveals diverse collective behaviours: Several collective states that are already known from Kuramoto-type coupling, such as the static π, phase wave, and static async states, are present, and it also gives rise to three previously unreported collective behaviours: x (antiphase) sync, θ (antiphase) sync, and an intermediate mixed state that emerges during the transition from disordered (static async) to ordered (θ(antiphase) sync) state transition. We predict that this mixed state can be a special form of the active async state presented in the Kuramoto coupling, as we witness a similar kind of freezing behaviour and very low correlation between the spatial dynamics and internal behaviour as well. And we have calculated the stability threshold for the states as well. Overall, this work extends swarmalator dynamics into a new pulsatile-interaction regime and opens avenues for future theoretical and applied studies.

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Dynamics of pulsating swarmalators on a ring

Samali Ghosh[1], Kevin O'Keeffe[2], Gourab Kumar Sar[3], Dibakar Ghosh[4]
[1]*Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata, India* - samalighosh816@gmail.com
[2]*Starling Research Institute, Seattle, Washington, USA* - kevin.p.okeeffe@gmail.com
[3]*University of Calgary, Canada* - mr.gksar@gmail.com
[4]*Physics and Applied Mathematics Unit, Indian Statistical Institute, 203 B.T. Road, Kolkata, India* - diba.ghosh@gmail.com

Abstract: The physics of complex systems aims to understand how collective, self-organizing behaviours arise from interactions in numerous individual components. Within this broad landscape, Swarmalators constitute a distinct class of systems that couple spatial dynamics with internal rhythmic behaviour. O'Keeffe et al. first introduced a minimal swarmalator model that unifies the self-organization between the agents' spatial as well as the internal dynamics. To date, the Kuramoto model remains the predominant framework for describing each oscillator's intrinsic phase dynamics, but there are several well-studied biological phenomena, such as flashing fireflies, neuronal spike trains, rhythmic clapping in crowds, and technical systems like communications in wireless sensor networks or drone swarms, that involve pulsatile rather than continuous interactions. In this work, we develop a new class of 1D swarmalator systems in which the agents move along the ring and interact through both long- and short-range pulse-like signals governed by Winfree-type phase coupling. Our analysis reveals diverse collective behaviours: Several collective states that are already known from Kuramoto-type coupling, such as the static π, phase wave, and static async states, are present, and it also gives rise to three previously unreported collective behaviours: x (antiphase) sync, θ (antiphase) sync, and an intermediate mixed state that emerges during the transition from disordered (static async) to ordered (θ(antiphase) sync) state transition. We predict that this mixed state can be a special form of the active async state presented in the Kuramoto coupling, as we witness a similar kind of freezing behaviour and very low correlation between the spatial dynamics and internal behaviour as well. And we have calculated the stability threshold for the states as well. Overall, this work extends swarmalator dynamics into a new pulsatile-interaction regime and opens avenues for future theoretical and applied studies.

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Analysis and Control of Rumor Spread Model with Strategic Behavioral Dynamics

Arijit Malakar[1], **Susanta Kumar Das**[2], **Moumita Ghosh**[3], **Arvind Kumar Misra**[4], **Pritha Das**[5]

[1] *Indian Institute of Engineering Science and Technology, Shibpur, India* - malakararijit3@gmail.com
[2] *Indian Institute of Engineering Science and Technology, Shibpur, India* - susantadas.maths@gmail.com
[3] *SR University, India* - ghosh.moumita1993@gmail.com
[4] *Banaras Hindu University, India* - akmisra_knp@yahoo.com
[5] *Indian Institute of Engineering Science and Technology, Shibpur, India* - prithadas01@yahoo.com

Abstract: Nowadays, the spread of rumors significantly affects people's everyday lives. With the rise of various social media platforms and advancements in the internet, social networking sites have become hotspots for the dissemination of rumors. Studies show that rumors targeting social or financial anxieties tend to spread more rapidly. Considering the similarities of rumor propagation with the disease spread dynamics, in 1964, the first rumor spread model was proposed by Daley and Kendall [1]. To date, numerous research articles have been published on the analysis and control of rumor-spread dynamics [2]. In this paper, we propose a three-compartment rumor-spread model consisting of the following categories: i) Ignorant population, ii) Spreader population, and iii) Aware population using delayed differential equations. In this article, we consider two types of rumor transmission rates, taking into account the influence of highly impactful spreaders, such as public figures and various webpages with vested interests and passive spreaders who spread rumor out of panic or out of peer-influence. Here we have considered delay in the transmission process of rumor by passive spreader as they have minimal influence on others. Additionally, we derive a parametric expression for the threshold value of the influence of rumor spread. Subsequently, we analyze the qualitative dynamics of the system, which includes the conditions under which a rumor can prevail and the criteria for local and global stability of this prevailing state. Significant numerical simulations are presented to compare the effects of transmission rates by influential spreaders with those of passive or normal spreaders. Furthermore, we conduct a normalized forward sensitivity analysis to identify key parameters that can help reduce the negative consequences of rumors. Finally, we validate our analytical results by illustrating some important numerical simulations.

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Posters

Dynamics of spiral waves with variation of gel concentration in a chemical reaction-diffusion system

Komal[1], Tejaswini Kalita[2], Sumana Dutta[3]

[1]*IIT Guwahati, Assam, India-komal2037@gmail.com*
[2]*Maniklal Borkakoty path, Jorhat, Assam, India-tejaswinikalita@gmail.com*
[3]*IIT Guwahati, Assam, India-sumana@iitg.ac.in*

Abstract:
Spirals find their presence in various biological systems such as in cardiac tissue, neural tissues, in a growing colony of slime mould etc. In cardiac system, a normal electrical impulse might break due to the presence of some obstacle giving rise to spirals. These spiral causes irregular heart rhythm or arrhythmia. If this persists there is a potential of forming multiple spirals out of the existing ones, resulting in a total chaos which might be fatal. Thus it is necessary to study the dynamics of spiral waves. One of the best laboratory model for this is Belousov-Zhabotinsky (BZ) reaction-diffusion system. Researchers are trying to control the dynamics of spirals from last three decades in context of the cardiac wave dynamics. In this work we varied gel concentration to study its effect on the spiral rotation and we found gel concentration plays a role in governing wave properties of the spirals.

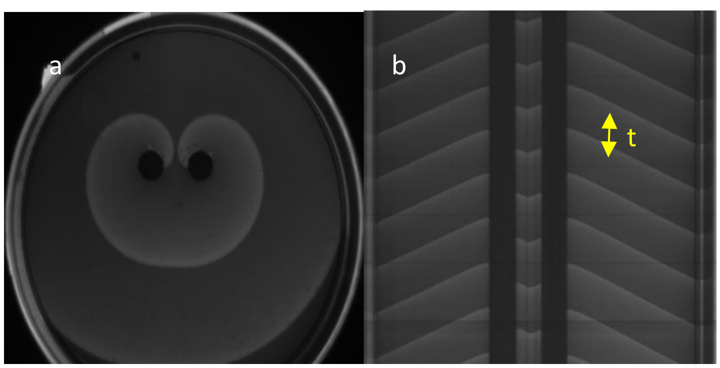

Figure 1: (a)snapshot of the experiment during the BZ reaction where the spiral wave is anchored to the circular heterogeneity(b)time space plot of the experiment showing the time period.

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Detecting Early Warning Signals for State Transitions in Nonlinear Dynamical Systems

Dr. Chandrakala Meena[1], **Adithya A.**[2]
[1] *Indian Institute of Science Education and Research Pune, India* - chandrakala@iiserpune.ac.in
[2] *Indian Institute of Science Education and Research Thiruvananthapuram, India* - adithyaajith21@iisertvm.ac.in

Abstract: Critical transitions in nonlinear systems, sudden cardiac arrhythmias or gradual forest-to-grassland shifts, occur with little warning in measured quantities, making them difficult to predict. This work will investigate whether early warning signals can be diagnosed before such critical transitions. Bifurcation analysis and Lyapunov exponent computation are done to determine the precise locations of parameters where such critical transitions occur[2]. Further, several quantitative early warning indicators are applied in order to detect signals preceding such transitions: variance, lag-1 autocorrelation, and Hurst exponent computed via detrended fluctuation analysis[3]. Additionally, recurrence quantification analysis will extract transition-sensitive measures– determinism, laminarity, and entropy from recurrence plots, allowing for early warning detection even on small datasets[2]. To validate these approaches, stochastic nonlinear systems such as Van der Pol-Duffing Oscillator and Lorenz-type models are numerically integrated across parameter sweeps with systematic noise injection[1]. This allows for a direct comparison of how early warning signals evolve relative to the bifurcation points identified in the first phase, as illustrated in Fig. 1. By analyzing how the above-defined statistical measures vary before transitions, we are able to show that several indicators produce characteristic changes, such as increased autocorrelation, elevated variance, and enhanced recurrence determinism, that serve as reliable precursors.

Keywords: bifurcations, critical transitions, Lyapunov exponents, recurrence plots, early warning signals

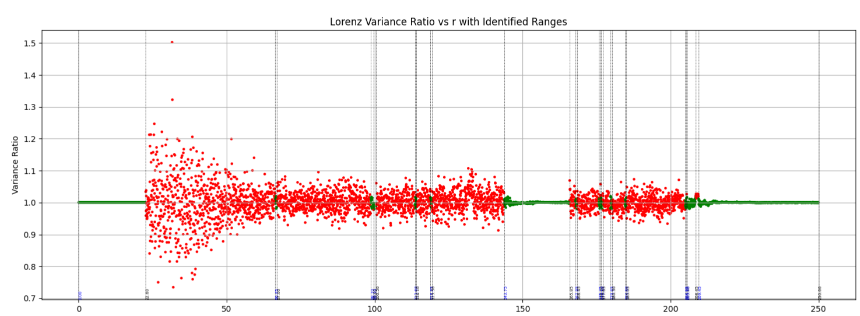

Figure 1: Identification of periodic windows in the Lorenz system using variance-based early warning analysis. The variance ratio metric (noisy-to-clean) reveals clear transitions between chaotic and periodic regions as the bifurcation parameter r varies, demonstrating the sensitivity of variance as an indicator of system state transitions.

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Transitions to oscillation death in coupled oscillators with competing higher-order interactions

Pratibha Verma[1]

[1] *Department of Physics, Central University of Rajasthan, Ajmer, India.*

Abstract: Complex networks have been a popular tool for modeling interacting systems. Dynamical processes on complex networks often display emergent phenomena, e.g., synchronization, oscillation-quenching, or chimera states. Oscillation death, in particular, stands out as an important phenomenon that has important implications in neuroscience, lasers, and climate networks [1]. The studies of such emergent phenomena on complex networks mostly take pairwise or dyadic links into account. But, the dyadic representation of systems does not present an accurate picture when dealing with specific systems, such as ecosystems with multiple species interacting [2], the human brain network [3], or rumors [4] spreading across societies. Thus, to represent such interactions, the mathematical framework of higher-order interactions or non-pairwise interactions is required. Recently, a plethora of studies have explored systems with higher-order interactions and uncovered rich dynamics such as explosive transitions to synchronization [5], oscillation death [6], chimera states [7], and others.

In this work, we explored the dynamics of globally coupled Stuart-Landau oscillators with competing higher-order interactions. We show that with such group interactions, the system undergoes a sharp transition to oscillation death at a critical value of the competing parameter. Our results will have significant implications in the study of dynamical systems such as ecological and chemical systems with competing interactions.

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Low-dimensional Watanabe–Strogatz approach for Kuramoto oscillators with higher-order interactions

Jayesh C. Jain[1], Sarika Jalan[2]
[1] *Complex Systems Lab, Indian Institute of Technology, Indore, India* - phd2301151010@iiti.ac.in
[2] *Complex Systems Lab, Indian Institute of Technology, Indore, India* - sarika@iiti.ac.in

Abstract:

Watanabe-Strogatz (WS) theory is a low-dimensional framework to describe the dynamics of a finite number of identical Kuramoto oscillators through the Möbius transformation. Using this approach, we present a unified description for a broad class of identical Kuramoto oscillator models with pairwise and higher-order interactions, as well as their corresponding higher harmonics [1]. We show that the dynamics of the WS parameters are the same as those of the mean-field parameters. In contrast to the Ott-Antonsen (OA) ansatz, the WS approach remains exact for a finite population, making it a more robust framework. Furthermore, the poles of the Möbius transformation serve as basin boundaries for global and cluster synchronization. Numerical simulations illustrate the evolution of basin boundaries for these models, providing a deeper understanding of their collective behavior.

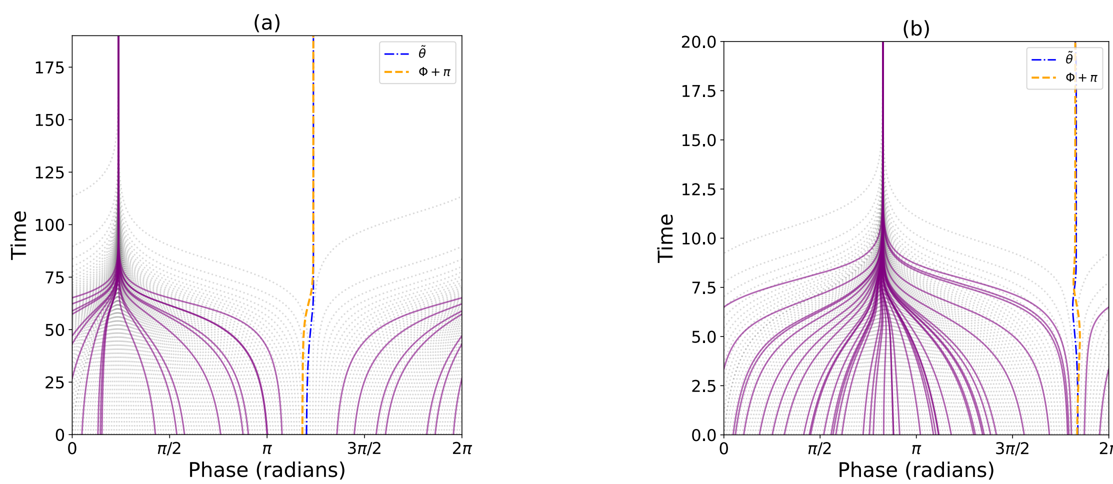

Figure 1: Evolution of basin boundaries for specific values of parameter for a given Kuramoto Model.

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Interplay of Direct and Indirect Modes of Spreading on the Persistence of Infection

Sudeshna Sinha[1], **Shivam Kumar**[2], Rajeev Kapri[3]
[1,2,3] *Indian Institute of Science Education and Research Mohali, India*
Email of presenter: ph24017@iisermohali.ac.in

Abstract: Mean-field epidemic models, such as the SIR and SIRS models, are based on the assumption of uniform mixing of susceptible and infected individuals. These models use deterministic ODEs, which include constant rates of infection (β) and recovery (γ), to describe disease dynamics [1]. However, the trends observed during the COVID-19 pandemic deviated significantly from the assumed homogeneity, indicating a substantial contribution of heterogeneity, such as "over-dispersion" and "superspreading" of the virus, within the population [2]. A modified SIRS model is proposed to investigate the spreading dynamics of an infectious disease, such as COVID-19. Our model incorporates dynamic, stage-dependent infection rates and multiple transmission modes, including both direct and indirect pathways, across different neighborhoods (Moore and Von Neumann). Local interactions at the individual level are modeled by a Cellular automaton to represent the population-level dynamics. For small reinfection rates within the system, we find a fluctuating endemic state. However, beyond a finite threshold, the system transitions to self-sustained oscillations, resulting in a persistent infection.

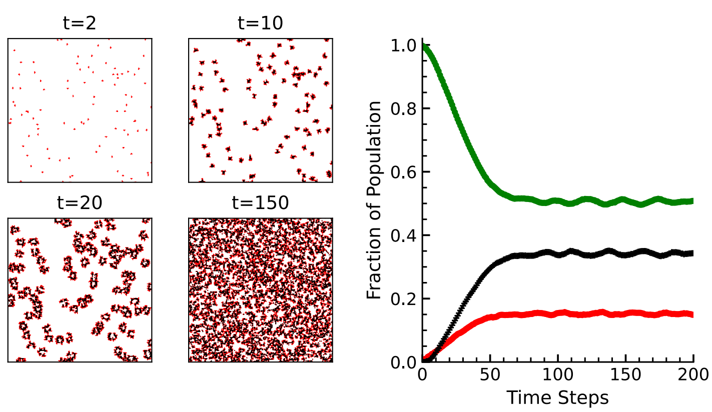

Figure 1: Snapshots and dynamics of the lattice SIR model with a Von Neumann neighbourhood. Left: spatial states at $t = 2, 10, 20, 45$; Right: temporal evolution of S/N, I/N, and R/N.

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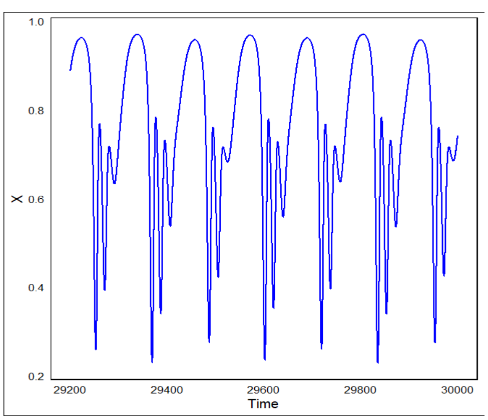
Evolutionary Dynamics of Basal Prey Shape Stability in Multi-Species Food Chains

Richik Bandyopadhyay[1], Joydev Chattopadhyay[1]
[1] *Indian Statistical Institute, Country -India, email-*bandopadhyayrichik@gmail.com
, joydev@isical.ac.in

Abstract: This study develops an analytical framework for a general n-species trophic model that integrates eco-evolutionary dynamics under arbitrary mutation rates of an evolving species. While previous work has mainly addressed two-species systems [1] or relied on numerical simulations, we provide analytical results that reveal how evolution shapes ecosystem stability across both slow and fast evolutionary timescales. Using Gaussian elimination, we quantify eco-evolutionary feedback in stability transitions and derive the n-dimensional Hopf bifurcation curve to assess how prey mutation rate influences dynamics. Through geometric singular perturbation analysis, we identify conditions for eco-evolutionary cycles and for the condition where evolution ends in extreme timescale limits. Applying the framework to the classical three-species food chain model of Hastings and Powell (1991), we show that prey mutation rate critically governs transitions between steady, cyclic, and chaotic states. Overall, our results establish mutation rate as a key factor in chaos control and ecosystem stability.



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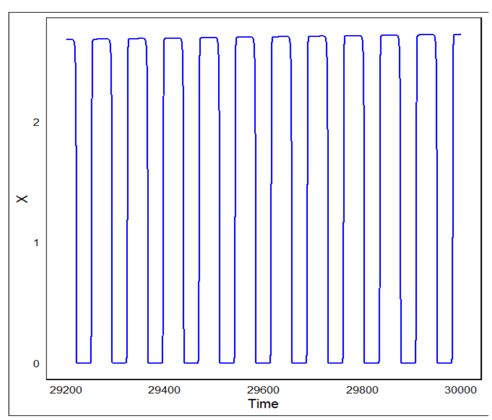

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Figure 1: Time series diagram for prey size x with prey mutation rate V as a parameter. Value of the parameter in figure 1a) $V = 0$, in figure 1b) $V = 0.001$.

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From Order to Chimeras: Unraveling Dynamic Patterns in Active Fluids with Nonlinear Growth

Joydeep Das[1], Abhishek Chaudhuri[2], Sudeshna Sinha[3]
[1]*IISER MOHALI, Country - INDIA* mp21022@iisermohali.ac.in
[2]*IISER MOHALI, Country - INDIA* abhishek@iisermohali.ac.in
[3]*IISER MOHALI, Country - INDIA*sudeshna@iisermohali.ac.in

Abstract: Pattern formation is ubiquitous in nature. It is available everywhere from ripples of sands, hydrodynamical systems, chemical systems, biological systems, combustion theory and even in the structure of galaxies. We explore pattern formation in an active fluid system involving two chemical species that regulate active stress: a fast-diffusing species (A) and a slow-diffusing species (I). The growth of species A is modelled using a nonlinear logistic term. Through linear stability analysis, we derive phase diagrams illustrating the various dynamical regimes in parameter space. Our findings indicate that an increase in the Péclet number results in the destabilisation of the uniform steady state. In contrast, counter-intuitively, an increase in the nonlinear growth parameter of A actually stabilises the homogeneous steady-state regime. Additionally, we observe that greater asymmetry between the species leads to three distinct dynamical phases, while low asymmetry fails to produce oscillatory instability. Numerical simulations conducted in instability regimes show patterns that range from irregular, arrhythmic configurations at high Péclet numbers to both transient and robust symmetry-breaking chimera states. Notably, these chimera patterns are more prevalent in the oscillatory instability regime, and our stability analysis indicates that this regime is the most extensive for high nonlinear growth parameters and moderately high Péclet numbers. Further, we also find soliton-like structures where aggregations of species A merge, and new aggregations spontaneously emerge, and these patterns are prevalent in the phase of stationary instability. Overall, our study illustrates that a diverse array of patterns can emerge in active matter influenced by nonlinear growth in a chemical species, with chimeras being particularly dominant when the nonlinear growth parameter is elevated.

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Intraday Order-Type and Price-Change Transitions across Market Capitalizations through Markov Analysis

Salam Rabindrajit Luwang[1], Anish Rai[2], Md. Nurujjaman[1], Filippo Petroni[3]
[1] *Dept. of Physics, National Institute of Technology Sikkim, India* - salamrabindrajit@gmail.com
[2] *Chennai Mathematical Institute, India* - anishrai412@gmail.com
[3] *Dept. of Economics, University G. d'Annunzio of Chieti-Pescara, Italy* - fpetroni@luiss.it

Abstract: A quantitative understanding of the stochastic dynamics of order submissions and their price implications is fundamental to advancing market microstructure research and designing robust, effective algorithmic trading strategies. This paper synthesizes findings from a comprehensive, two-part empirical analysis of high-frequency tick data from NASDAQ100 stocks, employing a Markov chain framework to decode intraday trading behaviors across High (HMC), Medium (MMC), and Low (LMC) market capitalization tiers.

The first part investigates the temporal dynamics of order-type transitions (market orders, limit orders, and cancellations). We identify three universal intraday phases—Opening, Midday, and Closing—characterized by distinct patterns: a peak in limit order inertia at the open, a shift to aggressive executions in the subsequent hour, midday stability, and a dominance of aggressive executions at the close. A clear capitalization effect emerges, with HMC stocks exhibiting stronger order inertia and buying dominance, while LMC stocks show higher cancellation and modification activity.

The second part extends this analysis by delving into the stochastic dynamics of limit order price changes, treating ask and bid orders separately. We categorize price adjustments into distinct states and uncover systematic intraday patterns, including peaks in price inertia during critical market hours. Quantified via spectral gap, entropy rate, and mean recurrence times, these dynamics reveal a pronounced capitalization gradient, with HMC stocks displaying the highest price stability and LMC stocks exhibiting lower stability and significant bid-ask asymmetry. Clustering of transition matrices identifies an earlier initiation of closing strategies on the ask side, suggesting sellers position themselves ahead of buyers. Stationary distributions are predominantly characterized by neutral and mild price changes, with Jensen-Shannon divergence confirming the closing hour as the most distinct phase.

Collectively, this research contributes a unified, data-driven framework integrating Markov chains, dimensionality-reduced clustering, and stationary analysis. It provides actionable insights into the multi-layered dynamics of order submissions and price formation, offering a solid foundation for developing trading strategies that are robust to intraday risks and nuanced cross-capitalization behaviors.

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Studying B cell receptor signalling mediated calcium dynamics through minimal mathematical model

Poulomi Chatterjee[1], Garhima Arora[1, #], Jayendrajyoti Kundu[1, #], Suvankar Halder[1], Samrat Chatterjee[1, *]

[1]Complex Analysis Group, Translational Health Science and Technology Institute, NCR Biotech Science Cluster, Faridabad-Gurgaon Expressway, Faridabad-121001, India

p.chatterjee@thsti.res.in, garhima@thsti.res.in, jayendrajyoti@thsti.res.in, suvankarhalderxii@gmail.com, samrat.chatterjee@thsti.res.in

Abstract: B cell receptor (BCR) signalling is one of the key regulators of cytosolic calcium (Ca^{2+}) in B cells, which governs different cell fates, including survival and apoptosis. Therefore, dysregulation of BCR signalling and Ca^{2+} homeostasis is an important factor for the pathogenesis of several B cell malignancies. However, the mechanistic link between BCR signalling mediated Ca^{2+} dynamics and cell fate regulation in B cell lymphoma remains poorly understood. In this study, we developed a mathematical model to investigate the role of BCR signalling in inducing pro- and anti-apoptotic Ca^{2+} dynamics in B cell lymphoma. The model captured the existence of Ca^{2+} oscillations in B cells and the effect of different model parameters on Ca^{2+} dynamics was explored. Restoration strategies were proposed to induce cellular apoptosis through sustained high Ca^{2+} level in B cell lymphoma. Thus, decoding the mechanism of BCR signalling pathway through a mathematical model helps in guiding the development of potential therapeutic strategies for B cell lymphoma.

[#] Equal contribution, * Corresponding author

Perfect synchronization in Sakaguchi–Kuramoto model on directed complex networks

Anath Bandhu Das[1,*], Prosenjit Kundu[2], Pinaki Pal[1]
[1] *Department of Mathematics, National Institute of Technology, Durgapur 713209, India*
[2] *Complex Systems Group, Dhirubhai Ambani Institute of Information and Communication Technology, Gandhinagar, 382007, India*
[*] **Electronic mail:** anathbandhu0498@gmail.com

Abstract: In this study, we analytically derive optimal frequency sets for achieving perfect synchronization at a targeted coupling strength in directed networks of phase-frustrated oscillators. With that aim, we construct a synchrony alignment function (SAF) that helps optimize the synchronization properties of that network and acts as a quantitative indicator of the network's synchronization level. We conduct extensive numerical simulations of the Sakaguchi-Kuramoto (SK) model on both directed scale-free and directed Erdős-Rényi networks to validate the suggested optimal frequency configuration. Numerical simulations demonstrate that the analytically determined frequency set ensures not only stable, perfect synchronization at the desired point in the network but also outperforms other frequency set options in achieving a high degree of synchronization in its vicinity. However, we observe that the synchronization level decreases after reaching perfect synchronization at the targeted point with our derived frequency set. In order to resist this synchronization loss, we give a network reconstruction approach without changing the number of edges in the network. Following the approach, significant improvement in the level of synchronization is achieved. The stability of the system's perfect synchronization state is assessed through a low-dimensional model of the network, while its robustness is evaluated by adding Gaussian noise to the derived frequency set.

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Impact of Non-Trivial Plus- and T-shaped obstacles on spiral wave Dynamics

Sharifa Yesmin, **Pritam Boro**, Dr. Dhriti Mahanta*
Gauhati University, India - yesminsharifa1@gmail.com
Pritamboro007@gmail.com
mdhriti@gauhati.ac.in*

Abstract: The interaction between spiral waves and inert heterogeneities in chemical and biological systems, including the human heart, has been a subject of extensive research. Experiments and simulations have shown that spiral waves can get anchored to inert obstacles, which is referred to as pinning.[1] [2] Several studies have reported the behaviour of spiral waves in the presence of conventional inert heterogeneities such as rectangular and circular geometries that can stabilize or destabilize wave dynamics. Here we focus on more complex geometries and explore in detail how unconventional geometries, such as T-shaped and plus-shaped obstacles, influence the dynamics of spiral waves. Our experiments are based on the ferroin catalysed BZ reaction and numerical simulations involve the two-variable Barkley model given by the following equations:

$$\frac{\partial u}{\partial t} = \frac{1}{\epsilon}\left[u(1-u)\left(u - \frac{u+b}{a}\right)\right] + D_u \nabla^2 u$$
$$\frac{\partial v}{\partial t} = u - v + D_v \nabla^2 v$$

Here u and v are the concentrations of the activator and inhibitor. The values of the system parameters were taken as a=0.84, b=0.07 and diffusion constants are D_u= D_v=1.0.

Our simulations revealed that in contrast to the highly regular oscillations characterized by a uniform frequency and wavelength in the presence of circular obstacles or in the absence of obstacles, the introduction of unconventional geometries such as T- shaped or plus- shaped obstacles induces some significant alterations of spiral dynamics. The wavefronts lose their uniformity often forming grouped clusters rather than evenly spaced trains. When multiple obstacle shapes are combined, an additional layer of complexity emerges. Interactions between obstacles may exhibit cooperative or competitive effects on spiral dynamics. In addition to the obstacle shape, the excitability parameter (ϵ) is found to strongly influence the spiral wave dynamics.

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Effect of Colored Noise on the dynamics of Coupled Thermoacoustic Oscillators

Robert Rai[1], Yuvrajsingh Patil[1], Lipika Kabiraj[2], Aditya Saurabh[3], Chandrakala Meena[1]
[1] *Department of Physics, Indian Institute of Science Education and Research, Pune 411008, India* - robert.rai@students.iiserpune.ac.in
[2] *Department of Mechanical Engineering, Indian Institute of Technology Ropar, Punjab 140001, India*
[3] *Department of Mechanical Engineering, Indian Institute of Technology Kanpur, Uttar Pradesh 208016, India*

Abstract: Thermoacoustic systems exhibit nonlinear behavior that is strongly influenced by stochastic fluctuations arising from turbulence and unsteady heat release. Earlier work have examined the effect of colored noise on single thermoacoustic oscillators[1], and how white noise influences the dynamics of coupled thermoacoustic systems[2]. However, the effect of colored noise on coupled systems has not been studied yet.

In this work, we investigate how colored noise with finite correlation time modifies the dynamics of prototypical coupled thermoacoutic systems comprising two horizontal Rijke tubes that interact through dissipative and time-delay coupling. The noise is modeled by an additive Ornstein-Uhlenbeck process, since the external noise and heat release fluctuations are expected to have a low-pass nature[3]. By systematically varying the correlation time and spectral properties of the noise, we analyze its role in shaping key dynamical features such as oscillation amplitude modulation, synchronization behavior, and transitions to amplitude death. The outcomes shed light on how colored noise interacts with coupling mechanisms and alters stability boundaries, offering new insights relevant to prediction and control of thermoacoustic instabilities in practical combustor configurations.

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Nonlinear Dynamics of Tree Swaying as a Biomechanical Oscillator

Adwdait A. Kulkarni[1], Sukruta A. Pethe[1,2], Kiran M. Kolwankar[1]
[1] *Department of Physics, Ramniranjan Jhunjhunwala College, Ghatkopar (West), Mumbai 400086, India*
[2] *Department of Physics, Sathaye College, Vileparle (East), Mumbai 400057, India*

Abstract:

The swaying motion of trees provides a compelling example of a biomechanical oscillator driven by environmental forcing. Many existing models describe this phenomenon using purely mechanical frameworks, often neglecting the biological characteristics of plant structures [1]. An early attempt to incorporate biological effects introduced inherent nonlinearities by modeling tree motion as a Duffing oscillator; however, this approach primarily emphasized hard-spring behavior, employed biologically unrealistic soft-spring parameters, and relied on truncated gravitational restoring forces [2].

In this work, we revisit a more recent modeling framework that retains the full, untruncated gravitational contribution [3],[4] and reassess it using biologically inspired parameter values. Experiments on multiple plant species indicate that the restoring force is more accurately described by a soft-spring response, which bends the resonance curve toward lower frequencies. This modification significantly alters the system dynamics, leading to the onset of chaotic oscillations at substantially lower forcing frequencies compared to hard-spring predictions.

Using these experimentally motivated parameters, we analyze two-segment and three-segment tree models. Under periodic forcing, representing natural wind fluctuations, both models exhibit rich nonlinear behavior, including robust chaotic dynamics that emerge at lower forcing frequencies and persist with increasing structural complexity. Under constant wind forcing, experimental observations reveal sustained oscillations, whereas the deterministic model converges to a stable fixed point. By introducing a small amplitude of additive white noise, we recover persistent oscillations consistent with experiments, providing clear evidence of noise-induced oscillations [5].

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Dynamics-Informed Reservoir Computing Using Visibility Graphs for Complex Nonlinear Systems

Vedanshee Patel[1], Bhavya Desai[2], Prosenjit Kundu [3], Mukesh Tiwari[4]
Complex Systems Lab (CSys Lab), School of Technology(SoT), Dhirubhai Ambani University (DAU), Gandhinagar, India
202203003@dau.ac.in, 202203019@dau.ac.in, prosenjit_kundu@dau.ac.in, mukesh_tiwari@dau.ac.in

Abstract:
Modelling and predicting complex dynamical systems is inherently difficult due to strong nonlinearity, chaotic behaviour, and dependencies spanning multiple time scales. Reservoir Computing (RC), particularly through Echo State Networks (ESNs), offers an efficient, model-free approach by training only a simple linear readout while keeping the recurrent dynamics fixed. However, most conventional reservoir designs rely on random connectivity, which often limits interpretability and can lead to stability issues.

Recent studies have shown that incorporating structural information from time-series data into reservoir computing can improve both model performance and interpretability. Building on this line of work, we examine the effects of using dynamics-informed reservoir constructions based on Natural Visibility Graphs (NVGs) and Horizontal Visibility Graphs (HVG). These methods transform time-series data into graph representations that retain the temporal ordering and geometric characteristics of the underlying signal. The resulting adjacency matrices for both weighted NVGs (wNVGs) and wHVG and unweighted NVGs and HVG are then used directly as reservoir connectivity structures. We assess this approach on the Lorenz Attractor, separation of chaotic signals of the Lorenz attractor, Parameter Estimation of the Logistic map, Bursting in Rulkov Neurons, Bitcoin daily data and S&P 500 daily data. Our findings indicate that wHVG-based reservoirs with time-difference-weighted edges provide a robust alternative to randomly connected reservoirs, with improved dynamical stability and reliable predictive performance.

Synchronization of Stuart-Landau Oscillators by Adaptive Coupling

Jubin George Mathew[1] , Prof. G Ambika[1]
[1] *Indian Institute of Science Education and Research, Thiruvananthapuram – 695551, India*
jubingeorge21@iisertvm.ac.in

Abstract: Synchronization is an important emergent phenomenon observed in nonlinear systems interacting on complex networks. Choosing an appropriate coupling scheme is relevant in deciding optimum strategies and desired outcomes. In this work, we investigate first the effect of the Connect-In-Range scheme on coupled Stuart-Landau oscillators. The coupling at every time step is a function of the pairwise distance between two oscillators. We consider two cases: a constant coupling strength when two oscillators are within a chosen range and a coupling strength proportional to the distance between pairs of oscillators. In the first case, we report the formation of clusters, the number of which varies with the range. In the second case, we study the dependence of asymptotic synchronization on changes in the coupling constant and network structure. Furthermore, we extend this to edge-based local adaptive coupling, which exhibits faster synchronization compared to state-dependent coupling.

Urban Street Network Complexity in India: What Shapes Their Structure?

Aradhana Singh[1], Ritish Khetarpal[1], **Amod Rai**
[1] *Department of Physics, IISER Tirupati, India*-aradhana22singh@gmail.com
[2] *Department of Physics, IISER Tirupati, India*- ritishkhetarpal@students.iisertirupati.ac.in
[3] *Department of Physics, IISER Tirupati, India*- amod20243412@students.iisertirupati.ac.in

Abstract: The topology of city street networks (SNs) is bounded by spatial embedding, which enforces non-crossing links and prohibits random node placement or overlap. This raises a fundamental question: how do such spatial constraints shape network topology? To address this, we analyze the SNs of 33 Indian cities. All studied networks exhibit small-world properties characterized by high clustering and efficiency. Notably, the efficiency of the empirical networks exceeds that of corresponding degree-preserved random networks. This elevated efficiency is attributed to the right-skewed distribution of Dijkstra's path lengths, a pattern also observed in random planar networks. While the average Dijkstra path length scales with the mean street length, the overall distribution is more strongly influenced by geometric structure and planarity than by scaling alone. Furthermore, we observe a clear preference for length-based connectivity: shorter streets preferentially connect to other short streets and longer ones to longer counterparts, which is more pronounced in empirical SNs than in degree-preserved or random planar networks. However, planar networks, preserving the spatial coordinates of empirical networks, replicate this connectivity pattern, pointing to the role of spatial embedding. Finally, the resilience of the Indian SNs to edge-based random errors and targeted attacks remains independent of the SN's size, indicating that other factors, such as geographical constraints, substantially influence network stability. Our findings provide insights into how spatial constraints shape the topology and function of urban street networks. This work has been published in [1].

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Effect of higher-order interactions on tipping cascades on complex networks

Richita Ghosh[1], Manish Dev Shrimali[1]
[1] *Central University of Rajasthan, India* - richita8594@gmail.com

Abstract: Tipping points are critical thresholds of parameters where tiny perturbations can lead to abrupt and large qualitative changes in the systems. Many real-world systems that exhibit tipping behavior can be represented as networks of interacting multistable units, such as vegetation patches or infrastructure networks, undergoing both pairwise and higher-order interactions. In this work, we explore how higher-order interactions shape the dynamics of tipping cascades in a conceptual system with tipping points. Numerical simulations on random, scale-free, and small-world networks reveal that higher-order interactions can induce cascades even at coupling strengths where only pairwise interactions fail to do so. We also investigate the interplay of the pairwise and higher-order coupling strengths in random networks and illustrate the route to cascades through bifurcation diagrams. These results have also been demonstrated on real-world social networks. Apart from this, we show that repulsive higher-order interactions suppress tipping cascades at coupling strengths where pairwise interactions would cause them, and shift the cascade route from a saddle-node to a supercritical pitchfork bifurcation. Our results highlight the critical role of higher-order interactions in shaping cascade dynamics, offering insights for anticipating and mitigating critical transitions in ecosystems, climate systems, and socio-technical infrastructures.

Earthquake and Aftershock Statistics from Energy Transport on Complex Networks

Sarvesh K. Upadhyay[1], Vimal Kishore[1] and R. E. Amritkar[1,2]
[11] *Department of Physics, Banaras Hindu University, Varanasi 221005, India*
[2]*Physical Research Laboratory, Ahmedabad 380009, India*

Abstract: We propose a model of energy transport in which discrete energy quanta move and interact on complex networks to investigate the fundamental mechanisms underlying earthquakes and their aftershocks Our approach is motivated by well-established observations in seismology, and therefore explicitly incorporates two essential ingredients: the dissipation of energy that follows each earthquake and the gradual readjustment of stress within the crust. we introduce an intuitive and statistically grounded definition of earthquake magnitude: it is given by the deviation of the instantaneous number of quanta from its long-term mean, expressed in units of the standard deviation. Remarkably, by relying solely on the intrinsic stochastic dynamics of quanta moving through the network, the model spontaneously generates sequences of earthquakes and aftershocks without imposing any external forcing or tuning. The synthetic time series produced by the model show excellent agreement with the three central empirical laws of seismicity. Specifically, they reproduce the Omori–Utsu law for the decay of aftershocks, the Gutenberg–Richter law for the distribution of event magnitudes, and Bath's law for the magnitude difference between main shocks and their largest aftershocks. Finally, we validate the model by comparing its predictions with real earthquake data.

Dynamics and Stability of Dark-Bright Solitons in Spin-Orbit Coupled Bose-Einstein Condensates

, **K. Rajaswathi**[1], R. Ravisankar[2], R. Radha[3], P. K. Mishra[4] and P. Muruganandam[1]
[1]*Department of Physics, Bharathidasan University, Tiruchirappalli 620 024, Tamil Nadu, India* - rajaswathi.bec@bdu.ac.in
[2]*Department of Physics, Zhejiang Normal University, Jinhua 321004, PR China.*
[3]*Centre for Nonlinear Science (CeNSc), Government College for Women (Autonomous), Kumbakonam 612001, Tamil Nadu, India.*
[4]*Department of Physics, Indian Institute of Technology Guwahati, Guwahati 781039, Assam, India.*

Abstract: We investigate dark-bright solitons in Bose-Einstein condensates with spin-orbit coupling and Rabi coupling, confined by harmonic and box traps. Solitons are localized wave packets with particle-like properties and are well-suited for study in Bose-Einstein condensates due to their tunable inter-atomic interactions. The presence of spin-orbit coupling can disrupt the stability of solitons, leading to changes in their shape. By utilizing numerical solutions of the Gross-Pitaevskii equations, we analyze how interactions, spin-orbit coupling, and Rabi coupling affect the behaviour of solitons. In a harmonic trap, we observe stable dark-bright solitons; however, spin-orbit interaction induces soliton motion. We also explore the reflections of single and multiple solitons without energy loss in a boxlike trap. The inclusion of spin-orbit coupling leads to soliton oscillations. Additionally, we perform stability analysis using the Bogoliubov-de Gennes excitation spectrum and explore non-equilibrium dynamics by simulating varying strengths of spin-orbit coupling.

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Obstacle mediated reconnection of straight scrolls in an excitable system

Rituporna Kashyap, Dhriti Mahanta*
Gauhati University, India - ritupornakashyap08@gmail.com
mdhriti@gauhati.ac.in

Abstract: The study of scroll waves in chemical media is of significant interest as it reveals crucial information on the propagation of reentrant waves in cardiac tissue [1]. It has been established that the dynamics of scroll waves may vary depending on the configuration of their respective filaments, a one-dimensional curve around which they rotate [2]. The interaction of scroll waves with other excitation waves and unexcitable heterogeneities often results in phenomena such as filament reconnection [3]. In this study, we focus on the reconnection phenomena occurring when two parallel scroll waves with I-shaped filaments interact in the presence of a spherical obstacle. Our experimental study is based on the ferroin-catalyzed Belousov-Zhabotinsky reaction and the numerical simulations are performed using the two variable Barkley model given by the following equations:

$$\frac{\partial u}{\partial t} = \frac{1}{\epsilon}\left[u(1-u)\left(u - \frac{u+b}{a}\right)\right] + D_u \nabla^2 u$$
$$\frac{\partial v}{\partial t} = u - v + D_v \nabla^2 v$$

Here u and v are the concentrations of the activator and inhibitor. The values of the system parameters were a=0.84, b=0.07, ϵ=0.02 and diffusion constants are D_u= D_v=1.0.

In the presence of an obstacle, at a certain inter-filament distance, the straight filaments of two parallel scroll waves attract each other at their closest point of contact. This interaction causes them to crossover and rearrange, resulting in the formation of two new U-shaped filaments. This reconnection phenomenon occurs only because of the presence of obstacle in between the two waves. Without the obstacle, the two scroll waves would rotate independently around their respective filaments without any interaction or rearrangement. Additionally, the orientation of obstacles influences the reconnection dynamics. This result offers valuable insights from both fundamental mechanism and biomedical perspectives.

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Noise induced stochastic switching in surface acoustic wave delay coupled two phase oscillators

Pratibha Yadav[1], Shashank Shekhar Jha[1]
[1] *Department of Physics, Nalanda College, Biharsharif, Nalanda-803101, Bihar, India* - ssank.5bhu@gmail.com

Abstract: In this study, we investigate the influence of additive white noise on a pair of surface acoustic wave (SAW)–coupled phase oscillators [1]. In the absence of noise, two delay-coupled oscillators synchronize to a common frequency for appropriate coupling parameters. When the oscillators are detuned, however, exact in-phase or anti-phase synchronization no longer occurs. Instead, the oscillators exhibit a finite phase difference determined by the locking frequency and the detuning [2]. Building on this framework, we analytically examine the phase evolution of two identical SAW delay–coupled phase oscillators in the presence of stochastic perturbations.

To make the analysis tractable, the original delay differential system is reduced to an equivalent non-delayed Langevin equation. This reduced stochastic phase model enables a systematic investigation of the noise-induced distribution of instantaneous frequencies and the associated residence times on different dynamical orbits [3]. Our results reveal that, under the influence of weak additive noise, the system explores only a small subset of the available noiseless orbits. Remarkably, the fraction of these visited orbits scales as the square root of the intrinsic delay time and is found to be largely independent of the coupling strength.

We further analyze how the delay of the SAW delay line, the coupling strength, and the intrinsic orbital frequency each contribute to the broadening of frequency distributions and the scaling of average residence times. The study highlights that the noise sensitivity of an orbit is strongly influenced by the coupling strength of the SAW device, whereas the effect of the delay is comparatively minor. These findings provide new insight into noise-induced dynamics in delay-coupled SAW oscillators and contribute to the broader understanding of synchronization robustness in coupled nonlinear systems.

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Asymmetric sampling enhances cooperation among procedurally rational players

Malay Garg[1], Joy Das Bairagya[2], Srinivas Arigapudi[3], Sagar Chakraborty[4]
[1] *Indian Institute of Technology Kanpur, India* - malayg23@iitk.ac.in
[2] *Indian Institute of Technology Kanpur, India* - joydas@iitk.ac.in
[3] *Indian Institute of Technology Kanpur, India* - arigapudi@iitk.ac.in
[4] *Indian Institute of Technology Kanpur, India* - sagarc@iitk.ac.in

Abstract: The classical framework of game theory, built on the assumption of perfect rationality, struggles to explain real-world strategic interactions. The Prisoner's Dilemma, for instance, predicts a pure Nash Equilibrium of mutual defection, a result that consistently conflicts with observed human behaviour [1]. This gap has motivated models of bounded rationality [2], where players learn by sampling their actions. Current literature on sampling typically assumes that players sample all actions equally — in the Prisoner's Dilemma (PD), for example, players sample cooperation as frequently as defection; one may term it symmetric sampling. However, asymmetric sampling arises naturally in both biological and social systems. Foragers, constrained by energy and time, disproportionately exploit high-yield patches while sampling low-yield regions only sparsely. Human decision-makers further exhibit well-established cognitive biases: alternatives believed to be promising are examined more thoroughly than those expected to perform poorly. Such bounded and selective exploration generically produces persistent asymmetric sampling patterns. Hence, moving beyond the assumption of symmetric sampling [4], we develop a general framework for bounded rationality where players can sample strategies a different number of times. Applying this framework to the Prisoner's Dilemma changes the outcome: Players who evaluate strategies by sampling can maintain persistent cooperation. In fact, by sampling cooperation more frequently, the rate of cooperation can approach as high as 50% at equilibrium. When the game is played between two distinct player types that can sample their own actions different number of times [3], the cooperation rate is seen to go even above 50%. Our numerics show that when one player type explores cooperation extensively, while the other type samples the alternate strategy only rarely, the rate of cooperation for the cooperating player can exceed significantly beyond 50%.

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Coevolution of normative conformity and strategic behaviour under payoff-biased social influence

Prosenjit Roy[1], Sagar Chakraborty[2]
[1] *Indian Institute of Technology Kanpur, India* - prosenjit21@iitk.ac.in
[2] *Indian Institute of Technology Kanpur, India* - sagarc@iitk.ac.in

Abstract: Understanding how conformity and payoff-based decision-making jointly shape behavioural evolution is essential for explaining phenomena such as norm formation, cooperation, and cultural stability[1, 2]. Nonlinear q-voter model without noise describe how individuals adopt behaviours through social conformity[3], whereas evolutionary game theory (EGT) captures adaptation driven by payoffs[4]. Real populations rely on both forces, and individuals may also change how strongly they conform[5].

We develop a unified framework that integrates the nonlinear q-voter model with payoff-biased imitation. First, we analyse a payoff-weighted q-voter model and show how strength of payoff modifies standard outcomes, shifting stability regions and enabling interior equilibria even in games such as the Prisoner's Dilemma.

Next, we introduce a heterogeneous population composed of payoff-driven updaters ($q = 1$) and updaters influenced by both payoff and conformity ($q > 1$). The resulting coupled dynamics exhibit rich behaviours—including coexistence, bistability, and dominance of one updating rule—depending on selection intensity and the proportion of conformity-based individuals.

Finally, we allow conformity itself to evolve through social copying. This produces a coevolutionary system in which both strategies and conformity levels change over time. Numerical analysis shows that conformity can become evolutionarily favoured, vanish, or coexist with payoff-driven updating.

Overall, our model provides a general framework for understanding how frequency-dependent payoff bias and conformity bias jointly shape the evolution of social behaviour in populations.

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Teaching small networks to synchronize big systems

Pritikana Pal*, Anath Bandhu Das, and Pinaki Pal
Department of Mathematics, National Institute of Technology, Durgapur 713209, India
* **Electronic mail:** pritikanapal496@gmail.com

Abstract: The emergence of synchronization in networks of interacting oscillators is a remarkable collective phenomenon, observed from biological systems to engineered infrastructures. The Kuramoto model provides a foundational framework for studying these dynamics, offering both an elegant mathematical description and a quantitative measure for the degree of synchronization. A central finding in this field is that a network's structural topology critically governs its synchronizability. In this work, we propose a computationally efficient method to optimize this property by evolving only a small, machine-learned representative subsystem rather than the entire network. We demonstrate that optimizing this reduced model effectively enhances global synchronization, achieving performance comparable to full-network optimization but at a significantly lower cost due to a drastic reduction in rewiring operations. Furthermore, we investigate how the synchronizability of the full network depends on the specific machine learning algorithm used to generate the subsystem, providing insights into the relationship between network reduction techniques and functional performance.

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Electronic circuit Realization of Nonlinearly Coupled Rössler Oscillators

Anukrati Agrawal[1]
[1] *Central University of Rajasthan, India* - 2021imsph006@curaj.ac.in

Abstract: Synchronization in coupled chaotic oscillators has been extensively studied both numerically and experimentally, including drive–response configurations and electronic circuit realizations. Previous works have demonstrated experimental implementations of chaotic oscillators in analog circuits and explored synchronization, phase transitions, and control mechanisms in coupled nonlinear systems. In particular, electronic realizations of Rössler and related oscillators have been used to validate theoretical predictions of synchronization and control strategies [1, 2].
In this work, We present a combined numerical and experimental investigation of synchronization in nonlinearly coupled Rössler chaotic oscillators. The dynamics of Two identical oscillators are coupled nonlinearly through the x^3-variable, Numerical simulations show that increasing the coupling strength drives the system from a desynchronized chaotic state to complete synchronization. To experimentally verify these results, an analog electronic circuit realization of the coupled Rössler system is implemented using operational amplifiers and JFET-based nonlinear elements. The experimental observations closely agree with numerical predictions, confirming that nonlinear coupling provides an effective mechanism for controlling chaotic synchronization in real physical systems.This study extends earlier drive–response and circuit-based investigations by demonstrating synchronization control through nonlinear coupling in a physically realizable electronic system.

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Enhancing Disease Control in Resource-Limited Settings through Bidirectional Behavioral Responses

Sujit Halder[1], Sudipta Panda[1], Amit Samadder[1] Joydev Chattopadhyay[1*]
[1] *Agricultural and Ecological Research Unit, Indian Statistical Institute, Kolkata, India.*
sujithalder01@gmail.com, sudiptapanda1994@gmail.com, math.amitsamadder18@gmail.com, joydev@isical.ac.in '*'- corresponding author

Abstract: Human behavior plays a pivotal role in mitigating the global spread of infectious diseases, rendering it an indispensable characteristic of effective disease control efforts. While prior research has examined behavioral changes in disease control either through the force of infection or prevalence-based recruitment, the combined effects of these approaches remain largely unexplored. To bridge this gap, we develop a mathematical model that integrates behavioral modifications from both perspectives, with a focus on resource-limited settings—a critical factor for managing re-emerging diseases. Our analytical results indicate that disease dynamics are influenced not only by the basic reproduction number ($\mathcal{R}_0$) but also regulated by a threshold value ($\mathcal{R}_c$), which can lead to disease persistence through backward bifurcation [1, 2]. The model reveals a complex dynamic view, highlighting the intricate role of behavioral modifications in suppressing multiple waves of infection. To optimize behavioral strategies, we introduce a contour-area optimization method to identify the most effective responses. Using real-world data from the Monkeypox outbreaks in the U.S. and the Democratic Republic of Congo (spanning January 7 to August 13, 2024), we estimated critical parameters for both regions [3]. The results highlight a significant reduction in $\mathcal{R}_0$ when behavioral interventions targeted both transmission pathways, compared to focusing solely on one. Furthermore, we provide short- and long-term forecasts of the effects of these interventions, offering actionable insights for resource-constrained countries. This research underscores the importance of behavioral adaptations in strengthening disease control measures and advancing sustainable public health efforts, even in regions with sparse resources.

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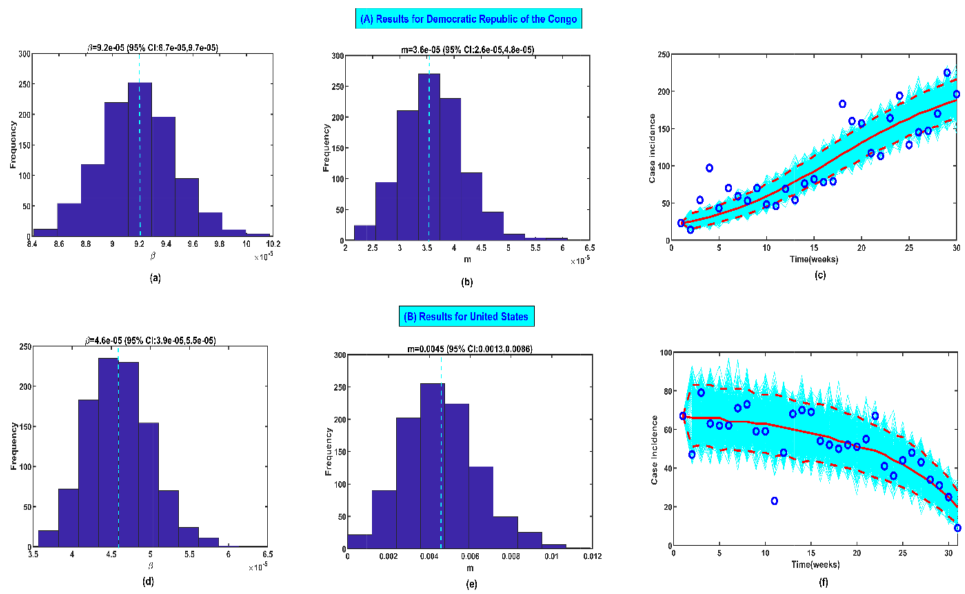

Figure 1: We fit the model to weekly reported monkeypox cases in the Democratic Republic of Congo (DRC) and the United States (US) from January–August 2024. Parameter uncertainties were quantified using the methodology described in our manuscript, with empirical parameter distributions obtained from 1,000 Poisson-based bootstrap realizations (true parameter values indicated by vertically dotted cyan lines). Blue circles represent the observed data, the solid red line in the bottom-left panel shows the best-fit model trajectory, and dashed red lines denote the corresponding 95% confidence bands. Cyan lines show 1,000 simulated epidemic curves under a Poisson error structure. For the DRC, RMSE = 27.83, MAE = 22.88, and MAPE = 0.2558; for the US, RMSE = 1

Influence of an Inert Spherical Obstacle on the Dynamics of Scroll-Wave Interactions

Sharifa Yesmin[1], Dhriti Mahanta[2]*
[1] *Gauhati University, India* - yesminsharifa1@gmail.com
[2] *Gauhati University, India* - mdhriti@gauhati.ac.in

Abstract: Scroll waves are three-dimensional excitation vortices that arise in excitable media, and the one-dimensional curves around which they rotate are known as filaments. Reconnection of scroll filaments typically occurs only within a narrow range of separation distances [1, 2]. In this work, we demonstrate through experiments based on the Belousov–Zhabotinsky reaction and numerical simulations using the Barkley model that the introduction of an obstacle significantly extends this reconnection range. Our results show that scroll waves, which continue to rotate independently in a homogeneous medium, can undergo obstacle-mediated reconnection when a spherical obstacle is placed between them. The Barkley model is given by the following equations:

$$
\begin{aligned}
\frac{\partial u}{\partial t} &= \frac{1}{\epsilon} u(1-u)\left(u - \frac{u+b}{a}\right) + D_u \nabla^2 u, \\
\frac{\partial v}{\partial t} &= u - v + D_v \nabla^2 v.
\end{aligned} \tag{1}
$$

Here, u and v represent the concentrations of the activator and inhibitor, respectively. We set the parameter values to $a = 0.84$, $b = 0.07$, and $\epsilon = 0.02$, and the diffusion coefficients to $D_u = D_v = 1.0$.

In addition to reconnection behavior, pinning is another interesting phenomenon. sometimes these waves can anchor to unexcitable heterogeneities present in the system, and this phenomenon is known as pinning [3]. We further observe that within a specific range of separation distances, the filaments become attached to the surface of the obstacle, indicating robust and sustained pinning dynamics.

Both numerical simulations and experimental results confirm reconnection and pinning phenomena at a certain distance. The results reveal that the geometry of the heterogeneity strongly influences the dynamics of the filament. Overall, our findings demonstrate that the presence of an inert heterogeneity significantly alters the dynamics of scroll-waves, influencing interaction mechanisms, their behavior, and long-term evolution.

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Transitions to Synchronization in coupled Kuramoto oscillators on Stochastic Block Model networks

Ankit Kumar Mishra
[1] *Central University of Rajasthan, India-* a9kitkumii@gmail.com

Abstract: This poster investigates synchronization in Kuramoto oscillators arranged in the Stochastic Block Model (SBM). By varying the coupling strength and inter/intra-community connectivity, we observe a transition from incoherent dynamics to synchronization across the network. The results highlight the significance of network structure in collective dynamics and show how modularity affects synchronisation. This work offers a clear framework for understanding synchronization in modular systems and may apply to real-world networks.